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AIRCRAFT FIRE SAFETY

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

PREPARED FOR
NORTH ATLANTIC TREATY ORGANIZATION

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on

Aircraft Fire Safety

NORTH ATLANTIC TREATY ORGANIZATION



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15. Abstract	<p>These Proceedings consist of the 28 papers presented, including the discussions after each paper, and the Round Table Discussion at the end of the Meeting for the 45th Propulsion and Energetics Panel Meeting on Aircraft Fire Safety held in Rome, Italy 7-11 April, 1975. The papers from eight nations were divided into 6 Sessions: New Aircraft Fuels (3 papers), Aircraft Fuel Handling (4 papers), Interior Materials and Associated Gas Emissions (8 papers), Fire Protection Technology (5 papers), Extinguishment (4 papers), Crash Evaluation (4 papers). The final session was a Round Table Discussion reviewing progress and recommending future programs. Topics include wide-cut vs kerosene issue, mist suppressing additives, fuel tank inerting, use of halons, special polymers, toxic fume generation, powder and foam extinguishant comparisons, as well as delivery systems, dynamic modelling, fundamental analysis, and vulnerability.</p>		

**NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT**

**ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD
GROUPE CONSULTATIF POUR LA RECHERCHE ET LE DEVELOPPEMENT AEROSPATIAL**

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AIRCRAFT FIRE SAFETY

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The Propulsion and Energetics Panel wishes to express its thanks to the hosts, the Italian National Delegates to AGARD, for the invitation to hold the meeting in Rome, Italy, and for the provision of the necessary facilities and personnel to make the meeting possible.

PREFACE

The meeting consisted of a review of fire, toxic and explosion hazards associated with aircraft accidents and fires. A major portion of the meeting dealt with prevention techniques: inerting, isolating, and survivability design. The impact of changes in fuel specifications on aircraft fire safety were also reviewed, along with evaluation of test techniques for flame propagation and extinguishment, as well as toxic product generation. Actual aircraft accidents were reviewed and analyzed and the meeting culminated in a Round Table Discussion by experts in the field of Aircraft Fire Safety, who reviewed progress and recommended the areas for future emphasis.



Au cours de cette réunion ont été passés en revue les dangers d'inflammation, de toxicité et d'explosion qui accompagnent les accidents et incendies d'avions. La majeure partie des exposés a été consacrée aux techniques préventives: inertage, isolement et conception en vue de la survie. Parmi les sujets traités, citons: l'influence, sur la sécurité en matière d'incendie, des changements intervenant dans les spécifications des carburants, l'évaluation des techniques d'essais en ce qui concerne la propagation des flammes et leur extinction, ainsi que l'émission de produits toxiques. Il a été procédé à l'examen et à l'analyse de divers accidents d'avions, et la réunion comprenait une "Table Ronde" à laquelle ont pris part des experts en matière de protection contre les incendies d'avions, qui ont dressé le bilan des progrès réalisés à ce jour et ont recommandé un complément de recherche dans certains domaines spécifiques.

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TECHNICAL EVALUATION REPORT
of the
PROPULSION AND ENERGETICS PANEL
45TH MEETING

on
AIRCRAFT FIRE SAFETY
by

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The success and response to the material presented at the 45th Meeting of the AGARD Propulsion and Energetics Panel on Aircraft Fire Safety made it most apparent that this field requires a greater exchange of technological information among the NATO nations. This meeting and the previous one held in 1971 were a few of the rare international meetings on this important subject.

As is the case of most developmental areas an archival literature does not exist and most information is reported in "in-house" documents. Because of lack of contact among many working in this field, it has become apparent that there has been great duplication of effort. Considering the level of support for research and development in fire safety matters, most attending the meeting agreed that AGARD would serve a most important function if the Propulsion and Energetics Panel were to establish a Working Group to coordinate efforts, evaluate progress, and recommend safety improvements to both military and civilian aviation authorities.

The 45th PEP Meeting gave good evidence of progress made. The following can be considered as some highlights of the meeting:

1. Increased evidence was presented that the low volatility fuels of the kerosene type have superior fire safety and combat survivability characteristics compared to the wide-cut, high volatility fuels. Availability and cost of converting to high energy ignition systems have been the factors hindering the use of kerosene fuels for military applications.
2. The use of mist suppressing additives has been shown to markedly increase the fire resistance of low volatility kerosene type fuels under simulated crash conditions. The use of these agents appears to be the most attractive of the modified fuel approaches. Pumping problems have been solved, although related shear stability and polymer degradation difficulties still exist.
3. The feasibility of separating oxygen from air so that the remaining nitrogen may be used for fuel tank inerting has been shown with the use of semi-permeable membranes. Additional Technical development effort is required to demonstrate suitability for aircraft applications.
4. Further evidence to the effectiveness of the halons as fire suppressants was presented.
5. It was shown that improvements in fire safety can be achieved by the use of polymers possessing certain basic thermo-chemical parameters such as char.
6. Proof was given that smoke and chemicals causing physiological mal-functioning have played a much greater part in airline crashes than most have generally thought. This evidence suggests that strong consideration should be given to the redesign of air breathing systems and procedures, as well as to isolating the pilot's cabin.
7. Although foam is the primary form of fighting aircraft ground fires, progress has been made in the use of powders. More fundamental work is needed in this area.
8. Progress has been made in the dynamic computer modelling of the fuel environment ignition hazards, and vulnerability of regions adjacent to and within fuel tanks.
9. The necessity of paying more attention to reaching crash fire areas was dramatized. A novel rocket launched fire-fighting package for remote areas was delineated.
10. More fundamental work was encouraged so that better understanding of ignition, flame spread, and extinguishment could be obtained and small scale test methods to evaluate non-flammable materials could be developed. A detailed report on the current understanding of the flame spread process was given.

Other valuable information exists in the thirty four papers presented. The Conference Proceedings should be examined for details.

SAFETY FUEL RESEARCH IN THE UNITED KINGDOM*

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SUMMARY

Development in the UK of aircraft fuels which resist fire in a crash has concentrated almost entirely on polymeric additives which prevent fuel mist formation. At 0.3% concentration these prevent kerosine fires under realistic crash conditions with both flame and heated duct ignition sources. High internal phase ratio emulsions gave no fire resistance in these tests.

Early additives caused considerable rumping difficulties at low temperatures. The latest additive, FM9, has largely overcome these. After degradation immediately before the engine control system, FM9 modified kerosine raised no serious problems during an eight hour Spey engine test. Degradation, which is necessary before the engine, must not be allowed to occur too early in the fuel system however, otherwise fire resistance would be lost; much effort is currently devoted to this aspect. Methods of introducing the additive are also under investigation as is the possible extent of water compatibility and filtration problems.

1 INTRODUCTION

In 1967 work was begun in Materials Department, RAE, aimed at producing fuels which would withstand fire in a severe but survivable aircraft crash. It was assumed that in a typical crash the aircraft would be damaged while still moving forward and that fuel could leak from damaged tanks or lines into a high speed airstream. This would lead to the formation of a fine mist which could readily ignite, thereby covering large areas of the aircraft in a fireball. While the burning mist might only last for a few tens of seconds it would inevitably ignite any major fuel spillage in the vicinity of the aircraft, thereby producing a longer lasting and therefore more destructive, fire. It was therefore argued that three properties would be important in affecting the incidence of fire and subsequent evacuation of passengers and crew:

- 1) Fuel mobility.
- 2) Tendency to form mists.
- 3) Rate of flame spread over spilled fuel.

Some work has been done on thickened fuels (mainly high-internal-phase-ratio emulsions) since fuels of this type should spill less readily from a damaged aircraft. By far the greater part of the programme, however, has been devoted to fuels containing mist-suppressing additives developed and produced under Ministry Contract by ICI Ltd, Paints Division. Although these additives pose problems it was felt that they would be more easily overcome than those arising from the use of conventional thickened fuels. Clearly fuels can be ignited through the vapour or through the mist and there is no point in suppressing mist formation in a volatile fuel where the former mechanism is possible. Mist-suppressing additives are therefore only of use in fuels which are below their flash points and have only been considered in this programme for use in aviation kerosine.

2 FIRE RESISTANCE

During the safety fuel development programme, a large number of different candidate fuels has been considered. To assess the fire resistance of these materials it has been necessary to use a screening test needing only a small quantity of fuel. The minitrack test¹ has been used for this purpose. A cylindrical fuel tank (40 cc) is accelerated to a speed of 38ms⁻¹ and then rapidly decelerated by a braking system (average deceleration 30 g). Immediately deceleration is applied the tank is opened up and fuel is spilled onto a series of ignition sources; the amount of flame produced is judged visually and depends on the fire resistance of the fuel. The speed and deceleration were adjusted to enable a correlation to be made between this test and full scale tests made using a rocket sled. It was found that the best fuel additives produced no flame in the minitrack test at a concentration of 0.1% w/w. By contrast conventional fuels such as kerosine, petrol or gas oil produced ten foot flames, the amount of flame being very little affected by the volatility of the fuel since, under these conditions, misting readily occurs.

Screening by the minitrack enabled the many hundreds of candidate fuels to be reduced to less than ten serious contenders. The fire resistance of these was investigated using a rocket-powered sled. The "standard" two-rocket test has been more fully described elsewhere². In essence a tank containing 45 litres of fuel is accelerated on a rocket sled up to a speed of 57 ms⁻¹ and then decelerated (F-10 g)

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by an aircraft arrester wire. On deceleration a slit on the forward facing edge of the tank is opened up and fuel is allowed to fall upon an array of ignition sources consisting of thirty six kerosine diffusion flames arranged on three gantries across the track. This test was chosen because of its severity and because the air shearing forces to which the fuel is subjected are similar to those to be expected in a severe but potentially survivable crash occurring at 80 mph. Such crash conditions were postulated using data supplied by USAVLABS² and the detailed arguments are set out in a previous AGARD paper³. Fuel containing FM3, the first additive to be produced, did not pass the standard test at 0.5% w/w although it passed a less stringent test using only one rocket and having lower speeds and decelerations. Six other additives, FM4-FM9, all showed no trace of fire in the "standard" test at a concentration of 0.5% w/w.

The fire resistance of three thickened fuels was investigated by this method, using a slit of 760 mm x 25 mm. The three fuels were Dow gel CX-7038, Petrolite emulsion EFA-104, both being studied at the time by FAA and one of the emulsions produced in our programme, Shell emulsion SE9. All three fuels produced large fires similar to kerosine. While these fuels have the advantage that under some conditions they would be retained more easily within the tanks, their fire resistance under the highly disruptive conditions to be found in a severe aircraft crash appears to be low. For this reason and because of the problems posed by the use of such materials in aircraft fuel systems, no further work on thickened fuels was done and the programme has been concentrated entirely on anti-misting kerosine. Typical fires produced by kerosine, an anti-misting fuel and a thickened fuel in the "standard" two-rocket test are shown in Figs 1, 2 and 3. Two additives, FM4 and FM9, both in Avtur at 0.3%, have been subjected to somewhat more severe conditions than the "standard" rocket sled test. The speed of the sled immediately before the arrester wire was raised to 78 ms^{-1} , corresponding to a severe crash at about 120 mph, without any trace of fire. This higher speed is now considered more applicable to landing and take-off conditions for modern aircraft.

An increase in fire resistance is also observed with the modified fuels when the ignition source is a heated duct: a horizontally mounted heated stainless steel duct, 610 mm long and 130 mm in diameter, was used for this purpose. With kerosine three types of behaviour were observed. At low duct temperatures no ignition occurred. At intermediate temperatures small fires occurred in the immediate vicinity of the duct after an ignition delay of some seconds; no mist explosion occurred because during the ignition delay period the mist had settled. Above a critical temperature, which in our experiments was about 500°C but which will depend on the exact experimental conditions, large fireballs were produced. Under these conditions the ignition delay is short in comparison with the mist settling time so that when the fuel reaching the duct spontaneously ignites the flame is able to propagate through the mist cloud.

With Avtur containing 0.3% FM4 this more hazardous high temperature region was prevented. At low duct temperatures no ignition occurred, while at higher temperatures (up to 645°C) only small localised fires were obtained; no fireballs were produced because there was no mist to allow propagation of these local fires. This is the behaviour to be anticipated with anti-misting kerosine since the mist-suppressing additives were considered unlikely to have any effect on the spontaneous ignition temperature of the fuel. Although such fuels do ignite they are considerably safer than kerosine because the fires produced are likely to be very much more localised. Typical fires produced by a hot duct from Avtur at temperatures above and below 500°C and from modified fuel at a temperature above 500°C are shown in Fig 4. Fire test results on the rocket sled at normal ambient temperatures are summarised in Table 1.

Recently, as a result of discussions with FAA, we have undertaken rocket sled tests of a number of fuels which have been used in the FAA aircraft crash test programme. Several of these fuels have been studied at elevated temperatures and the concentrations needed to pass the test at 95°F have been established where possible. These tests were undertaken as a result of the recognition that the two-rocket sled test represented one of the most severe of the smaller scale tests which have been used to study safety fuels. As such it should give a correlation with full scale crash tests and to enable such a correlation to be more readily established a large scale propane torch was included with the "standard" ignition array on a few runs, as was the case with the fourth FAA crash test. Some typical results are summarised in Table 2. For the limited range where comparison can be made the results are in agreement with the full scale tests. Dow fuel, for example, passed the test at a concentration of 0.7% and at normal ambient temperature as was found with the third FAA crash test. When the concentration was lowered to 0.5% it failed even at ambient temperature and would certainly have done so at 95°F, the conditions of the fourth crash test.

As the next part of the fire test programme we plan to run the rocket sled test with a Viper engine as the ignition source. In a short programme various engine running conditions will be investigated and attempts made to ingest both kerosine and FM9 modified kerosine into the engine intake to see whether there is any significant difference in behaviour.

3 HANDLING PROPERTIES

The work described in the previous section clearly demonstrates the considerable increase in fire resistance to be obtained from mist-suppressing additives when used in fuels at temperatures below their flash points. In order to achieve this fire resistance the physical and rheological properties of the base fuel have been altered and this might be expected to lead to problems elsewhere in the aircraft.

The first problem to arise was that of low temperature pumping. The first modified fuel to be used, containing FM3, caused a drop in the efficiency of a conventional aircraft centrifugal pump of about a factor of ten below that obtained with kerosine at -30°C ⁴. Later fuel modifiers, however, have given much more encouraging results. Using a miniature centrifugal pump as a screening test it has been possible to assess the relative pumpability of a number of modified fuels. This minipump has been used for candidate safety fuels in much the same way as the minitrack was used to screen fire resistance. From a 100 litre sample it is possible to obtain curves of pump efficiency vs delivery pressure over a range of pump speeds (2000 to 10,000 rpm) and temperatures (-35° to $+20^{\circ}\text{C}$). Furthermore the results appear to correlate well with data for pumpability obtained using full scale aircraft fuel pumps⁵, where large enough samples have been available for full scale tests to be made. Miniature pumping test results are shown in Table 3 for

five mist-suppressing additives. It can be seen how pumping efficiency has improved until with fuel containing the latest additive, FM9, a centrifugal pump gives efficiencies about 90% as high as with aviation kerosine at -35°C. FM9 fuel is also outstanding in that its pumpability is apparently independent of time. With other fuel modifiers the results were dependent on the length of time at which the fuel had been kept at low temperature. Table 3 also shows that with FM5 fuel pumping efficiencies are very low. For this reason FM5, an excellent additive in certain respects, was discarded early in the programme.

Although initial tests on many of the mist-suppressing additives studied in this programme indicated that there might be difficulties in the presence of water, work carried out by Shell Research Ltd has so far indicated no insuperable problems with anti-misting fuels⁶. Thus kerosine containing any of the additives FM4, 6, 7, 8 or 9 produced white lacy deposits when shaken with free water and bottle storage tests at Shell Research Centre with FM4 and FM9 showed that both fuels took up water far in excess of saturation levels for Avtur. However, pick up from an underlying water layer could be limited by venting the ullage space. In a simulated flight environmental rig, FM9 fuel was subjected to 100 six-hour flight cycles in which the fuel was progressively cooled with a reducing tank pressure and moist air was then admitted during the descent phase. At the end of the test there were no emulsified deposits in the tank, suggesting that, under practical conditions, water compatibility problems with FM9 fuel may not be as severe as was feared. This work is continuing.

Filtration tests at ambient temperature led to blockage of discs of less than 142 μ m porosity unless the fuel had been previously degraded. Using 10 μ m Purolator aircraft filter paper, four shearings through a diesel injector degraded FM9 fuel sufficiently to give acceptable filtration performance. With FM4 fuel this treatment was not quite sufficient.

Work on both the Thornton Flask test and a gas-driven coker without the test filter led Shell to conclude that FM9 fuel poses no great threat to the thermal stability of Avtur, although the effect on borderline fuels remains to be determined. Heat transfer coefficients of modified fuel are decreased by about 50% below that of base Avtur. This effect diminishes as the fuel is degraded, however, and after four passes through a diesel injector FM9 fuel produces a reduction in heat transfer coefficient of 5-11%. Apart from a slightly adverse effect on the wear of bronze on steel contacts, FM9 fuel appears to be beneficial to the lubricity of Avtur. It also raises the conductivity of base Avtur above that obtained with the recommended concentration of antistatic additive. This could pose some problems with fuel capacitance gauges.

While the six additives FM4-FM9 are all very similar with respect to fire resistance, the handling tests described in this section have shown marked differences between them. In particular the pumping results in Table 3 show that FM9 has considerable advantages over the other fuels. FM5 fuel was so difficult to pump that it was discarded, despite the fact that it and FM3 alone of the additives we have investigated showed no problems of water compatibility. Of the other additives, none show any advantage over FM9 and, on balance, FM9 is regarded as the best available mist-suppressing additive available to date.

4 ENGINE PROBLEMS

The fire resistance of FM9 fuel and similarly modified Avtur has been obtained at the price of making formation of fuel mists more difficult and the combustion chamber is therefore an area in which we must look for problems.

Early work on an Avon chamber showed that atomisation and combustion of FM3 modified Avtur was satisfactory provided that the fuel system was arranged to produce maximum degradation of the fuel upstream of the atomiser⁷. Some deposits were formed at idling conditions but were burned off at the cruise conditions. Tests on FM4 fuel included both spray and vaporising systems. In the former system an Avon chamber was again used, while vaporising chamber tests were done on a Mamba combustion chamber with "walking stick" type vaporisers. FM4 modified Avtur showed satisfactory combustion properties in both types of chamber. Once again, with the spray chamber the engine fuel system had to be run in such a way as to impose maximum degradation on the additive before a suitable spray pattern could be achieved. In the vaporising chamber no pre-degradation was necessary. In both chambers black deposits were formed which could be removed at take-off conditions. It was considered possible that such deposits might cause problems with jet pipe instrumentation or in blocking nozzle guide vanes after a prolonged period of idling.

More recent tests on FM9 fuel at Rolls-Royce (1971) Ltd using an M45H chamber with a row of stators and at NGTE using an Avon chamber with a two-dimensional cascade of cooled stators downstream showed no trace of deposit on the nozzle guide vanes; in the NGTE tests some liquid deposits formed but these simply ran off. The Rolls-Royce tests used undegraded FM9 fuel while NGTE used FM9 fuel which had been degraded in a diesel injector.

In October 1974 the first full scale engine test was made with a Spey-Phantom engine at NGTE. It had been found in earlier tests that FM9 modified Avtur produced blockage of the fine orifices of a "Moog" valve used in the fuel control system and the fuel was therefore degraded by four passes through a diesel injector rig. Runs were made at jet pipe temperatures of 550°C, 500°C, 450°C and 400°C and the engine was stopped and restarted a number of times on the modified fuel (including one restart after being left over a weekend). More than eight hours' testing was done and at all conditions the engine's performance was indistinguishable from that obtained with Avtur. No problems occurred either with nozzle guide vanes or jet pipe instrumentation. Rupture of a fuel filter did occur and this is currently being investigated to see whether it was due to the modified fuel. Deposits found in the fuel bowser after the test appeared to be due to water contamination and these are also being checked.

At this stage we regard the engine problems as less exacting than those in other areas. Providing that a means of degrading the fuel before it reaches the fuel control system can be found which can be used on an aircraft, the atomisation and combustion of such fuels appears to be perfectly feasible. There may be problems with engine designs giving lower temperatures than the Spey and the aspect of atmospheric pollution has not yet been covered. Nevertheless, no more work is planned in this area until several more pressing problems have been overcome.

5 DEGRADATION

The mist-suppressing additives developed during the course of this programme are all high molecular weight polymers. A property of such materials is their tendency to degrade under shearing conditions. The process is associated with the breakdown of the larger molecules to form materials of lower molecular weight and a number of the problems discussed above are alleviated by such degradation. Indeed, substantial degradation appears to be essential if anti-misting fuels are to be filtered or be made acceptable to the engine fuel control system. Mechanical devices are available which will produce the requisite amount of degradation and large batches of fuel were prepared by means of a diesel injector for use in the Spey engine test. Unfortunately no mechanical device is yet available which would be suitable for aircraft use.

In addition to making the fuel easier to handle, degradation also destroys the fire resistance conferred by the anti-misting nature of the fuel. The signs are that relatively small amounts of degradation will substantially affect fire resistance. The problem is then two fold:

- (1) the fuel must be handled in the low pressure fuel system in such a way as to avoid degradation;
- (2) it must then be rapidly and substantially degraded before encountering the engine fuel control system.

The adverse effect of fuel system components on the fire resistance of anti-misting kerosine has been known for some time. A few passes through a centrifugal pump is sufficient to remove much of the fire resistance of the fuel⁸. It is planned to subject FM9 modified fuel to an aircraft fuel system in the very near future. More information should then be available on the amount of degradation to be expected under operating conditions. It is possible that some effort may have to be devoted to the design of components which will handle materials of this type without causing degradation.

Considerable effort is being devoted to methods of achieving degradation with a view to producing a degrading unit for aircraft use. Early work was hampered because of the difficulty of defining and measuring a degree of degradation. As the additive is a very high molecular weight polymer, with any sample there is a certain spread of molecular weight. It is believed that only the largest molecules are capable of conferring fire resistance and it is these molecules which are most readily broken down. For moderate amounts of shear, therefore, it is possible to lose all fire resistance while still retaining material of moderately high molecular weight. Such a sample would appear to be completely degraded if degradation were assessed by means of a fire test; its flow properties, however, might be very different from that of kerosine and certainly its ability to form deposits in a combustion chamber would differ very little from that of the undegraded fuel. Very different estimates of the degree of degradation would, therefore, be obtained from different types of measurement. In early work the minitrack was used to measure the degree of fuel degradation and this method is particularly useful for the low degradation area where we are considering loss of fire resistance due to various fuel system components. However, it leads to high apparent degrees of degradation when only relatively small changes have occurred in the additive. More recently, the measurement of spread of molecular weight in a degraded sample has been used at RAE as a more fundamental method of measuring degradation. Gel permeation chromatography (GPC) has been utilised and the method has yielded useful results. It has confirmed that only small changes in molecular weight are needed before extensive loss of fire resistance. Furthermore, it has shown that even four passes through a diesel injector, which to date is the most effective mechanical degrader we have found, produces only a moderate fall in molecular weight. Fortunately this moderate fall is sufficient to make the fuel acceptable to the engine. The degraded fuel is still capable of forming chamber deposits under certain conditions, however, and very much greater amounts of degradation would be needed to overcome completely this problem; again it is fortunate that these deposits do not appear as serious as was first thought possible.

A number of methods of producing degradation have been investigated. Of the purely mechanical methods the diesel injector is so far the most promising but others are being investigated. Ultrasonic methods have also been studied but are thought to be impractical. Large irradiation times are needed and the results show no improvement over those obtained with mechanical degraders⁹. A number of chemical methods of degradation have recently been studied at RAE. These produce very considerable degradation, molecular weights one or two orders of magnitude lower than those obtained by the best mechanical methods being observed¹⁰. While the methods so far discovered are unlikely to be applicable to aircraft use, the study of chemical degradation is continuing. The simplest type of in-flight degrading unit would undoubtedly be a mechanical one. The amount of energy required to degrade the additive is extremely small and the problem is one of efficiently imparting this energy to the polymer molecules rather than to the base kerosine. So far this efficiency has not been achieved but to date very little effort has been devoted to the design of a degrader and only items of existing equipment have been investigated. It is planned to devote more effort to this key aspect in future. The measurement of degradation by GPC is time consuming. It is used, therefore, as a primary standard and a number of flow experiments are currently being developed to study degradation. One of these in particular has proved most useful and once the method has been calibrated against the GFC it has yielded useful results.

6 CONCLUSIONS

The use of mist-suppressing additives in low concentrations has been shown to increase markedly the fire resistance of kerosine type fuels under simulated crash conditions. The fire resistance of fuels of this type appears to be much greater than that of conventional thickened fuels.

The use of mist-suppressing additives introduces a number of handling problems. So far as the engine is concerned, while combustion chamber deposits have been observed under idling conditions these have caused no serious problems in the turbine or with jet pipe instrumentation. So long as the fuels were subjected to moderate degradation before the engine no serious engine problems were observed. In the fuel system, while early fuels gave serious pumping difficulties these have largely been overcome with FM9 fuel. Filtration and water compatibility problems exist with this material; the former can be overcome however

by degrading it while the latter is now thought less serious than was at first feared. The problem of degradation is a key aspect of the whole programme. It is necessary to avoid degradation of the fuel additive in the low pressure fuel system otherwise loss of fire resistance would occur. It is also necessary to produce moderate degradation upstream of the engine fuel control system and before meeting fine filters. Both these aspects of degradation are currently receiving much attention.

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Table 1

FIRE TEST RESULTS FOR AVTUR AND FOR FM4 MODIFIED AVTUR USING "STANDARD"
TWO-ROCKET SLED TEST CONDITIONS IN THE PRESENCE OF A VARIETY
OF IGNITION SOURCES

Fuel	Ignition Source	Remarks
Avtur	One kerosine flame	Intense fireball covering wide area
Gas oil	36 kerosine flames	Intense fireball covering wide area
Avtur containing 0.3% FM4	36 kerosine flames	No ignition
Avtur containing 0.3% FM5	36 kerosine flames	No ignition
Avtur containing 0.3% FM6	36 kerosine flames	No ignition
Avtur containing 0.3% FM7	36 kerosine flames	No ignition
Avtur containing 0.3% FM8	36 kerosine flames	No ignition
Avtur containing 0.3% FM9	36 kerosine flames	No ignition
Petrolite emulsion EFA-104	36 kerosine flames	Large and intense fireball similar to that produced by Avtur
Dow gel CX7038	36 kerosine flames	Large and intense fireball similar to that produced by Avtur
Shell emulsion SE-9	36 kerosine flames	Large and intense fireball similar to that produced by Avtur
Avtur	Electric arc	Intense fireball covering wide area
Avtur containing 0.3% FM4	Electric arc	No ignition
Avtur	Heated duct, 610 mm x 130 mm, stainless steel; duct temperature 610°C	Intense fireball covering wide area
Avtur containing 0.3% FM4	Heated duct, 610 mm x 130 mm, stainless steel; duct temperature 610°C	Small fire confined to immediate vicinity of duct. No further propagation
Avtur	Duct as above, duct temperature 410°C	Small fire confined to immediate vicinity of duct. No further propagation
Avtur containing 0.3% FM4	Duct as above, duct temperature 410°C	Small fire confined to immediate vicinity of duct. No further propagation

TABLE 2

FIRE RESISTANCE OF SOME SAFETY FUELS OVER A TEMPERATURE RANGE USING RAE "STANDARD" SLED TEST

Fuel Additive	Concentration	Temperature	Test Result
FM4	0.3%	70°F	Pass
FM4	0.3%	95°F	Fail
FM4	0.4%	95°F	Pass
Conoco	Unknown (as supplied)	62°F	Fail
Conoco	Unknown (as supplied)	95°F	Fail
Dow	0.5%	65°F	Fail
Dow	0.7%	66°F	Pass
Dow	0.7%	95°F	Fail

TABLE 3

MINIATURE PUMPING TEST DATA FOR ANTI-MISTING FUELS

Fuel Additive	Maximum pump efficiency with fuel at 0.3% concentration relative to that with Avtar at -35°C and 8000 rpm	Time dependence of pump efficiency
FM4	0.33	Time dependent: varies from 0.25-0.33
FM5	Very low; fuel tended to gel	-
FM7	0.33	-
FM8	0.44	Time dependent: varies from 0.33-0.44
FM9	0.88	Independent of time.



FIG 1 STANDARD FIRE TEST WITH AVTUR



FIG 2 STANDARD FIRE TEST WITH FM4 MODIFIED AVTUR

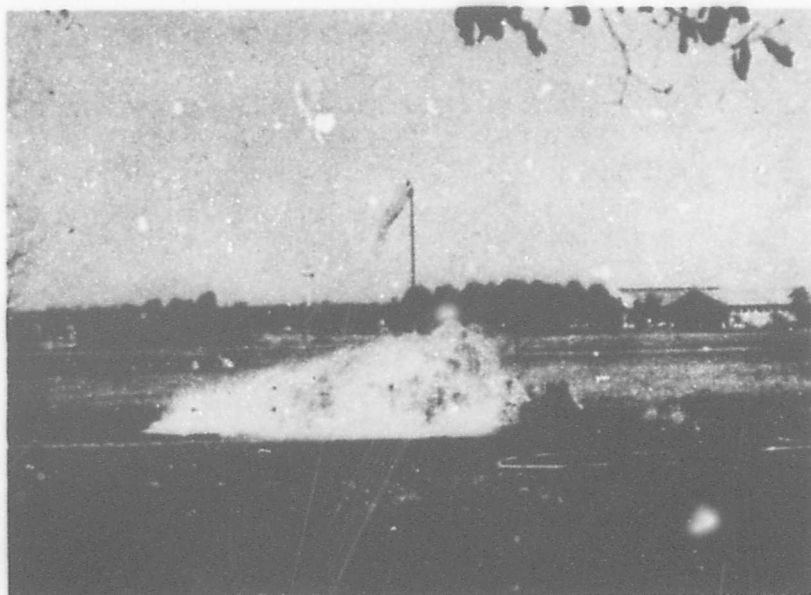
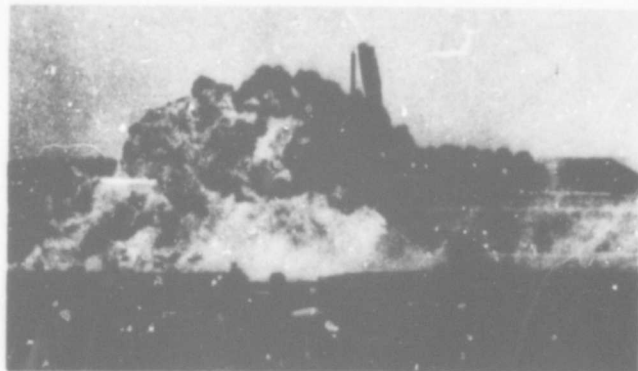
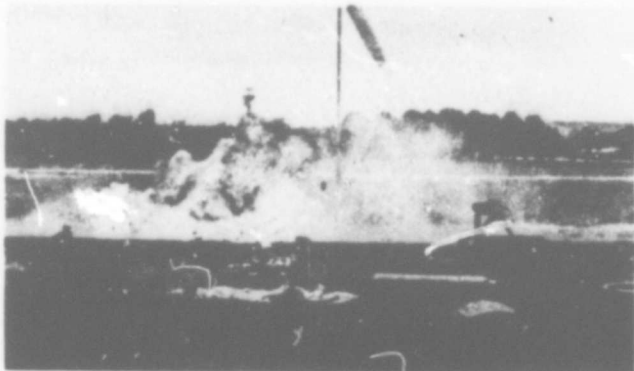


FIG 3 STANDARD FIRE TEST WITH CONVENTIONAL THICKENED FUEL
(SHELL S29 EMULSION)

(a) Avtur at
T 500°C



(b) Avtur at
T 500°C



(c) FM4 fuel at
T 500°C

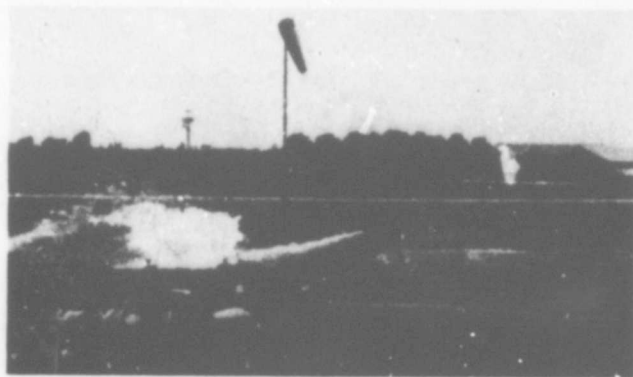


FIG 4 SLED TESTS USING A HEATED DUCT AS THE IGNITION SOURCE -
SPONTANEOUS IGNITION OF AVTUR AND FM4 MODIFIED AVTUR

Note: A Consolidated Discussion was conducted for Papers 1-5. It is documented at the end of Paper 3.

STATUS OF RESEARCH ON ANTIMIST AIRCRAFT TURBINE ENGINE FUELS IN THE UNITED STATES

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SUMMARY

Research being conducted by the U. S. Army, Air Force, Navy, and the Federal Aviation Administration (and the U.K. Royal Aircraft Establishment) has been directed toward establishing the physical, compatibility, and fire-safety characteristics of fuel blends containing polymeric antimist agents. This antimist additive approach has been shown to be both feasible and potentially practical for substantially reducing the frequency of in-flight and post-crash aircraft fires. This paper describes the experimental bench (and larger-scale) evaluation procedures that are being used in the antimist fuel studies, and reviews the experimental results obtained by various U. S. organizations, using several different polymeric antimist additives. Both fire-safety and systems-compatibility characteristics and problems are addressed, and projections are made regarding the future direction of research on such antimist aircraft turbine fuels.

Prior to 1969, both the U. S. Air Force and the Federal Aviation Administration had investigated the use of low concentrations of high molecular weight hydrocarbon-soluble polymers as dispersion-reduction agents in JP-4 fuel.(5-15)* However, because of the high volatility of this base fuel, only marginal flammability reduction was observed. Similar additives were also investigated in the United Kingdom using low-volatility aviation fuel, and the results of simulated aircraft crash tests conducted by the Royal Aircraft Establishment were described at the 37th Meeting of the AGARD Propulsion and Energetics Panel held at the Hague, Netherlands, in 1971.(1) These latter results demonstrated the potential of such additives for diminishing mist fire hazards with low-volatility fuels. At this same AGARD meeting, the U. S. Army (20) and the Federal Aviation Administration (1) described on-going research using low-consistency, high-internal-phase-ratio aqueous emulsions and nonaqueous gels of low-volatility fuels, such as JP-5, Jet A-1, etc. The fire-safety and systems-compatibility characteristics of such modified low-volatility fuels appeared promising. During the years since the 37th PEP meeting at The Hague, laboratory and bench tests demonstrated that the low-consistency high-internal-phase-ratio emulsions under investigation did not have adequate batch-to-batch reproducibility or storage and handling stability for use as aircraft turbine engine "modified fuels". (20) Subsequent and current efforts by the U.S. Army, Air Force, Navy, and the Federal Aviation Administration (and the U. K. Royal Aircraft Establishment) have been directed toward establishing the physical, compatibility, and fire-safety properties of the fuel blends containing polymeric antimist agents. The antimist additive approach appears both feasible and potentially practical for substantially reducing the frequency of in-flight and post-crash aircraft fires. It is the purpose of this paper to discuss the unique nature of mist flammability hazards; review the experimental bench (and larger-scale) evaluation procedures that are being used in the antimist fuel studies; and to describe the experimental results obtained by various U. S. organizations, through 1974, using several different polymeric antimist additives. The following tabulation summarizes the possibly promising antimist agents (and suppliers) being investigated by U. S. organizations.

<u>Antimist Agent</u>	<u>Supplier</u>
FM-4	ICI, Ltd.
AM-1	Continental Oil Company
XD-8132	Dow Chemical Company
PEP-4	Shell Development Company

All of these products are proprietary; hence, little can be said about their chemical constitution except that they include hydrocarbons, aliphatic polysulfones, and polyacrylic esters, and have molecular weights in excess of one million.

Much of the U. S. research activities information presented in this paper has been assimilated from presentations made at numerous information exchange meetings by the various organizations conducting antimist fuel research. In addition to such information, the authors have been in personal communication with personnel in these organizations (as indicated by appropriate reference citations) to confirm the accuracy of the information presented in this document.

*Numbers in parentheses refer to references at end of the paper.

TECHNICAL CONSIDERATIONS

The physical and chemical processes involved in flame propagation through fuel mists are among the least studied and understood combustion phenomena. The following discussion points out the major differences between flame propagation in heterogeneous mixtures of liquid droplets with air and in homogeneous mixtures of fuel vapor with air and offers technical explanations for such differences.

Unique Flammability Properties of Mists

The flammability limits of mists are strongly influenced by the droplet size distribution of the dispersed liquid phase. In fact, on the basis of hydrocarbon weight per unit air volume, the lower flammability limit for mists can be less than that of the same hydrocarbon in a homogeneous vapor-air mixture. (2,3) It is partly because of this latter phenomenon that fuel mists represent a significant flammability hazard even though their ignition energy is greater than that of gaseous fuels. It should be noted that mists also create a substantial hazard because they may be flammable even when the droplet temperatures are substantially lower than the theoretical flash point of the fuel. This anomaly is caused partly by the fact that the vapor pressure of a liquid is significantly increased by surface tension effects (for extremely small droplets).

The anomaly in the lower limit of flammability stems partly from the fact that, at the surface of each drop, the fuel vapor concentration varies from the equilibrium (or dynamic) vapor pressure through a decreasing concentration range to zero (or near zero) in the bulk air surrounding the drop. Hence, if the equilibrium (or dynamic) vapor pressure (as enhanced by surface tension effects) at the liquid droplet surface exceeds the lower limit of flammability, a flammable mixture may occur somewhere between the drop surface and the bulk air phase, irrespective of the weight concentration of fuel in the air, and flames can propagate unless the mist dispersion is too dilute to support combustion.

In some cases, the anomalously low "apparent" lean limits of mists have been attributed to fuel droplet sedimentation-enrichment of the flame front. In these cases, such sedimentation effects were believed to increase the flame-front fuel concentration to nearly the same value as would be required for the lean limit in a homogeneous system. (2) However, more recent research has indicated that liquid droplet suspensions with drop sizes exceeding 0.010 mm display flame-front lean limits that decrease significantly as the drop size increases. (3) This phenomenon is attributed to different mechanisms of flame spread in heterogeneous, relative to homogeneous, systems. Even if the sedimentation mechanism were responsible for "apparent" low lean limits, such limits could be applicable to aircraft crash or other fuel-mist-producing situations. In such cases, the flame front could propagate perpendicularly or obliquely to sedimentation-generated fuel droplet concentration gradients, and a small quantity of fuel could go a long way toward generating a flammable mist.

In another respect, fuel mists in air could be potentially more dangerous than pre-vaporized fuel in air. Flame propagation rates through fuel mists may be faster than through vapor-phase fuel air mixtures, the extent depending upon the characteristics of the particular mist dispersion. (2) This enhanced flame velocity of mists has been attributed to the presence of acetylenes and hydrogen formed by pyrolysis in the "thicker" flame. (2) However, this has not been confirmed as the sole mechanism. Such flame-speed enhancement could also result from the significantly increased "expansion factor" (increase in the number of moles in the vapor phase due to the passage of the flame front) that results when liquid fuel droplets are enveloped by the flame front and are consumed by the flame. In such cases, the unburned mist dispersion being entered by the flame front would be accelerated more by flame-generated expansion than would the unburned mixture in the absence of mist, and the observed flame space velocity would be increased correspondingly.

In the light of these unique properties of flammable mists, the importance of such phenomena relative to aircraft fuel fire safety cannot and should not be understated. In fact, it is at least indirectly because of these properties that so much research and development attention is being devoted to preventing or inhibiting fuel mist formation during ballistic- or crash-impact events.

Antimist-Fuel Evaluation Methodology

The methodology utilized by the various organizations participating in antimist fuel research has included flammability characterization, hazard simulation, and determination of trade-offs. Routine flammability characterizations of liquid fuels normally comprise laboratory measurements of flash point or vapor pressure, boiling range, and minimum autoignition temperatures in accordance with standardized test methods (usually ASTM). These flammability indicators are useful, but they do not encompass all flammability properties that may participate in fuel conflagration events. Hence, out of necessity, other procedures have been developed (or adapted) to simulate potential fire-hazard exposure situations. In general, such simulation techniques comprise laboratory-, bench-, and field-scale fuel-dispersion procedures. These procedures range from relatively simple drop tests, impingement tests, and spray-type tests through ballistic, catapult, and sled tests to full-scale aircraft crash tests. The status of the activities of the various U. S. organizations participating in antimist fuel research is discussed in later sections of this paper, and the specific hazard simulation and other test procedures developed (or applied) by each organization are described (or referenced).

ANTIMIST FUEL RESEARCH SUMMARIES FOR VARIOUS U. S. ORGANIZATIONS

Brief reviews of activities of those U. S. organizations that are known to be conducting antimist fuel research are presented in the following pages. These reviews are not intended to be all-inclusive, rather, their purpose is to synopsize those activities and experimental results, through 1974, that are familiar to the authors (and confirmed by the organizations involved).

U. S. Air Force

The U. S. Air Force conducted a series of gunfire tests on several antimist additives at 0.3% concn-

tration in JP-8 fuel. (4,8) In these tests, about 23 liters of fuel were contained in a simulated fuel tank with a fuel depth of about 7.5 cm. The fuel was introduced by gravity flow to preclude any possibility of shear degradation. The M-8, 50 calibre, armor-piercing incendiary was fired at a velocity of about 730 m/s through an actuating plate (replaceable) into the bottom (replaceable) of the simulated fuel tank at 30° obliquity. The projectile traveled about 10 cm through the liquid into the ullage and exited through the top (replaceable) of the vessel. This technique resulted in ignition of about 95% of the various fuel blends tested. Detailed results are presented in reference 8.

The additives found to be effective in this test series included AM-1, XD-8132, and FM-4. These significantly reduced the overpressure following ignition of the JP-8 fuel blends. Limited testing confirmed that antimist additives are not effective in reducing explosion hazards of JP-4 fuel blends.

Because of the rheological behavior of the antimist fuel blends, it was concluded that system (filter and orifice) problems may be encountered. Viscosity measurements indicated that low temperatures could create additional compatibility problems. The JP-8 base fuel utilized by the Air Force exhibited ice crystals at -34°C; hence, the antimist additive blends displayed precipitation and/or non-Newtonian behavior at this temperature.

U. S. Army

Experimental evaluation of antimist additive blends has been conducted by the Army utilizing many different experimental techniques. The Army Fuels and Lubricants Research Laboratory (AFLRL), San Antonio, Texas, has conducted most of these experiments which include determination of physical properties, measurements of mist-flashback and impact-dispersion flammability characteristics, systems compatibility tests, and ballistic tests. (21,22) In addition, AFLRL has conducted a relatively low-level-effort study of the mechanism by which the polymeric additives inhibit mist formation. The possibility of complications due to bacterial growth has been investigated by the U. S. Army Natick (Massachusetts) Laboratories. The Army has also sponsored a series of simulated full-scale helicopter crash tests, conducted by Dynamic Science, Phoenix, Arizona, and a 50-hour engine test, conducted for the Army by the Naval Air Propulsion Test Center, Philadelphia, Pa., using a small helicopter gas turbine engine (T-63). The foregoing experimental studies are summarized in the following paragraphs.

Physical and Flammability Property Measurements

The physical properties of base fuels and fuel-additive blends were determined at AFLRL by ASTM and other established techniques. The AFLRL mist flashback and impact-dispersion techniques were described in references 20 and 21. However, during the investigation of flammability properties of antimist fuels, it became necessary to significantly refine the techniques involved in these test procedures in order to obtain quantitative results. Hence, the methods of expressing the results of these two evaluation procedures are different from those shown in reference 20. The procedures presently employed with these test techniques will be briefly reviewed in the following paragraphs.

Mist Flashback Technique: In the mist flashback apparatus, three intersecting air streams impinge upon the liquid fuel issuing at a steady flow rate from the tip of the capillary tube, causing the liquid stream to break up (into a mist if no antimist agent is present). An ignition source is positioned perpendicular to the fuel-air jet 30 cm downstream from the air impingement point. This pilot flame is developed by a horizontal pipe having a series of orifices, providing a natural gas-air flame sheet. In operation with either volatile or kerosene-type jet fuels, the mist is ignited as it passes through the pilot flame sheet, and a relatively large flame brush develops downstream of the pilot. This flame is about the same for JP-4R as for the JP-8R neat fuels.

Depending upon the nature of the fuel, intermittent flames may propagate upstream from the pilot toward the fuel-air source. This "flashback" can be measured by observations along a horizontal line of sight perpendicular to the fuel-air jet. A video camera and a video tape recorder are utilized for recording the phenomena occurring during each experiment so that data reduction may be accomplished during subsequent video playback, using slow motion and stop action as necessary. Details of the current evaluation procedure and data reduction techniques are presented in reference 22. In essence, a mist flashback rating, expressed as a mean distance of flashback, is assigned to the fuel. This average rating is based on triplicate experiments, each conducted at three different misting air rates, ranging from relatively low to extremely high shear conditions.

The relative mist flammability properties determined by this technique for AM-1, FM-4, XD-8132, and PEP-4 additive when blended with JP-8R, are illustrated in Figure 1. It should be noted that at the 0.3% concentration level and greater, no significant differences are apparent between the AM-1, FM-4, and PEP-4 blends. On the other hand, the resistance of XD-8132 to misting is less than that of the previously mentioned agents. However, based upon impact-dispersion flammability tests and results obtained for the Army by Dynamic Science using a simulated full-scale helicopter test procedure, the mist flashback levels displayed by the XD-8132 in Figure 1 appear to represent reasonable mist fire safety. This simulated full-scale test procedure and results is described later, and the results are summarized in Table 1.

Sprayability Test: During the systems compatibility portion of the Army study, it was desired to investigate the effects of the unusual rheological properties of the antimist fuels on turbine combustor nozzle performance. Therefore, for such experiments, the air-assist capillary tube of the AFLRL mist flashback apparatus (preceding paragraphs) is temporarily removed and replaced with one of the 22 nozzles used in the T-53 engine of UH-D/H helicopter. The fuel pressure at the inlet to the nozzle is monitored with a piezoelectric transducer as the flow rate is varied, and the flammability characteristics of the fuel discharging through the pilot flame sheet are documented. As indicated by the dashed line in Figures 2 and 3, neat, reference-grade JP-8R forms a flammable spray, as expected, throughout the entire flow range -- from less than ground-idle conditions to greater than "take-off" conditions. It displays a near-exponential increase in back pressure with increasing flow rate. On the other hand, 0.3% AM-1 or FM-4 yield higher back pressures at low flow rates and exhibit more nearly linear relationships between flow rate and back pressure, displaying back pressures less than those shown by neat fuel at the higher

flow rates. No breakup of the fuel jet is obtained with either of these antimist fuel blends, and, hence, no ignition occurs as the jet passes through the pilot flame. As the additive concentration is decreased, the low-flow-rate back pressure decreases, and the high-flow-rate back pressure remains less than that exhibited by the neat fuel, indicating fluid-friction-reduction activity of the antimist agents.

Impact Dispersion Test: Impact dispersion experiments are conducted in a well ventilated enclosed facility developed for this purpose. These tests involve allowing a glass vessel, containing about two liters of fuel, to fall freely 6 meters onto a steel target plate, embedded in concrete and surrounded on two sides by gas pilot flames. The relatively low vertical velocity of 11 meters per second developed during this free fall corresponds to total occupant survivability during a vertical helicopter crash, but it is near the onset of marginal survivability. The glass containers are filled to an ullage of about 2% of the total volume for each test. A television camera is located about 6 meters from the impact point, and this is used to document the test results on video tape. A background grid provides a dimensional frame of reference, and subsequent examination of the video tape by slow-motion and stop action provides reduced data. Tests are conducted at several different temperature levels, from about 25 to 90°C, by preheating the fuel sample and the steel target plate to the desired temperatures. Because of the only slight effects of antimist fuels on the pilot flames, the following data reduction system was devised for placing the impact dispersion results on a somewhat quantitative basis. A rating from "A" through "E" is assigned to the results of each experiment, depending upon the observed flammability characteristics, as shown in the footnotes of Tables 2 and 3. These range from "no pilot flame enlargement" for highly effective antimist fuels through "pilot dimensions less than doubled", "pilot dimensions more than doubled", and "pilot flames totally obscured by transient mist fireball" [neat, low-volatility fuels] to "coalesced fireball with simultaneous pool burning" [volatile liquid fuels]. This method of quantifying the results of impact dispersion tests has proved useable and correlatable with other experimentally measured flammability properties. Experimental results obtained with the impact-dispersion and mist-flashback techniques for various neat and antimist fuel blends are summarized in Table 2. Elevated-temperature impact-dispersion test data are presented in Table 3.

Compatibility Tests

Tests with components of UH-1D/H Fuel Systems: Experiments have been conducted by AFLRL with various antimist fuels using selected components of the UH-1D/H helicopter fuel system. These components include the boost pump and the fuel-transfer ejector pump from the lower (beneath the floor) fuel tanks. These system compatibility studies have not included all of the candidate antimist agents. Rather, limited studies were conducted with AM-1 additive to establish possible trends. More extensive system compatibility experiments would be undertaken in the future if the research results from the various organizations involved in such studies confirm indications that the use of such antimist agents is feasible. In the case of the electric boost pump of the UH-1D/H helicopter, the flow rate (against zero head) developed by the pump (under 28 volt normal excitation) was found to be 525 kg/hr for 0.2% AM-1 in JP-8R. This discharge rate is about 60% of the 900 kg/hr flow rate developed by this pump with neat JP-8R (against zero head). Internal recirculation within the boost pump for a period of four hours caused no degradation in mist flammability resistance, as measured with the mist flashback apparatus. In the case of the ejector pump, the presence of virgin AM-1 was much more deleterious to the pump performance than in the case of the boost pump. With 0.2% AM-1 in JP-8R, the ejector pump is virtually inoperative. Dilution improves performance somewhat, as evidenced by the fact that the pump is operative with virgin 0.05% AM-1.

Water Compatibility Tests: As part of the AFLRL compatibility studies, a series of simple experiments was conducted to investigate the compatibility of antimist fuels with water. In each of these experiments, 100 ml of deionized water was mixed with 400 ml of fuel in a one-liter screw-cap jar and allowed to stand 24 hours before documentation of results. When JP-8R containing 0.2% AM-1 was mixed for 30 seconds in a high-shear food blender, the AM-1-containing fuel layer appeared hazy after 24 hours, but the aqueous layer comprised an oil-in-water emulsion. In the case of 0.3% FM-4 in JP-8R, the aqueous layer did not exhibit an interface with the fuel as had the AM-1; rather, there appeared to be a progressive transition from hazy fuel at the top to an oil-in-water emulsion at the bottom. When these experiments were repeated with 5 seconds of wrist-shaking, rather than food-blender-mixing, somewhat different results were obtained. The AM-1-containing fuel layer appeared slightly hazy, but the aqueous layer was clear, and the interface was clean. The FM-4-containing fuel layer was opaque (probably a water-in-oil emulsion) and the aqueous layer appeared to be an oil-in-water emulsion (the interface was not distinct). PEP-4 (0.2%) was also subjected to this manual-agitation aqueous exposure, and the results were the same as those observed with AM-1 except that there was a "lacy" substance at the fuel/water interface.

AFLRL T-63 Combustor Tests and Antimist Agent Degradation Studies

A modern facility for conducting combustor tests has been constructed at the Army Fuels and Lubricants Research Laboratory (AFLRL) for the Army. The "air factory" of this facility is capable of providing unvitiated air at a rate up to 1.2 kg/sec., at temperatures up to 815°C, and at pressures up to 16 atm. The combustor rig presently in use with this "air factory" is constructed from the hardware of the T-63 turbine engine. The burner is a single-can type with a pressure atomizer centered in the dome. A water-quench chamber is attached directly to the exit of the instrumentation section that is mounted aft of the combustion chamber. The entire rig is mounted on linear bearings that provide two degrees of freedom of motion to permit rapid dismantling and reassembly of the combustor rig.

The T-63 engine is known to exhibit marginal start and restart characteristics with low-volatility jet fuels such as JP-8, and the engine test conducted for the Army by the Navy (to be discussed subsequently) demonstrated that concentrations of AM-1 in JP-8R as low as 0.05% prevent successful start-up of the T-63 engine (4-8 g/sec. air rate at start-up). On the other hand, once the engine is started with neat JP-8R, its performance (except for exhaust emissions; see Table 5) is insensitive to the presence of 0.2% AM-1 in the JP-8R fuel. Similar characteristics are shown by the AFLRL T-63 combustor, and it has been established that start-up of the combustor with neat JP-8R fuel cannot be achieved if the inlet air temperature is less than about 30°C.

This T-63 start-up difficulty and the pumping and filtering difficulties mentioned previously, identify critical problem areas for polymeric antimist agents. A possible solution to this problem could involve intentional degradation of the size of the antimist agent molecules when mist inhibition is no longer desired. Toward this end, AFLRL has conducted numerous screening tests of methods for achieving such molecular degradation. These techniques have ranged from the pumping of antimist fuel blends through nearly-closed valves with back pressures up to about 6 atm, through on-line shearing of the fuel in a device containing opposed, counter-rotating food blender blades (10,000 RPM each), to on-line shearing by passing the fuel through gear teeth spinning at 10,000 RPM on each side of (and in near-contact with) a stationary gear. Each of these techniques substantially enhances the mist flammability, relative to fire-safety considerations, but none have yet provided an adequate extent of on-line shear degradation to achieve start-up of the T-63 gas turbine engine combustor. The spinning-gear technique appears to be the most promising of those yet investigated, and typical results obtained with the previously described "sprayability" test are portrayed in Figure 4 for PEP-4 antimist agent. The mist flammabilities of the fluids subjected to these tests are summarized in table 4. The results of these studies demonstrated that the shear-degraded antimist fuels do not yield successful ignition in the T-63 combustor. However, the results are encouraging in that at least one of the degraded antimist agents (PEP-4) demonstrates substantial spray ignition at moderate flow rates through the T-63 combustor nozzle used in the sprayability test.

T-63 Turbine Engine Test

The Army, as part of its antimist fuel program, supported an engine test with the T-63 engine from the OH-58 (or 6A) helicopter using 0.2% of AM-1 in reference grade JP-8 base fuel (JP-8R). This test was conducted for the Army by the U. S. Navy (U. S. Naval Air Propulsion Test Center, Mr. J. T. Salvino, Project Engineer). In brief, this 50-hour preflight rating test confirmed that the engine performance was not adversely affected by operation with this fuel blend. However, it proved impossible to start or restart the engine on AM-1 concentrations as low as 0.05% (the T-63 engine demonstrates marginal start and restart capabilities with neat JP-8 fuel, hence, this test of the antimisting fuel blend represents a "worst-case" situation).

Therefore, the 50-hour test was conducted by starting the engine with JP-8R base fuel and then switching to the antimist fuel blend to accumulate operating time under the various conditions of the engine test. The engine operated satisfactorily at flight idle and above, but operation at ground idle was marginal. Final inspection and evaluation of the dismantled engine parts did not reveal any detrimental effects of the additive. Exhaust emissions were measured during this test, and the results are compared in Table 5 with earlier data obtained by NAPTC with the same engine, using JP-4 fuel.

Incendiary Ballistic Tests

In order to further evaluate the fire safety effectiveness of AM-1 antimist agent, a series of gunfire tests was conducted by AFLRL at Southwest Research Institute and the results are itemized in Table 6. Basically, this test utilized a 20 mm HEI-T projectile fired into the end of a 114-liter drum (Spec. No. DOT-17E-2030-73) containing 76 liters of test fuel (DF-M [NATO F-76], flash point of 63°C). The gun was located at approximately 20 meters from the target and aimed horizontally. A 6 mm aluminum plate, inclined backward at a 45° angle and with its center 30 cm in front of the drum face, served as an actuator plate. The projectile followed a horizontal trajectory at a velocity of about 1000 meters per second, striking the actuator plate just below the fuel level (about the center of the drum face).

The scope of this series of experiments was to substantiate results obtained with the impact-dispersion technique for antimist fuels at elevated temperatures. The results of this series of experiments indicated that AM-1 does not eliminate burning of fuel that is actually contacted by the incendiary fragments. However, 0.2% AM-1 does effectively eliminate both the transient mist fireball (of fuel not actually in contact with incendiary fragments) and ground fires when the fuel is at normal ambient temperatures (25°C) or heated to 14°C below its flashpoint (49°C). When the fuel is preheated to as much as 14°C above its flashpoint, the presence of 0.2% AM-1 effectively reduces the mist fireball but does not prevent sustained ground fires. Although the fuel was not a jet fuel, other tests have indicated that the mist flammability effects observed with this fuel are not distinguishable from those observed with a normal jet fuel. The results of all these tests are summarized in Table 6 which also compares these results with those obtained earlier with the AFLRL impact-dispersion procedure. It is apparent upon examining these data that the impact-dispersion test is not as severe as the above-described ballistic exposure (as anticipated).

Rheological Studies of Antimist Fuel Blends

Because of the unusual rheological properties of polymeric antimist fuel blends, rheological studies have been conducted by AFLRL to better understand the observed phenomena and in order to ultimately develop experimental procedures for determining the viscoelastic properties of such blends. These unusual properties are exemplified by the fact that at high shear rates, fuels containing low concentrations of antimist agents exhibit pronounced viscoelastic properties. For example, relatively thin (less than about 4cS low-shear viscosity) blends produce elastic strings when attempts are made to subdivide the bulk liquid (i.e., spinability). At relatively low shear rates, most of these additives appear to form essentially Newtonian solutions in jet fuel.

The rheological studies have led to the development of a novel technique for characterizing the viscoelastic properties of polymeric antimist additive blends. This technique utilizes sintered metal porous discs through which the fuel blend is caused to flow by an imposed back pressure. These studies have shown that the flow of such viscoelastic fluids through porous media requires much higher pressure gradients (10 to 100 times as great) than would be predicted from the low-shear viscosity of the blend (this is not a "plugging" of the pores, but is a viscoelastic effect). These AFLRL antimist-agent rheology and antimist mechanism studies are not yet complete; however, it is anticipated that the substantially higher pressure drops shown by antimist fuel blends in porous media can be explained in terms of the viscoelastic properties of the fuel blends. The possibility of relating the pressure drop of antimist

fuels in porous media to their mist flammability characteristics appears promising and is currently being investigated.

Simulated Full-Scale Helicopter Crash Tests

These tests were conducted by Dynamic Science, Phoenix, Arizona, using the same experimental techniques as those employed earlier with emulsified fuels. (20) These experimental techniques and the results obtained with antimist fuel blends are described in reference 18.

Liquid JP-4 and JP-8 fuels produce a tremendous fireball when the fuel tank impacts the abutment spraying dispersed fuel past the spark source up and over the earth mound. When the test is conducted with smudge-pot ignition sources and with 0.2% AM-1, 0.3% FM-4, or 0.7% XD-8132 antimist agent*, a very small transient mist fireball (<30 cm diameter) occurs at the first smudge pot. However, this fireball quickly dissipates, and no fire spreads through the fuel sprayball. When the spark source is used, no fire is observed at all with antimist fuel blends. However, because of the characteristics of the open-flame smudge pots, a ground fire slowly develops after each test in which smudge-pots are used with the antimist fuel blends.

Bacteriological Studies

As part of the Army modified fuel research program, antimist additive concentrates and JP-8 fuel blends have been evaluated for bacterial growth support by the U. S. Army Natick Laboratory (Dr. Arthur Kaplan, Chief, Biotechnology Group). (17) These studies indicated that the presence of hydrocarbon additives such as AM-1 does not alter the biocidal efficacy of the icing inhibitor (2-methoxyethanol) used in military jet fuel. In the absence of icing inhibitor, the bacterial-growth effects of AM-1 concentrates are not significantly different from the base fuel, JP-8R.

U. S. Federal Aviation Administration

Antimist fuels have been evaluated by the FAA using a variety of experimental procedures (9,16). These range from nozzle atomization studies through wind-tunnel liquid-fuel break-up studies to full-scale aircraft crash tests. The following is a summary of the FAA procedures and pertinent results.

Airgun Test

The FAA airgun test has proved to be the most used of the flammability test procedures employed by FAA. In this test, fuel is placed in a frangible plastic container and propelled by compressed air horizontally at a speed of 150 to 250 km/hr (depending on the air pressure used) against a steel grid (5 x 10 cm expanded metal). The shearing action of still air, following impact with the grid, causes the formation of a fuel/mist cloud that decelerates to zero velocity about 3-1/2 meters beyond the steel grid. This impact provides complete atomization of a 4-liter specimen of neat fuel within 0.3 seconds, subjecting the fuel to an average longitudinal deceleration of 20g's. Rectangular pans of low-volatility kerosene are positioned about 20 cm above the ground beyond the steel grid to serve as pilot flames.

Results obtained with this technique indicated that, prior to shear degradation, 0.3% FM-4 is somewhat superior in mist fire resistance to 0.2% AM-1 and 0.3% XD-8132. However, after pre-shear by 8 passes through a vane pump, 0.7% XD-8132 additive appeared more effective for preventing mist fire than the FM-4 or the AM-1. This relative performance was obtained using 192 km/hr (fuel speed) airgun tests. This and other FAA experiments on the effect of hand mixing versus centrifugal or vane pump recirculation for blending the antimist agent into the neat Jet A-1 base fuel indicated that the mist flammability resistance of AM-1 was more easily degraded by the pump mixing process than was that of FM-4.

Catapult Test

Another test procedure employed by the FAA is the catapult test. This test comprises the catapulting of a 75-liter aluminum cylinder (with flat circular welded heads) into a rolling mode at about 130 km/hr along a concrete surface containing a steel rake ("ripper") positioned in front of an inclined impact plate (45°). An open-flame ignition source near the inclined impact plate causes ignition of the fuel mist as the drum impacts the inclined plate. The resulting fireball with neat Jet-A fuel was quite similar to that observed in the simulated full-scale helicopter tests conducted by Dynamic Science as part of the Army modified fuel program. A series of smudge pots beyond the inclined plate flared up as the dispersed fuel "rained" down following the impact. With both FM-4 and AM-1, one of these smudge pots generated a transient fireball that "self-extinguished" as it moved up through the mist spray cloud, with the AM-1 fireball being somewhat more extensive than the FM-4 fireball. However, with these antimist additives, by far the bulk of the fuel survived the catapult impact test without burning.

Full-Scale Crash Tests

As part of their antimist fuel studies, the FAA has sponsored four full-scale crash tests using RB-66 (or the A-3, Navy version) aircraft at Lakehurst Naval Air Test Facility, New Jersey. In the first test (1 June 1972), all fuel had been replaced with dyed water, and the resulting mist droplet "sprayball" produced during the crash event was most impressive. In this test, the aircraft was catapulted from a sled into an embankment with a 6° slope, the aircraft moved upward, out, and down to a 0.6 meter high earth pad which was anticipated to be the point of final rest. The aircraft was impacted at 220 km/hr, and it landed at the anticipated final resting place. It was noted that dyed water was everywhere throughout the wreckage and on the ground, from the point of initial impact to the final resting place of the wreckage.

*The first batch of XD-8132 subjected to this test produced a fireball identical to that of neat JP-8R fuel. However, a subsequent sample of the same batch did not (different history). See Table 1.

The second crash test (1 September 1972) was conducted with a 3° impact embankment (rather than 6° as in the initial test) followed by a 15° sloped hill for the come-to-rest point. The primary purpose of this test was to confirm mathematically predicted dynamic crash forces. A secondary objective was to establish the spray pattern of modified fuel in the absence of ignition sources. Each wing tank system contained about 2800 liters of modified fuel at an antimist additive concentration of 0.2% AM-1, dyed red, in the port wing and 0.3% FM-4, dyed green, in the starboard wing. The aircraft impacted at 214 km/hr and nosed over the crest of the 15° sloped hill before coming to rest; however, the crash was considered to be within passenger survivability limits. The spilled modified fuels were dispersed as relatively large aggregates rather than as a spray or mist.

The third crash test (20 October 1972) utilized 5678 liters of Jet A-1 containing 0.7 weight % XD-8132 at 16°C in the RB-66 fuel tanks (engine inoperative). Railroad-type flare ignition sources were provided downstream of the crash point. Following impact with four utility poles at 194 km/hr, the fuel was released from the wing tanks through the "ripped-out holes" as the aircraft impacted a 3° embankment. At this point, railroad-type flares were suspended above and below and in line with each damaged area, and an array of 40 additional flares, located about 30 cm above the ground, provided ignition sources throughout the path of the crashed aircraft until it came to rest at the crest of a 15° embankment. During this test, no ignition occurred, and the fuel was not dispersed as a mist.

In the fourth crash test (24 January 1973), the concentration of XD-8132 was reduced to 0.5% and the fuel was preheated to an average temperature of about 27°C, using heated air in a wing cover. During this test, the engines were operating on the modified fuel. The ignition environment was more severe than that in the previous crash test, and the shear forces were significantly increased. Four propane torch flames (1.5 to 2.5 meters high) were located at the crest of the 3° embankment, in line with the anticipated damaged wing areas. Rather than railroad flares, 40 burning fuel-soaked waste filters were located in eight rows and spaced at 30 meter intervals along the crash path (0.6 meter-high earth pad about 215 meters long) and located about 1-1/2 meters above ground. The test was designed so that impact of the wings with the vertical utility poles (at 190 km/hr during actual test) would drive I-beams into the front spar of the wing to increase the area opened in the fuel tanks during the crash. Simultaneously upon crash, two access plates on the under surface of the wing would be torn off (by levers) just prior to impact with the poles. The entire fuel load (5678 liters) was released in 8 seconds and created a fine mist. Initial ignition occurred in the vicinity of the starboard engine before the aircraft arrived at the propane torches. Subsequent to this initial ignition, the torches also ignited the mist cloud, and the ignitions developed into an all-inclusive conflagration.

Wing Section Air Shear Test

Rather than conducting additional crash tests at that time, the FAA commenced a series of experiments at their NAFEC facility using a simulated wing section. This apparatus comprises a steel mock-up of an aircraft wing section, in line with the ducted by-pass air of a fan jet engine which provided a simulation of high speed wind. The leading edge of this wing section contains a 15 cm circular opening from which the fuel is discharged during each experiment. A 1136 liter reservoir is located 3 meters above the wing section, and a balloon is positioned in the exit of the reservoir, blocking the entrance to the 20 cm discharge pipe. The reservoir is then filled with about 568 liters of fuel, and the hole in the leading edge is temporarily closed with a slip-in cap. During each test, the balloon is punctured, dumping the fuel through the 20 cm pipe into the leading edge of the wing section at about 75 liters per second (to simulate the rate of discharge obtained during the last aircraft crash test). Pulsating propane torches are located 30 cm below and 30 cm in back of the leading edge. A second propane torch is located at the trailing edge, 75 cm below it.

Tests have been conducted with this facility using air velocities (relative to the fuel) ranging from 130 to 240 km/hr. At the higher air velocities, all of the additives under investigation failed, even though they had passed the FAA airgun test. On the other hand, at a relative air velocity of 200 km/hr, the additive, XD-8132, at a concentration of 0.7%, appears to resist ignition (fuel temperature 35°C). When half of this fuel is pumped 8 times with a vane pump and then blended with unpumped fuel (0.7% XD-8132), the fuel blend fails this test at 200 km/hr. FM-4 at 0.3% concentration failed at a relative air speed of 185 km/hr. No data are available on AM-1.

Other Activities

The FAA has sponsored research on the development of turbine engine nozzles that can accommodate the antimist fuels without performance degradation. This work was discontinued when the contractor determined that the effort was more extensive than originally estimated. The FAA is also sponsoring a continuing theoretical and experimental study of mist flammability at Rutgers University. This latter research (Reference 14) has led to the development of a plausible analytical model of flame propagations in mists.

U. S. Navy

Experimental studies have been conducted by the Naval Air Propulsion Test Center to determine horizontal flame propagation characteristics of liquid fuels containing antimist additives. These studies were conducted in channels 10 cm wide by 61 cm long, and the results indicated that, for a specific wick-type ignition source, the presence of 0.1 to 0.3% AM-1 in JP-5 fuel reduced the time-to-flame-propagation across a liquid surface by about one-fourth (12). On the other hand, these studies indicated little or no influence of 0.3% XD-8132 on this flammability property.

The Navy is primarily concerned with thickened fuels (gel-type), rather than antimist-additive fuels, to retard fuel spreading in aircraft carrier environments. However, in order to remain abreast of antimist-additive fuel potentialities, the Navy has conducted gunfire tests on fuels containing these additives (6) at the Naval Weapons Center (China Lake, California). In these tests, 4 liter, rectangular steel cans were filled half-full of JP-5 fuel and placed behind a steel striker plate (6). These targets were then subjected to 50 caliber API projectiles below the fuel level, and the results were recorded on movie film at 128 frames per second. In this series of tests, the temperature was controlled at 0, 4,

27, 49, and 71°C with AM-1 concentrations of 0, 0.1, 0.2, and 0.3%. The fireball effects for AM-1 concentrations of 0.1 to 0.3, at temperatures from 0 to 49°C, were not significantly different. At 71°C, the JP-5 fuel containing AM-1 produced fireball effects about equivalent to the neat fuel. It was concluded that these tests were probably too severe, and a new series of gunfire experiments will be undertaken to determine the numerical probability of sustained fires versus temperature and antimist additive content.

Other U. S. Organizations

Lockheed-Georgia Simulated C-5A Fuel System Compatibility Tests

As part of an in-house program, the Lockheed-Georgia Company conducted a series of compatibility tests using part of the C-5A Galaxy fuel system (13). In this series of tests, 0.3% concentrations of AM-1 and FM-4 were evaluated for general compatibility and stability characteristics. The C-5A fuel system simulator is a full-scale replica of a portion of the wing (left and center sections) fuel system. In order to evaluate the fire safety properties of the fuel utilized in this test series, the Lockheed-Georgia Company assembled an FAA-type airgun test.

The 0.3% concentrations of antimist additives chosen for this series of tests were not at levels that provide equivalent viscosity or viscoelastic effects. During the C-5A fuel system simulator tests with 0.3% AM-1, the tank ejector pumps were inoperative, and it was observed that flow from the sump could not be sustained throughout the duration of the programmed flight envelope of 0 to 12 km altitude. This difficulty was not experienced with the less viscous, 0.3% FM-4 fuel blend; however, there was evidence that the engine pump filter had been by-passed (in the latter test) because of the high pressure drop across the filter.

AFLRL conducted mist flammability tests on composite samples of 0.3% FM-4 and of 0.3% of AM-1 exposed to recirculation for 2 and 3 hours and/or pumped once-through by the boost and engine pumps. The results of these tests indicated that the mist flammability resistance of both additives had deteriorated substantially.

NASA Antimist Mechanism Studies

Until recently, NASA has not been involved in the antimist fuel development program (11). However, at the present time, the NASA Jet Propulsion Laboratory, Pasadena, California, is undertaking a basic study of the rheology of polymeric antimist additives. The objectives of these NASA studies are to study the mechanisms by which these additives inhibit mist formation.

OVERVIEW AND PROJECTIONS

Extensive research has been completed on the physical, flammability, and compatibility properties of aircraft fuel blends containing polymeric antimist additives. An "ideal antimist aircraft fuel" would exhibit excellent mist flammability resistance throughout handling and transport operations, but then could be efficiently rendered innocuous by mechanical or other means before being transported through the aircraft fuel system to the engine.

Research described in this paper has identified significant advantages and disadvantages of polymeric antimist agents relative to physical, flammability, and systems compatibility characteristics. These identified items are summarized as follows to place antimist fuel characteristics in proper perspective.

- The described antimist agents effectively prevent the formation of flammable mist of low-volatility fuels under many conditions of high-shear exposure. However, different concentrations in the fuel, ranging from about 0.1 to 0.7%, are required for the various agents in order to attain equivalent antimist effectiveness.
- The ease and completeness of dissolution in jet aircraft fuel varies among the candidate agents. Those antimist agents studied that appear to form true solutions may be pumped through filters without causing filter clogging. However, the apparent viscosity (through filters) exhibited by such solutions can be orders of magnitude greater than that of Newtonian fluids having the same low-shear viscosity as the antimist fuel blends.
- The sensitivity to loss of antimist effectiveness when subjected to shear forces, which varies among the candidate agents, represents a potential handling problem.
- The degree of shear degradation required to restore engine atomizer-nozzle compatibility of fuel blends containing the candidate agents is substantially greater than that which renders the fuel blends flammable in an air-shear misting situation.
- Potential system compatibility problems that may occur with some or all of the present-generation antimist agents include: fluid friction penalties at low Reynolds numbers because of higher low-shear viscosities, especially at low temperatures; fluid friction penalties through filters because of viscoelastic effects that cause the apparent viscosity (through porous media) to be orders of magnitude greater than that of Newtonian fluids having the same low-shear viscosity; filter clogging at very low temperatures because of precipitation observed with some antimist agent batches; and ejector pump penalties because of viscoelastic effects.

The precise physical mechanisms by which the polymeric antimist agents under investigation exert their influence upon misting phenomena are subject to some conjecture. Hence, rheological and antimist-mechanism studies should be continued, and, as more knowledge is gained regarding such mechanisms, improved mechanical and/or other means for intentional degradation of antimist agents could be developed. This improved knowledge of antimist mechanisms should permit the tailoring of antimist agents having fewer disadvantages. For example, studies comprising the systematic variation of antimist agent molecular size

and structure could lead to the development of new candidate agents. Such developments could eventually yield antimist fuels having properties more nearly like those attributed to the aforementioned "ideal antimist aircraft fuel".

Throughout future antimist fuel research, a conscious effort should be made to inter-relate the various test procedures with the objective of ultimately defining standardized diagnostic and quality-control techniques for evaluating the physical, flammability, and compatibility properties of antimist fuels.

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TABLE 1. COMPARISON OF MIST-FLASHBACK MEASUREMENTS WITH LABORATORY AND SIMULATED FULL-SCALE IMPACT FLAMMABILITY TEST RESULTS

Fuel Blend	Mist Flammability (Mist Flashback, Mean cm) (25°C)	Impact Flammability (Impact Dispersion Rating) ^a (25°C)	Simulated Full-Scale Helicopter Crash Test (Mist Fireball Rating) [†] (38°C)
JP-8R/Neat	21.2	D	SMF
JP-8R/0.07% AM-1	3.8	B	NMF
JP-8R/0.2% AM-1	0.8	A	NMF
JP-8R/0.3% FM-4	0.8	A	NMF
Jet A-1/0.7% XD-8132‡	13.1	D	SMF
Jet A-1/0.7% SC-8132**	2.7	A	NMF

^aA. No pilot flame enlargement.
^bPilot flame dimensions less than doubled.
^cPilot flame dimensions more than doubled.
^dPilot flames totally obscured by transient mist fire.
[†]Tests conducted (in duplicate or more) for the Army by Dynamic Science, Phoenix.
 SMF: Substantial mist fireball.
 NMF: No mist fire.
[‡]Fuel blend provided to the Army by FAA/NAFEC and tested by Dynamic Science after storage at Phoenix for 2 months prior to test. (Storage temperature range 7.5°C to 45°C)
 **Same fuel batch as above tested by Dynamic Science after storage at Phoenix for only 6 days prior to test.

TABLE 3. ILLUSTRATION OF EFFICACY OF ANTI-MIST AGENT IN JET FUEL AT ELEVATED TEMPERATURES

Fuel Description	Flash Point °C	Impact Dispersion Flammability Rating ^a	Fuel Temperature, °C
0.2% AM-1 in JP-8R	52	A	54
JP-8R Neat	52	D	54
0.2% AM-1 in JP-8R	52	A	68
JP-8R Neat	52	E	68

^aA. No pilot flame enlargement.
 B. Pilot flame dimensions less than doubled.
 C. Pilot flame dimensions more than doubled.
 D. Pilot flames totally obscured by transient mist fireball.
 E. Coalesced fireball with simultaneous pool burning.

TABLE 2. SUMMARY OF AFLRL DATA ON TYPICAL PHYSICAL PROPERTIES VS TEMPERATURE AND FLAMMABILITY CHARACTERISTICS AT 25°C FOR NEAT AND ANTIMIST JET FUELS

Fuel Type	Zero-Shear Viscosity, cS			Freeze Point, °C	Mist Flashback, Mean cm	Impact Dispersion Rating ^a
	5°C	25°C	-40°C			
JP-8R	-	-	-	-60	29.2†	E
JP-8R plus 0.2% AM-1	-	-	-	-	0.8†	E
JP-8R	1.2	2.1	15.1	-52	21.2	D
JP-8R plus 0.025% AM-1	-	-	-	-	13.1†	C
0.05% AM-1	1.7	3.0	20.9	-	6.9	B, C
0.07% AM-1‡	2.0	3.3	24.5	-53	3.8	B
0.1% AM-1	2.3	3.9	29.9	-	1.3	A, B
0.2% AM-1**	3.8	6.5	71.1	-	0.8	A, A
0.3% AM-1	5.7	9.0	(-)-†	-	-	-
JP-8R plus 0.3% XD-8132	2.1	3.6	18.1‡	-58	4.8†	B, C
0.5% XD-8132	-	-	-	-	3.0†	A
0.7% XD-8132	3.8	7.1	(-)-***	-56***	2.7†	A
JP-8R plus 0.3% FM-4‡	3.3	5.4	33.1	-40	0.8	A
JP-8R plus 0.2% PEP-4	2.12	3.5	20.8	-57	0.8	A

^aA. No pilot flame enlargement.
 B. Pilot flame dimensions less than doubled.
 C. Pilot flame dimensions more than doubled.
 D. Pilot flames totally obscured by transient mist fireball.
 E. Coalesced fireball with simultaneous pool burning.
[†]Values obtained prior to enclosing mist flashback flame area corrected by base-line shift that occurred when wall was installed. Other values obtained with present, enclosed system.
[‡]Fuel blends also utilized by Dynamic Science for simulated full-scale helicopter crash tests.
 **Fuel blends also utilized by Naval Aero Propulsion Test Center for T-63A engine test.
 ††Erratic replicate results. Traces of precipitate.
 †‡White precipitate at -20°C. Viscosity decreased after each soak period at -40°C.
 ***Too many solids to permit viscosity measurements at -40°C.

TABLE 4. MIST FLASHBACK FLAMMABILITIES OF VIRGIN & DEGRADED ANTIMIST FUELS

Fuel	Low-Shear Viscosity at 38°C, cS	Mist Flashback Mean cm
JP-8R	1.7	20.1
0.2% AM-1 (virgin)	5.3	0.8
0.2% AM-1 (3 passes through gear "chopper" at 10,000 rpm)	3.0	11.9
0.2% PEP-4 (virgin)	3.9	0.8
0.2% PEP-4 (3 passes through gear "chopper" at 10,000 rpm)	2.5	13.5

TABLE 5. SUMMARY OF EXHAUST DATA OBTAINED BY NAPTC FOR T-63 TURBINE ENGINE

Engine Power Rating	CO ^a			THC ^a			NO _x ^a		
	JP4	JP8	JP8/AM-1	JP4	JP8	JP8/AM-1	JP4	JP8	JP8/AM-1
Ground Idle	71.27	111	110	19.66	49	80	1.759	2.1	1.9
Flight Idle	52.23	75	105	8.712	21	64	1.230†	2.6	2.1
30-percent MIL	34.21	49	74	3.190	8	31	2.719	3.2	2.8
60-percent MIL	18.49	27	46	0.8869	3	9	4.194	3.9	3.6
75-percent MIL	12.63	19	30	0.4346	2	3	4.193†	4.4	4.0
Military	7.26	9	13	0.3366	1	1	6.264	5.2	5.0

^aEmission Index - lb pollutant/1000 lb fuel.
 †NO measurement only.

TABLE 6. COMPARISON BETWEEN GRAVITY-IMPACT-DISPERSION AND INCENDIARY-BALLISTIC TEST FLAMMABILITY RESULTS

Fuel Temp. °C	Wt% AM-1	Impact Dispersion Flammability Effects*	Ballistic Exposure Flammability Effects†
17	0.0	-	Transient fireball with totally-involved ground fire‡
26	0.0	Transient mist fireball with no pool burning	-
26	0.2	No fire effects	Incendiary fireball only**
49	0.2	-	Incendiary fireball with single small localized ground fire
54	0.0	Transient mist fireball with no pool burning	-
54	0.2	No fire effects	-
66	0.0	Transient mist fireball with small localized pool burning spot	-
66	0.2	Slight pilot flame enlargement only	Incendiary fireball with retarded development of ground fire**
71	0.0	Cooled fireball with simultaneous pool burning	-
71	0.2	Slight pilot flame enlargement only	-
77	0.0	Cooled fireball with simultaneous pool burning	Transient fireball with totally-involved ground fire‡
77	0.2	Slight pilot flame enlargement with delayed pool ignition	Incendiary fireball with retarded development of ground fire**
77	0.5	-	Incendiary fireball with retarded development of ground fire**
88	0.0	Cooled fireball with simultaneous pool burning	-
88	0.2	Slight pilot flame enlargement followed by retarded pool burning	-
Water Only		-	Incendiary flash only ††

*Fuel: 1.5 kg of 63°C flash point F-76 diesel fuel (DF-M) in glass container (2 liters). Impact surface: 2.5 cm thick steel plate imbedded in concrete. Impact velocity: free fall at about 11 m/s.
†Fuel: 63°C flash point F-76 diesel fuel (DF-M). Target: 76 liter fuel in horizontal 114 liter drum (Spec. No. DOT-175-2030-73) with small bung hole open at top rear of drum. Ammunition round: XM-599, 20 mm HEI-T. Actuator: 6 mm aluminum plate inclined backward at 45° angle with center 30 cm in front of drum face. Trajectory: 50 meters horizontally to center of drum face (zero degree obliquity) with about 1000 m/s projectile velocity.
‡Transient mist and/or vapor fireball throughout target-containing tunnel (duration greater than 2.5 sec).
**Apparently only that fuel contacted by the hot fragments burned (tracer-like fragment paths visible near end of event) (duration less than 2 sec).
††Brief flash (less than about 1 sec), ending with visible scattering of tracer-like fragments (less than about 1.5 sec. for entire event).

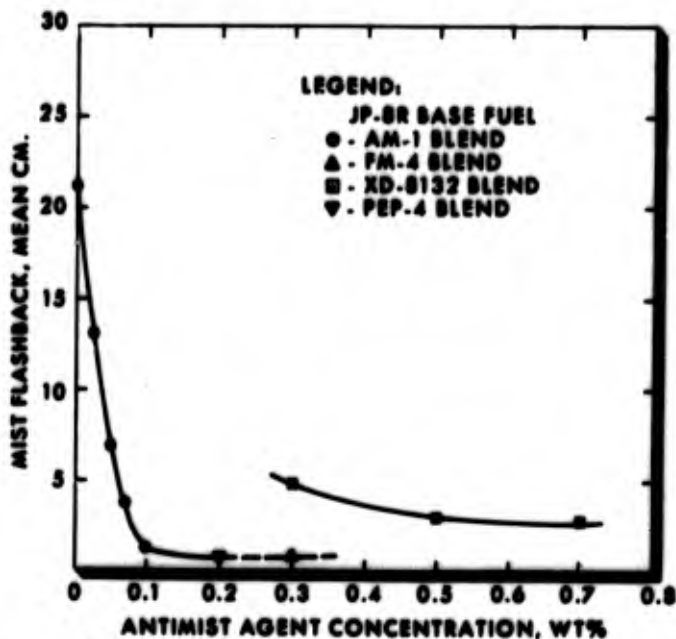


FIGURE 1. INFLUENCE OF CONCENTRATION OF VARIOUS AGENTS ON MIST FLAMMABILITY OF JP-8R

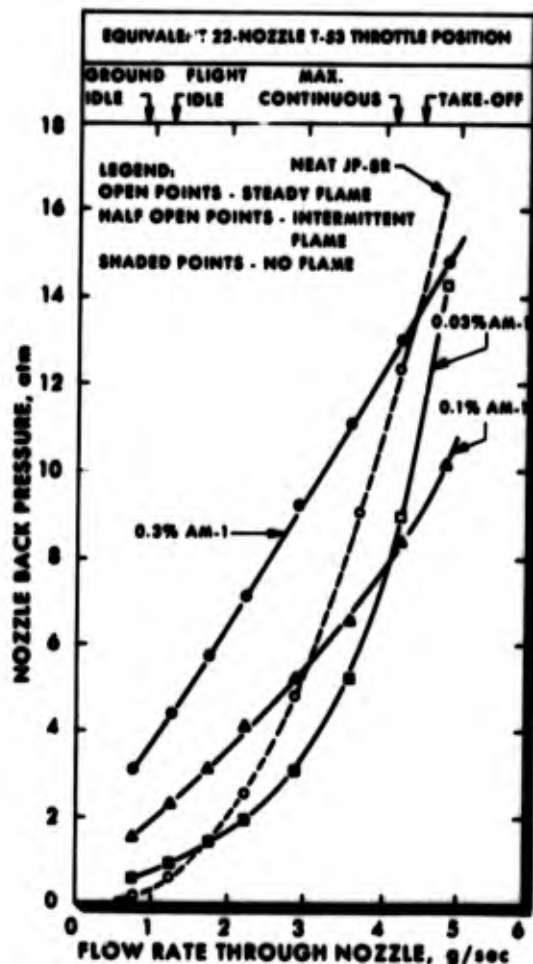


FIGURE 2. PILOTTED SPRAY TEST OF AM-1 ANTIMIST AGENT WITH SINGLE T-53 ATOMIZING NOZZLE

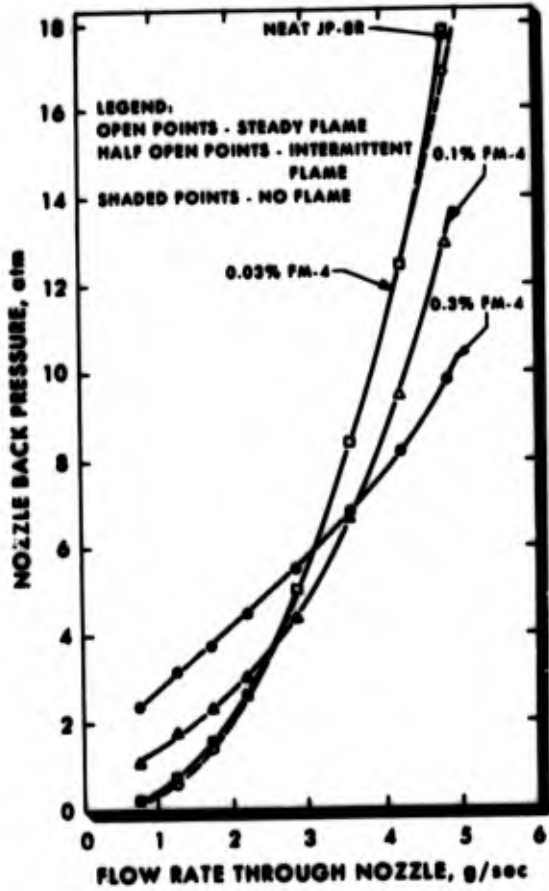


FIGURE 3. PILOTTED SPRAY TEST OF FM-4 ANTIMIST AGENT WITH SINGLE T-53 ATOMIZING NOZZLE

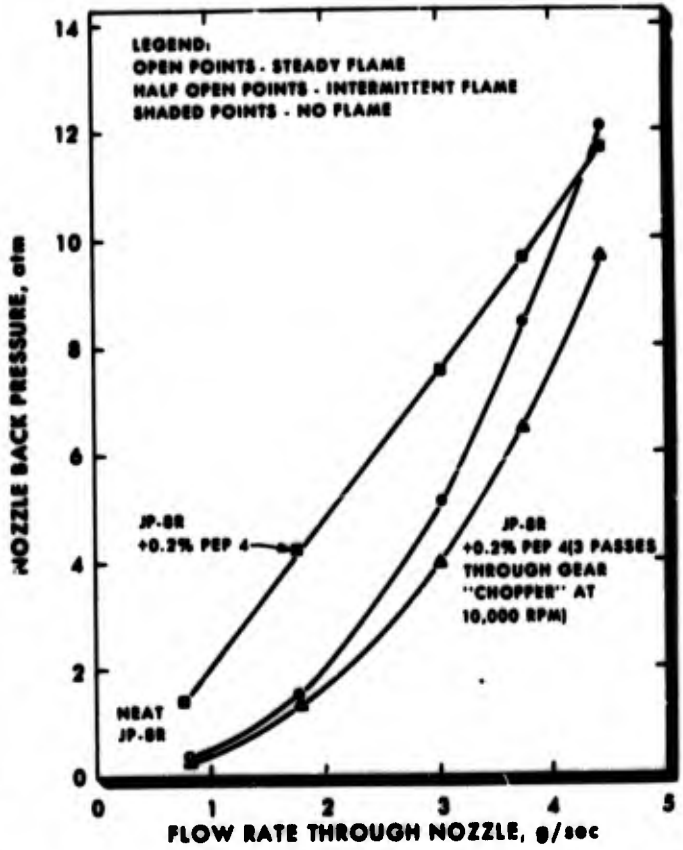


FIGURE 4. PILOTTED SPRAY CHARACTERISTICS OF VIRGIN AND SHEAR DEGRADED PEP-4 ANTIMIST FUEL

Note: A Consolidated Discussion was conducted for Papers 1-3. It is documented at the end of Paper 3.

WIDE-CUT VERSUS KEROSENE FUELS: FIRE SAFETY
AND OTHER OPERATIONAL ASPECTS

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Summary

The paper presents a summary of the present knowledge and experience of the relationships between fuel properties and safety and aircraft operation.

From the fuel viewpoint it compares the specifications for wide-cut and kerosene types with emphasis on the properties which can affect operation and safety. The difference in volatility and effects on ignition, combustion and explosion are discussed as well as other properties (fluidity, cleanliness and vapour release) which can affect aircraft operations.

From the operational viewpoint ground operations (handling, maintenance and engine starting), flight operations (fire hazard, engine relight, fuel system icing and freezing, range and payload) are considered.

Finally the fuel supply situation, present and future, in Canada is outlined.

The authors conclude that, provided all necessary precautions are diligently enforced the risks involved in using wide-range fuel are at worst only marginally greater than with kerosene.

1. Introduction

Because of continuing interest in and increasing knowledge of the influence of fuel type on aircraft safety, this review is an attempt to collect the relevant information and experience on fuel properties and aircraft operations to delineate the hazards involved.

In the interests of simplification only the two widely used fuel types are considered - the wide-cut type (NATO F-40 typified by CGSB 3-GP-22h and ASTM D1655 Jet B) and kerosene (NATO F-34 typified by CGSB 3-GP-23h and ASTM D1655 Jet A and Jet A-1). Basically the specifications within each fuel type are equivalent and the minor differences were fully discussed in a previous paper⁽¹⁾. The properties related to operation and safety are presented in groups and where specification requirements do not exist, typical data are presented in brackets. The majority of this data was extracted from U.S. Bureau of Mines Summaries⁽²⁾⁽³⁾.

2. Ignition & Flammability

The combustion of a liquid hydrocarbon fuel requires that the vapours from the liquid must mix with an oxidant such as air in certain proportions and the mixture must then receive a sufficient energy input to initiate an oxidation reaction. This reaction releases additional energy such that self-sustaining combustion occurs. Turbine fuel mixtures are flammable only at fuel/air ratios between 0.035 and 0.28 by weight (1.3% to 8% by volume).

In normal use combustion is controlled by throttling the amounts of fuel and air supplied and useful energy is the result. However under uncontrolled conditions large quantities of heat energy are liberated in a short time. When ignition occurs under optimum reaction conditions in a confined space the ensuing combustion causes almost instantaneous rise in both temperature and pressure resulting in an explosion.

2.1 Volatility Characteristics

The three main volatility factors relating to flammability are flash point, vapour pressure and distillation and these are compared in Table 1.

TABLE 1 - Volatility Characteristics of Aviation Fuels

Properties	Wide-Cut	Kerosene	Aviation Gasoline
(1) Distillation			
Initial Boiling Point, °F	(142)	(131)	(108) ¹
10% recovered, °F	(216)	400 max.	167 min.
20% recovered, °F	290 max.	(382)	-
40% recovered, °F	-	-	167 max.
50% recovered, °F	370 max.	450 max.	221 min.
90% recovered, °F	470 max.	(473)	275 min..
Final Boiling Point, °F	(456)	550 max.	338 max.
(2) Flash Point, °F	(below 0)	105 ² min.	(below -40)
(3) Reid Vapour Pressure, lb. min.	2.0 ³	(0.1)	5.5
max.	3.0	(0.2)	7.0

Footnotes to Table 1

- () typical values
- (1) Aviation gasoline distillation as % evaporated.
- (2) 3-GP-23, Flash Point, 103°F min.
- (3) Minimum RVP, no requirement in ASTM Jet B, optional in 3-GP-22h.

These three properties, which are themselves closely interrelated, are measures of the tendency to vaporize. The volatility of a fuel is of fundamental importance in considering flammability since a fuel will not burn in the liquid phase. It must first vaporize and the vapours when mixed in the correct proportions with air are then combustible.

From Table 1 it is obvious that aviation gasoline is the most volatile, wide-cut fuel is intermediate and kerosene the least volatile of the three fuels. Wide-cut fuel spans the distillation range of both aviation gasoline and kerosene as shown in Figure 1. The significance of these large volatility differences between fuel types in relation to safety is considered in detail.

(a) Flash Point

The flash point of a fuel is the minimum temperature at which its vapour pressure is sufficient to form a flammable vapour/air mixture at atmospheric pressure. The flash point is a laboratory measured property which is apparatus and method dependent and cannot be considered absolute. In addition the flash point measured is the "lower flash point" (corresponding to the lower limit of flammability) below which vapour/air mixtures are too weak for combustion.

Wide-cut turbine fuel specifications do not include a Flash Point requirement, because this property cannot be adequately measured for these fuels. Values are normally below 0°F. However an "upper flash point" exists above which the vapour/air mixtures are too rich. Aviation gasolines have extremely low flash points (normally below -40°F) but the tendency is for the vapour/air mixtures in equilibrium with these products in tanks at normal ambient temperatures to be too rich to be inflammable.

In summary therefore although Flash Points of kerosene fuels can be used as an indication of maximum temperatures for safe handling, this property is not particularly meaningful for wide-cut fuels or aviation gasoline.

(b) Vapour Pressure

Vapour pressure is a relative measurement of the ease of release of vapour from a liquid. For a pure single substance the vapour pressure is dependent only on temperature, increasing with an increase in temperature. For a petroleum fuel, which is a mixture of several hydrocarbons with different boiling points, the vapour pressure will also depend on the relative concentrations of these hydrocarbons, (with the more volatile components being most significant) and on the ratio of the volume of vapour in equilibrium with a unit volume of fuel (V/L ratio). The vapour pressure determines the number of fuel molecules that are released from the fuel into the vapour space and hence the strength of the fuel/air mixture present in that space.

The Reid Vapour Pressure is normally measured and is, like flash point, apparatus and method dependent so that the results cannot be translated directly into practical situations. Vapour pressure is not a specification requirement for kerosene fuels but typical values for such fuels are given in Table 1 together with the requirements for wide-cut fuels.

(c) Distillation

Distillation characteristics are another measurement of volatility with the initial boiling point being closely related to both vapour pressure and flash point. As stated previously the distillation range of wide-cut fuel spans both aviation gasoline and kerosene. Distillation characteristics of aviation fuels are compared in Table 1 and Figure 1.

(d) Flammability Limits

Flammability limits are not specification requirements but are related to the three previously discussed fuel properties. The lower or lean flammability limit is a measure of the lowest temperature at which a fuel can form a flammable vapour/air mixture while the upper or rich flammability limit is the maximum temperature at which a fuel can form a flammable vapour/air mixture. At temperatures below or above these limits the mixture is either too weak or too rich.

In an aircraft fuel tank the quantity of air available for mixing with fuel vapour is dependent on altitude above sea level (atmospheric pressure). Hence for equilibrium conditions, curves of the upper and lower flammability limits for fuels of different volatilities can be plotted against altitude. These curves are called flammability loops or envelopes; typical curves are presented in Figure 2 (4).

(i) Equilibrium Flammability Limits

Equilibrium limits apply only when the vapour/air mixture is at equilibrium with the liquid fuel. Such conditions would occur in a closed vessel or a tank in which sufficient time has been allowed for equilibration. Limits can be determined experimentally or calculated from such properties as vapour pressure and distillation. Equilibrium flammability limits must be used with caution because they will vary from one batch of fuel to another due to variations in fuel properties and calculated values may not agree with measured values. In addition the measured limits are dependent on the method of measurement. Most important however is the fact that the limits only apply to equilibrium vapour/air mixtures. While equilibrium conditions do occur in practice e.g. a partially filled fuel tank stationary at reasonably constant temperature for a period of time; non-equilibrium conditions can also occur. Within a tank in which the vapour/air mixture is not equilibrated, zones can exist ranging from too lean to too rich, passing through a flammable region. Data extracted from Figure 2 show the following approximate equilibrium flammability limits for wide-cut and kerosene at sea level:

Wide-cut: -10°F to 75°F
Kerosene: 95°F to 175°F

To illustrate the approximate nature of flammability limits, values for three individual wide-cut fuels have been reported (5).

-10 to +47°F
-20 to +38°F
and -4 to +60°F

(ii) Dynamic Flammability Limits

The actual flammability limits which may exist under dynamic conditions (refuelling, flight, landing and take-off) will be significantly different because of numerous influencing factors. All of these dynamic situations can cause an extension of the equilibrium flammability envelope for a given fuel/tank situation. Probably the most prevalent situation is fuel mist or spray formation. Fine fuel mists behave almost like vapour except that the energy required for ignition is somewhat higher and is dependent on droplet size (see later section on ignition requirements).

Spray or mists can be produced by dynamic fuel movements such as flight turbulence, crash landings involving fuel tank penetration, fuel jettisoning, refuelling (as the first fuel hits baffles) and during climb as bubbles of air come out of solution and break the surface. The mists can cause a significant expansion of the temperature range at which the tank vapour space is in a flammable condition (5). This expansion occurs at the lean limit only and its extent is dependent upon several factors including the rate and degree of shear of the fuel droplets. The degree of extension is therefore considered indeterminate. However it can extend the lean limit of kerosene into the normal envelope of the wide-cut fuel.

2.1.1 Fuel Tank Vent Conditions during Fuelling

During fuelling a mixture of fuel vapour and air is expelled from the fuel system vents. Because of the higher vapour pressure of wide-cut fuel the mixture expelled will be richer and the flammable envelope larger with wide-cut fuel. Measurements have shown, however, that even the wide-cut fuel/air mixtures are only flammable close to the vent (*). This hazard is therefore not considered significant if correct procedures are followed for locating service vehicles and other potential ignition sources away from the vent area.

Indeed the development of safe handling practices for all aviation fuels has resulted in the handling of very large quantities with comparative safety for many years.

2.1.2 Fuel Tank Conditions in Flight

In addition to the variation in flammability limits for both types of fuel with temperature and altitude as depicted in Figure 2, in flight they will also depend on many other factors such as quantity of fuel in the tank, weather and seasonal variations, speed, tank location and geometry. However an indication of the hazards during a typical long range flight are illustrated in Figures 3 a and b (?). The data presented is based on equilibrium flammability limits and one flight pattern so can only be considered as indicative. They can be summarized as follows:

- (1) Flammable mixtures can occur in an aircraft fuel tank in flight with both types of fuel.
- (2) Flammable zones are governed by fuel temperature and altitude and initial fuel temperature is of considerable importance.
- (3) Based on equilibrium flammability limits wide-cut fuel will be flammable for longer periods of flight including descent and landing but there will be some widening of the kerosene inflammability zone if mist or foam formation occurs.

2.2 Ignition

With exception of spontaneous or autogenous ignition, flammable vapour/air mixtures require a discrete energy source such as a flame or spark to cause ignition. In addition the source has to have sufficient energy to promote ignition. The two factors (i) ignition energy (ii) ignition source (fuel related, only) will be discussed separately.

(a) Energy Requirements for Ignition

The minimum energy required for the ignition of hydrocarbons under ideal conditions is 0.2 millijoules (6×10^{-3} calories). The minimum energy requirement within an homologous series of hydrocarbons is about the same however the minimum occurs at higher stoichiometric ratios with increasing molecular weight e.g. 1.3 for propane to 1.8 for heptane (⁸, ⁹, ¹⁰, ¹¹).

For gasoline and kerosene, the 0.2 mJ minimum energy requirement occurs with a mixture of 100-150 mg of hydrocarbon per litre of air (¹²). This corresponds to an air/fuel ratio approximately midway between the lower and upper flammability ratios. The minimum energy requirements for ignition of wide-cut and kerosene fuels under these ideal vapour conditions are therefore considered similar. Pressure, temperature and concentration of vapour all affect the minimum ignition energy and it would be expected that a higher energy requirement would be necessary under many practical conditions.

Fuel mists, sprays or foams represent a special case. These suspensions of minute droplets in air act like an inflammable vapour except that a stronger source of ignition is required. This situation is depicted in Figure 4(¹³) where it will be seen, for example, that the ignition energy at 50°F required to ignite wide-cut fuel is about 1.3 millijoules whereas to ignite kerosene requires about 18 millijoules. The extra energy required for kerosene mists or sprays is related to the need to provide energy to vaporize its less volatile droplets. If, however, the temperature of each fuel is adjusted to its flash point, then they all require about 5 to 6 millijoules.

(b) Ignition Sources

(1) Electrostatic Charging. Although many ignition sources are available within the environs of an aircraft during fuelling there is only one source which is produced by the fuel. This source is the discharges caused by electrostatic charging within the fuel.

The electrostatic charge is generated within the fuel as it flows through a fuelling system, with any filter/separator acting as a major charging source. Although the currents are very weak (10^{-6} to 10^{-8} amperes), with high flow rates and little time for relaxation, the potential or field strength accumulated within a receiving tank can be sufficiently high to exceed the breakdown voltage of air and produce a spark. The sparks produced can exceed the minimum energy requirements discussed in the previous paragraph. There have been many incidents of explosions and fires in both aviation and other related fields which have been caused by electrostatic discharges.

The rates of charge generation and relaxation of a turbine fuel which does not contain a static dissipator additive (see 11) is related to its "natural" conductivity which is produced by electrokinetically active impurities. Any difference in these rates between wide-cut and kerosene fuel types due to physical properties such as ion mobility is overshadowed by the variations in "natural" conductivities that can be obtained with each fuel. In addition the charge generation is also related to the type and condition of the prime charger i.e. the filter separator. This is such an important factor that in comparison differences between fuel types become insignificant. It can therefore be stated that for practical purposes the rates of charge generation and relaxation for non-additive wide-cut and kerosene fuels are essentially the same. For similar reasons to those just mentioned the same would apply to additive treated fuels of the same conductivity. The only difference between the two fuel types will therefore depend on whether one or the other contains static dissipator additive.

(11) Electrical Conductivity. Hydrocarbons are virtually perfect insulators however the trace quantities of electrokinetically active material impart a small measure of conductivity to fuel ($1 - 5 \text{ pS/m}$, $1 \text{ pS/m} \approx 10^{-12} \text{ ohms}^{-1} \text{ per metre}$ being typical). This level of conductivity is too low to promote sufficient charge relaxation since the Relaxation Time (a standard term defining the time to relax charge to 36.6% of its original value) for a 1 pS/m fuel is in the order of 18 seconds. Increasing the fuel conductivity artificially can increase the rate of relaxation to a sufficiently high level that charges generated relax before the fuel enters the receiving tank, a 100 pS/m fuel having a Relaxation Time of 0.18 seconds. Following fires and explosions due to electrostatic charge in RCAF aircraft during refuelling the use of a static dissipator additive (ASA-3) in aviation turbine fuel was evaluated. Following the successful conclusion of these evaluations CGSB Specifications for wide-cut and kerosene aviation turbine fuels were amended in 1964 to make the use of this additive mandatory. Specification conductivity limits are presented in Table 2.

TABLE 2 - Electrical Conductivity of Turbine Fuels

Property	Wide-Cut	Kerosene
Electrical Conductivity at time, place and temperature of delivery to aircraft pS/m.	50-300 ¹	50-300 ²

Footnotes to Table 2

- 1 Mandatory in 3-GP-22h, optional in ASTM Jet B (if used same limits apply).
- 2 Mandatory in 3-GP-23h, optional in ASTM Jet A, A-1 (if used same limits apply).

All fuel of these two types produced in Canada contain the additive and the hazards associated with electrostatic charging during refuelling in Canada are considered to be minimized. Although the additive is widely used in Europe the availability of treated fuel in the US is limited. This constitutes a problem for carriers who have to refuel in the US particularly if mixing of fuel types is also involved. Reduction in flowrate during fuelling is usually an aid to reducing charge generation since this generally reduces current and increases charge relaxation. This measure is however not 100% effective since in some cases a reduction in flow rate through a filter has been observed to increase charge density (14) and it certainly does not replace the desirability of using additive treated fuels.

(11) Charging Tendency. Although the charging tendency of fuels is related to conductivity recent work by several investigators has shown that fuels can contain prostatic agents which increase charge rates beyond what would be expected from conductivity measurements. These agents produce so-called "hot fuels" for some, at the moment, inexplicable reason. There are no known instances where the effectiveness of ASA-3 would be negated by the presence of prostatic agents although some reduction in fuel response to ASA-3

may occur. The FAA have sponsored a study of prostatic agents and, although not a specification requirement, the measurement of charging tendency is gaining interest.

(c) Spontaneous or Autogenous Ignition

Ignition of a fuel vapour/air mixture can occur spontaneously without the presence of an open flame or spark at temperatures high enough (but far below open flame or spark temperatures) to permit the onset and progress of the oxidation reaction. Two conditions are recognized. At low temperatures, the oxidation reaction is slow, resulting in only a small rise in temperature and pressure and little or no light. This slow reaction is termed a "cool flame". When temperatures are higher the chemical reaction of the fuel-oxidant mixtures becomes increasingly rapid and is characterized by light emission and large increases in temperature and pressure.

The laboratory method for measuring spontaneous ignition temperature is satisfactory for establishing the relative self-ignition temperatures for various fuels but it is incapable of establishing the true self-ignition temperatures that would be experienced in aircraft with fuel vapours and air in contact with hot surfaces. This is because the temperature at which the fuel/air mixture will ignite spontaneously is affected by additional factors such as pressure, contact surface, geometry of the space involved, liquid/vapour/air ratios and dwell times. When tested using ASTM Procedure D2155, the laboratory test figures for wide-cut fuel and kerosene spontaneous ignition temperature range from about 400 to 490°F with wide-cut generally being slightly higher than kerosene by about 50°F. In general the more volatile (lighter) hydrocarbons are more difficult to ignite spontaneously than the heavier ones.

(d) Hot Surface Ignition

The ignition characteristics of various aircraft fluids under conditions in which they impinge upon a hot surface in the presence of air flow similar to that possible in an aircraft enclosure, have been investigated (15). At all test conditions, the ignition temperatures of the fluids were markedly higher than their minimum auto-ignition temperatures determined in uniformly heated vessels. Table 3 provides typical data from this work.

TABLE 3 - Comparison of Ignition Temperatures of Aircraft Fluids in Quiescent Air with Heated Steel Targets and Heated Glass Vessels.

Aircraft Fluid	Heated Steel Target Ignition Temperatures ^a °F	Heated Vessel Ignition Temperatures ^b , °F
Wide-cut	920	468
Kerosene	900	440
MIL-H-5606 ^c	960	437
MIL-H-83282 ^d	1080	670
MIL-L-7808 ^e	1010	728

Footnotes to Table 3

- a. Ignitions with 4-inch diameter cylindrical targets.
- b. Ignitions evidenced by flame in ≥ 13 in.³ (213 cc) vessels.
- c. Petroleum base hydraulic fluid.
- d. Synthetic hydrocarbon base hydraulic fluid.
- e. Synthetic engine oil.

In general, differences between the ignition temperature characteristics of wide-cut and kerosene were small. The ignition temperatures increased with increasing air velocity and depended significantly on factors such as air flow, temperature, target dimensions and configuration. Hence fuel leaks in flight are not generally hazardous but chances of ignition with kerosene would be somewhat greater than with wide-cut.

(e) Spark Ignition

As discussed previously the energy requirements for ignition vary from a minimum of 0.2 millijoules under ideal vapour conditions to 30 or 40 millijoules for a kerosene spray at 0°F. This small amount of energy is readily available as sparks caused by poor electrical connections, improper grounding, faulty switches or relays, broken electrical wires or from friction sparks under crash landing conditions.

(f) Ignition by Projectile

In the case of a major engine failure in flight in which a hot engine component penetrates the fuel tank conditions created by temperature and the energy of the projectile causing atomization of the fuel are such that ignition would be relatively independent of fuel type.

(g) Ignition at Fuel System Vent in Flight

Although fuel system vents are sited so that a direct lightning strike is minimized the possibility exists and whether or not ignition occurs would be determined by the composition of the air/vapour mixture at the vent. This will depend not only on the air/vapour mixture in the tanks but also on whether the aircraft is in level flight or climbing or descending since this will determine flow within the vent system. As discussed in 2.1.2 the hazard of ignition will probably extend over a longer period of a flight with wide-cut fuel than with kerosene.

2.3 Flame Propagation(a) Flame Spread Rate

With a pool of fuel which is at temperature above its flash point there is a combustible mixture above the pool surface and if ignited the flame will propagate through the combustible mixture in a similar manner to a flame propagating through pre-mixed gases. If the fuel temperature is below the flash point the advancing flame has to heat the fuel ahead of the flame to the flash point. In this case the flame spreading is controlled by the properties of the liquid phase. Flame spread across fuel pools at and above their flash point will therefore be much more rapid than when the fuel temperature is below the flash point. The upper limit of flammability will normally not enter into this process because of the abundance of air that will be readily available. From these considerations therefore the flame spread across a wide-cut fuel will be much more rapid than across kerosene. This is illustrated in Figure 5 (?).

(b) Fuel Climbing Rate

Situations can arise where fuel is dropping from a tank on to an ignition source and under certain conditions fire can climb up the dropping fuel and ignite the bulk fuel in the tank. Atkinson (16) has studied this phenomena and found that in the dripping mode (discrete drops instead of a stream) under the conditions used in the test which involved fuel dropping on to an open flame, flame climbing was not observed for either wide-cut fuel or kerosene. This led to the conclusion that the possibility of flame climbing a column of dripping fuel of either type is extremely remote. In the unbroken stream mode flame climbing was observed with the following results:-

- (a) as wind velocity increases the minimum temperature for flame climbing increases significantly even over the limited range covered in the investigation.
 - (b) there is no significant effect of fuel flow rate or wind temperature on the fuel temperature necessary for flame climbing.
- and, (c) the minimum temperature for flame climbing is significantly higher for kerosene than for wide-cut fuel under all conditions.

Two curves (Figures 6 & 7) taken from Atkinson's work show the difference in flame climbing rate between wide-cut fuels and kerosene together with the effects of wind velocity and position of the ignition source.

3. FUEL EFFECTS ON AIRCRAFT OPERATION3.1 Fuel Fluidity

Prolonged flight at high altitudes will cause the fuel temperature to approach the ram air temperature. As the fuel cools and approaches its freezing point it becomes increasingly more viscous and eventually flow to the boost pump and through the fuel system to the engine could be reduced causing fuel starvation. This problem could be of particular importance for Arctic and certain military operations where fuel may be loaded at extremely low ambient ground temperatures. In such cases flights need not be of prolonged duration for such problems to occur. Fuel filter heaters are used essentially to prevent ice blockage but they will assist in preventing filter blockage due to the freezing of marginal freezing point fuels. However fuel of sufficiently low freezing point is necessary where experience dictates that freezing could be a problem.

Specification requirements for these properties and some typical values for viscosities are presented in Table 4.

TABLE 4 - Fluidity Characteristics of Aviation Fuels

Property	Wide-cut	Kerosene	Aviation Gasoline
(1) Freezing Point, °F max.	-72 ¹	-58 ²	-72
(2) Viscosity, cSt @ -30°F	(2.2-3.43) ³	15 max. (5.3-13.5) ⁴	(1.18-1.40) ⁵

Footnotes to Table 4

() Typical values

- 1 Jet B freezing point is -58°F. -58°F also optional for 3-GP-22h.
- 2 Jet A-1 freezing point. Jet A calls for -40°F.
- 3 Range of 4 values presented in Reference 3.
- 4 Range of 63 samples presented in Reference 3 with an average of 9.38. Range of averages from 1960-1973 also presented in Reference is 8.21-9.45.
- 5 Data from Reference 17.

Comparison of these requirements shows that aviation gasoline and wide-cut fuel have better low temperature properties than kerosene. For long range high altitude flights and certain Arctic military operations fuel to ASTM Jet A specification would not be suitable. Jet A-1 could be marginal for certain Arctic military operations.

3.2 Contamination

Contamination of fuel by undissolved water from sources described in para 3.3.2(b) can cause fuel filter and fuel transfer valve freezing resulting in fuel starvation. Water settling in tanks can lead to microbiological contamination with resultant problems of structural corrosion, filter plugging and fuel quantity gauge malfunctions. Fuel quantity gauges can also be affected by undissolved water directly. Particulate contamination can cause fuel pump and fuel control system wear. Normally such wear may not be catastrophic but markedly affects operational costs. Catastrophic failure, particularly in single engine aircraft, can occur if contamination causes fuel controls to jam. In addition solids can provide the nutrients required for micro-organisms to grow. Exclusion of contaminants from an aircraft fuel tank is therefore an important safety necessity.

Fuel properties related to contamination can be divided into two groups:-

- (a) Inherent Fuel Properties Affecting Cleanliness - This covers fuel properties inherent in the fuel which can affect the ease by which solid contaminants and undissolved water can be settled or separated from the fuel.
- (b) Contamination Content - This relates to the amount of undissolved water or particulate matter that is present or should be tolerated in the fuel.

3.2.1 Inherent Fuel Properties Affecting Cleanliness

Since both particulate matter and undissolved water are heavier than fuel they will settle out on standing. Under quiescent conditions the settling rate is directly proportional to particle size and the difference in density between the fuel and particle, and inversely proportional to the fluid viscosity. Typical settling times for various fuels in relation to particle size are given in Figure 8 and Figure 9 (17). Ice particles would be expected to settle at a similar rate to water and particle sizes of ice crystals formed during fuel cooling could range from 5 - 20 micrometers depending on cooling rate.

Contaminants are not all removed by settling and the principal method of decontamination is by the use of filter water separators. Filter water separators filter out solid contamination from the fuel and coalesce water hazes so that larger water droplets are formed. Some of these droplets will settle immediately while the remainder are carried on to a hydrophobic separator stage which retains the droplets and then allows them to settle. Although fuel properties such as viscosity and density will assist in the settling process in the filter housing another property called the water separation characteristics of the fuel is of prime importance in the coalescing stage. The coalescing ability of a filter separator can be impaired to a point where undesirably high quantities of undissolved water are present in the filter effluent if the fuel has been contaminated by trace quantities of surface active materials. A test procedure which produces a water separation rating of the fuel known as the Water Separation Index, Modified (WSIM) is used to attempt to predict how a fuel will coalesce in a filter separator. A rating of 0-100 is obtained by

this method with 100 representing very good water separation characteristics. Another method used for attempting to predict water separation characteristics is the Water Reaction Test.

In summary therefore fuel properties which can be included in the category of "Inherent Cleanliness" are

Specific gravity
Viscosity
WSIM
Water Reaction

Specification requirements for these properties are compared in Table 5.

TABLE 5 - Inherent Cleanliness Properties of Fuels

Property	Wide-Cut	Kerosene	Aviation Gasoline
(1) Specific Gravity 60/60°F	0.751-0.802	0.775-0.840	(0.705)
(2) Viscosity, cSt @ -30°F	(2.2-3.43)	15 max. (5.3 - 13.5)	(1.18 - 1.40)
(3) WSIM	75 min ¹ (80-95)	75 min ¹ (80-95)	Not used
(4) Water Reaction Interface rating, max.	1 b	1 b	1 b

Footnotes to Table 5

() typical value.

¹ Specification requirement in 3-GP-22h and 23h, ASTM D1655 does not have a WSIM requirement for either Jet B or Jet A-1. Values in brackets are considered typical for fuels purchased under any of the specifications.

3.2.2 Contamination Content

As mentioned previously the two main contaminants are particulate matter (solids) and undissolved water.

(a) Particulate Matter (Solids) - Particulate matter can be picked up by fuel throughout the complete transportation system from refinery to aircraft. Typical contaminants are iron rust (Fe₂O₃) and pipe-scale (Fe₃O₄), mineral matter (silica etc.) filter media, paint flakes and many other miscellaneous types of solids. The problems associated with solids have been discussed previously.

(b) Undissolved Water - The solubility of water in aviation fuels is limited and varies exponentially with temperature. Typical solubility/temperature data is depicted in Figure 10 (NRC lab. data). The solubility at a particular temperature varies somewhat dependent not only on fuel type but also on hydrocarbon composition, water being more soluble in aromatics than in saturates. On cooling below the saturation point additional water (approximately 1 ppm per °F) will come out of solution and will be present as undissolved water. The water coming out of solution will be present as a haze which will eventually coalesce and settle. Fuels will also dehydrate in tanks where the relative humidity of the air above the fuel is less than the percent saturation of the fuel. Additional water can be gained or lost throughout the whole transportation system from refinery to storage and to the aircraft due to contact with water present in the system and with the atmosphere. The use of filter separators is therefore essential at strategic points in the distribution system. Even if the fuel entering the aircraft is free from undissolved water, water can be precipitated as the fuel cools in flight. In addition on descent a considerable amount of water can enter the tank as warmer, moist air reaches the cold tank internals.

As stated previously undissolved water is an undesirable contaminant mainly because of potential fuel system freezing. To overcome filter icing problems in B-52 and KC-135 aircraft the USAF introduced a fuel system icing inhibitor into wide-cut fuel in 1960. This additive, ethylene glycol monomethyl ether, is now widely used in NATO military fuels at a concentration of 0.10 - 0.15% by volume. This additive has been extremely effective in preventing fuel system icing. In Canada this additive is being used in all military fuels as well as in many Arctic commercial operations and during the winter for DC-9 aircraft during overnight stop-overs at certain stations.

Properties relating to contaminant content and fuel system icing content are presented in Table 6.

**TABLE 6 - Specifications Requirement for
Contaminant Control**

Property	Wide-cut	Kerosene
(1) Total Solids		
(a) Delivery to Aircraft	2 mg/IG max. (<1 mg/IG)	2 mg/IG max. (<1 mg/IG)
(b) Delivery to bulk storage	10 mg/IG max.	10 mg/IG max.
(2) Undissolved Water, ppm	(30 max.) ²	(30 max.) ²
(3) Fuel System Icing Inhibitor, % vol.	0.10 - 0.15 ³	- ³

Footnotes to Table 6

() typical values.

- 1 Specification requirement in 3-GP-22h and 23h, no requirement in ASTM D1655 for either Jet B or Jet A-1 but most airlines use limits of 1 - 4 mg/gallon.
- 2 Not a specification requirement, 30 ppm.max. is general accepted level.
- 3 Optional in 3-GP-22 and 3-GP-23. A general additive clause in the ASTM specification would permit its use.

3.3 Vapour Lock and Air Release

Aircraft fuel systems are designed to prevent vapour lock with wide-cut or kerosene fuels under all normal operating conditions. Practical difficulties have recently occurred which may be linked with air release and volatility of wide-cut fuel but insufficient evidence is available at present to define the causes of the problem. Limited data on air solubility in kerosene and wide-cut fuels is given in References 18 - 19.

4. Other Operational Considerations

4.1 Tank design

Bulk storage tanks for wide-cut fuel require vapour containment devices to minimize breathing and filling losses because of the high vapour pressure of this type of fuel. However NFPA Bulletin No.407 - Aircraft Fuel Servicing 1973 - requires all aviation fuel storage tanks to meet requirements for storage of Class I flammable liquids although kerosene with a flash point of 105°F min. is a Class II liquid.

4.2 Switch Loading

Switch loading refers to the practice of fuelling a tank with fuel having flammable characteristics significantly different from those of the fuel remaining in the tank. When fuels are mixed in this manner the resulting fuel vapour/air mixture above the liquid will have new and possibly broader flammability characteristics. The principal hazard occurs when the fuel being loaded does not contain static dissipator additive. This is of particular concern when aircraft are fuelling in the United States where little or no static dissipator treated fuel is available. The hazards involved are illustrated in Figure 11.

The subject of switch loading has been covered by recent documents issued by the FAA (20) and the CAA (21) when it was realized that, during the fuel shortage in 1974, US and UK civil operators might have to accept wide-cut fuel. The documents recommend the use of static dissipator additive and where this cannot be made available that other precautions, such as reduced fuelling rates, should be observed.

4.3 Defuelling

The observations made on fuelling apply also to defuelling but in addition there may be a disposal problem in defuelling either type of fuel at an airfield where only the other type is regularly used.

4.4 Aircraft Maintenance

For aircraft maintenance purposes, kerosene is favoured over wide-cut fuel because fuel tank purging to reduce the air/vapour mixture to below the lean inflammability limit is more easily accomplished. Also when fuel lines are broken during maintenance more care must be taken if the lines contain wide-cut fuel.

Carbon build up on engine components would be expected to be greater with kerosene than with wide-cut fuel and with certain sensitive engines this may lead to increased maintenance requirements.

4.5 Engine Starting and Relighting in Flight

Operations at very low ambient ground temperatures are theoretically favoured by the use of wide-cut fuel because of its higher vapour pressure and lower viscosity and freezing point. These advantages are however not required except under Arctic conditions with engines equipped with low energy starters or ignitors.

The higher volatility of wide-cut fuel also increases the ability to relight in flight compared with kerosene. However most commercial aircraft engines have been designed to relight satisfactorily with either fuel. There are limited exceptions in smaller commercial and certain military equipment.

4.6 Range and Payload

A gallon of kerosene contains, on the average, 3 - 4% more BTU's than a gallon of wide-cut fuel whilst a pound of wide-cut fuel contains, on the average, 0.5% more BTU's than a pound of kerosene. Therefore when an aircraft is volume limited maximum range can be obtained with kerosene and when the aircraft is weight limited maximum range can be obtained with wide-cut fuel.

5. Survivable Accidents

The sequence of events in an aircraft accident vary widely from one accident to another. Many accident reports do not even quote what type of fuel was in the aircraft tanks and statistics from the relatively few accidents where full data are known could be completely misleading. However full scale crash tests have shown that on rupture of fuel tanks and lines following severe impact and deceleration fuel can be dispersed as a fine mist or cloud surrounding the aircraft. When the aircraft comes to a stop the remaining fuel may be released forming a pool or draining away depending on the terrain. With a less severe impact or an aircraft clipping an obstruction on landing, mist formation may not occur and only liquid fuel may escape.

There will be several ignition sources present such as an external engine fire, engine ingestion and flash-back, engine hot surfaces, friction sparks, electrical arcs or sparks, etc. In the mist situation there would be little difference between the two types of fuel. In the absence of extensive misting the flammable vapour envelope formed with wide-cut fuel would be considerably larger than with kerosene increasing the chance of interface with an ignition source.

As previously discussed once ignition has taken place flame spread across the surface of spilt wide-cut fuel will be much faster than with kerosene and there is also more chance of fire spreading by climbing up a stream of fuel from a ruptured tank with wide-cut. The intensity and duration of fires with both fuels are approximately equal.

The probability of explosion of a fuel tank enveloped by fire is possibly higher with kerosene than with wide-cut since the increase in temperature will bring kerosene into the flammable region whilst with wide-cut it can only become richer and will then only burn on contact with the atmosphere.

The energy released in a fuel tank explosion will depend on the quantity of fuel vapour involved. For equal fuel/air ratios the energy release for the two types of fuel will be comparable however conditions are likely to be such that the mixture in a wide-cut fuel tank will be near the rich limit (high fuel/air ratio) and in a kerosene tank without mist toward the lean limit. Hence in the absence of mist, energy release with wide-cut fuel would normally be expected to be higher than with kerosene.

6. Canadian Supply Situation

Amongst the Western industrialized countries Canada is unique in its winter requirement for large quantities of low pour point heating fuel and diesel fuel competing with the aviation kerosene supply. At present about 37% of Canadian jet fuel sales are kerosene (Jet A-1) and it appears that with the present refining capacity this could be expanded to about 54% without disruption of supply to other markets. The present market split between the wide-cut and kerosene type fuel has been the result of free decisions on the part of the airlines influenced by availability, price and performance factors on the premise that there is no measurable or universally accepted difference with respect to safety. Kerosene type jet fuel has generally been priced about 3 or 4 cents per Imperial gallon higher than wide-cut and forecasts of future market demands suggests that this will also be the pattern for the future. If for any reason the kerosene/wide-cut ratio must be substantially increased then refinery construction will be involved and therefore to be an economical proposition it must be carefully phased into normal refinery expansion over a five to ten year period. Even so, if the added processing is charged completely to jet fuel, there would be an added incremental cost of another 3 or 4 cents/I.G.

Obviously in a military emergency the only fuel which would be available in Canada in sufficient quantities from secure sources would be wide-cut and it would therefore seem essential to maintain all airport facilities and aircraft capable of safely handling this fuel quite apart from any decisions affecting peace-time operations.

7. Conclusions

Although much of the evidence presented here suggests that kerosene is a safer fuel than wide-cut throughout the systems of ground handling and use in the aircraft it must be emphasized that this impression is given entirely by laboratory information on volatility, flash points, flammability limits etc. The projection of these properties into usage situations is far from rigorous because of the apparatus-dependency of the measured quantities and unknown situations such as mist formation within tanks under different conditions, the time required to establish equilibrium in a tank etc. This is even more true of crash conditions where so many variables are possible depending on how fuel tanks and lines are ruptured and their relationship with ignition sources.

In handling all fuels there are obvious hazards and suitable precautions must be taken. These are essential even with kerosene but wide-cut fuel gives less tolerance for mistakes or untoward happenings. Motor gasoline is daily handled in much larger quantities by much less experienced personnel under far less control with a minimum of problems.

It is the authors' opinion that, provided all necessary precautions are diligently adhered to, including obvious steps such as the mandatory use of static dissipator additive, fitting of flame arrestors or suppressors to all fuel tank vent systems, regular inspection and maintenance of refuelling equipment and aircraft fuel systems to minimize the possibility of leaks, and suitable educational programs for all personnel involved in handling fuel, the risks involved in using wide-range fuel are at the worst only marginally greater than with kerosene.

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H.H.Kristiansen	-	Transair
H.J.Londeau	-	Nordair
T.A.Miller	-	Air Canada
D.E.Salter	-	Shell Canada
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J.E.Shillingford	-	Dept. of Energy, Mines & Resources
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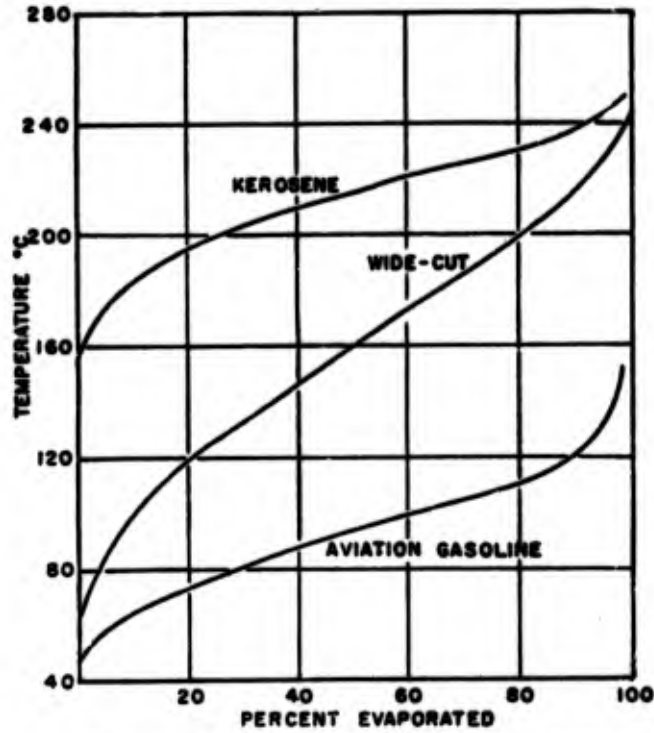


Figure.1. TYPICAL DISTILLATION CURVES OF AVIATION FUELS.

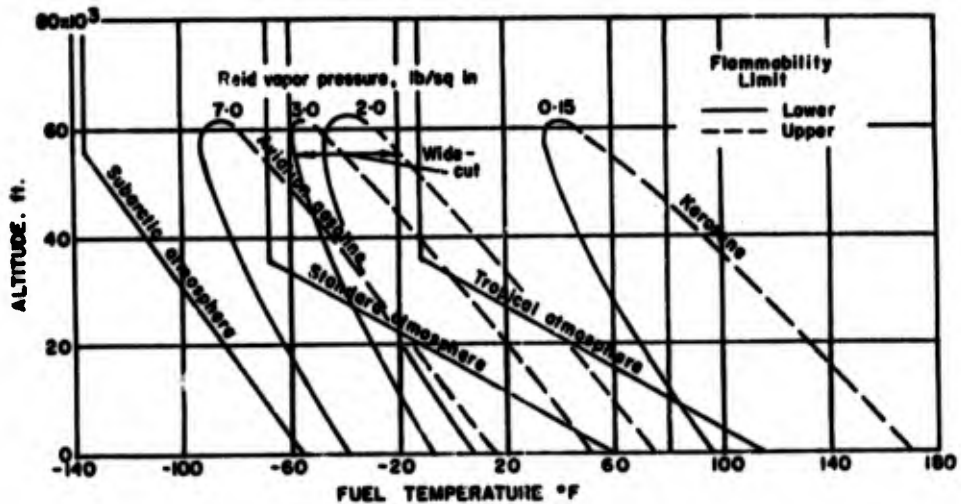
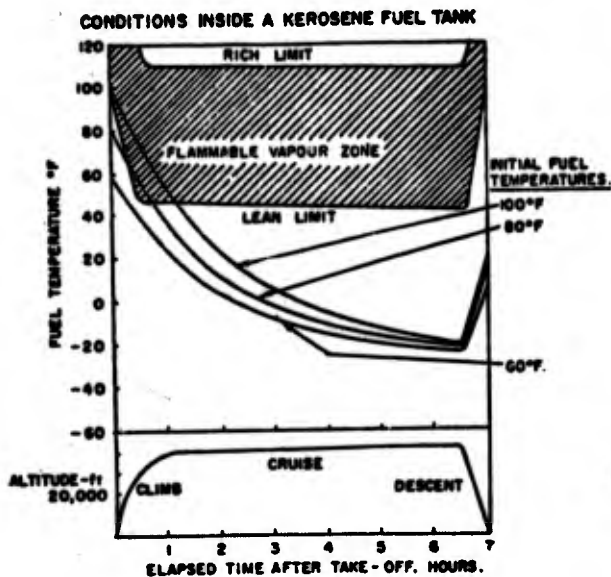


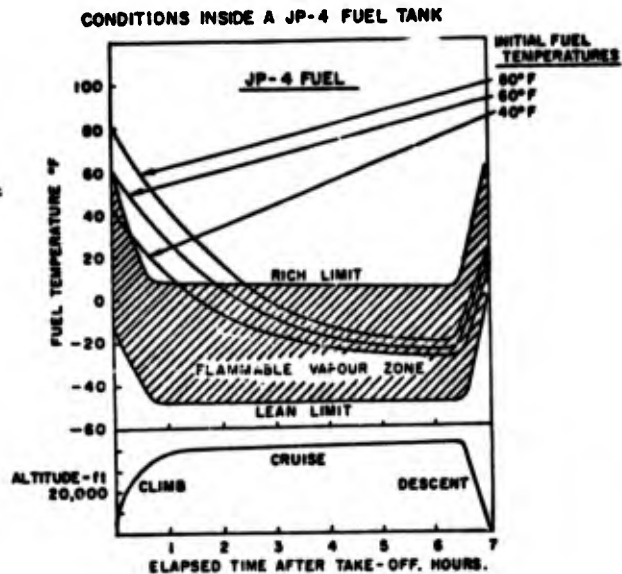
Figure.2. Altitude-temperature flammability limits for fuels of varying vapor pressure.

FIGURE 3a.



TYPICAL FUEL TEMPERATURES IN FLIGHT — JET TRANSPORT CRUISING AT 525 MPH. BASED ON DATA OF BOEING AIRPLANE CO. AND DeHAVILLAND AIRCRAFT CO., LTD.

FIGURE 3b.



TYPICAL FUEL TEMPERATURES IN FLIGHT — JET TRANSPORT CRUISING AT 525 MPH. BASED ON DATA OF BOEING AIRPLANE CO. AND DeHAVILLAND AIRCRAFT CO., LTD.

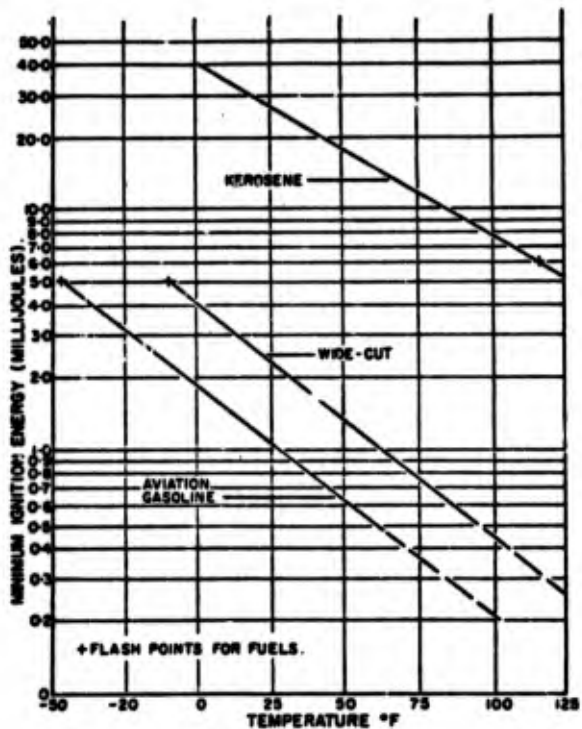


Figure 4. MINIMUM SPARK IGNITION ENERGIES FOR FUEL-AIR SPRAY MIXTURES.

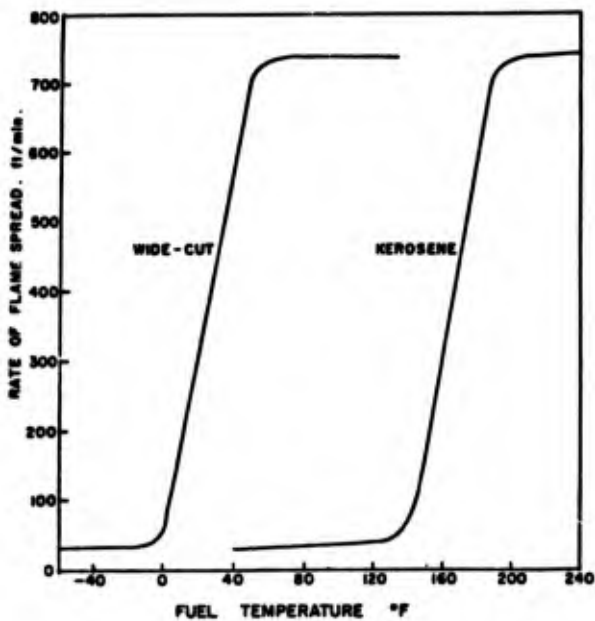


Figure 5. RATE OF SPREAD OF FLAME ACROSS A LAYER OF FUEL

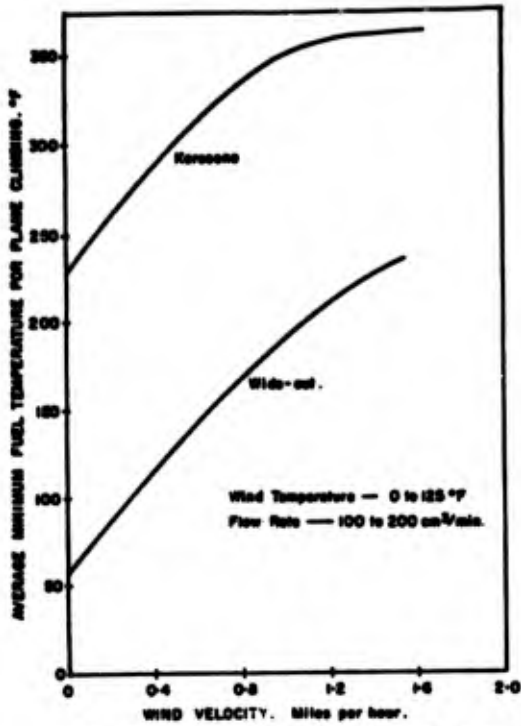


Figure 6. The Effect of Wind Velocity on the Minimum Fuel Temperature Required for Flame Climbing up a Fuel Stream.

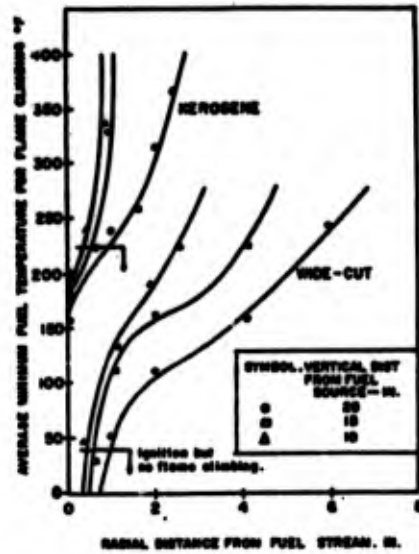


Figure 7. THE EFFECT OF THE SPARK IGNITOR LOCATION ON THE MINIMUM FUEL TEMPERATURE REQUIRED FOR IGNITION AND FOR FLAME CLIMBING UP A FUEL STREAM.

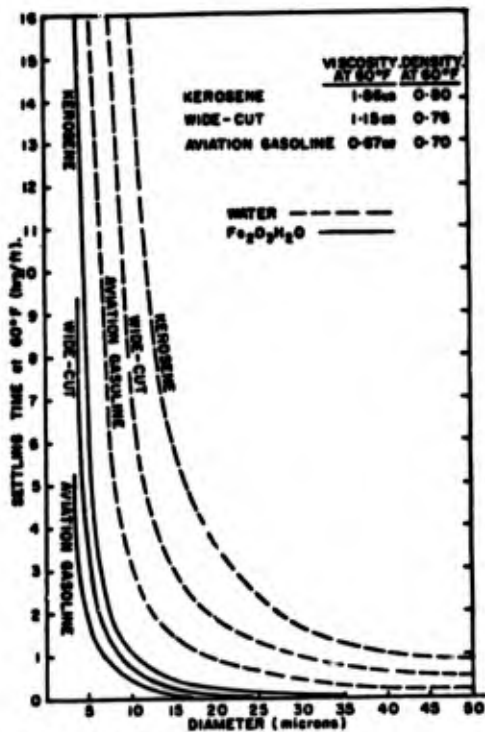


Figure 8. Settling times - Fuel vs Water (calculated from Stokes' Law)

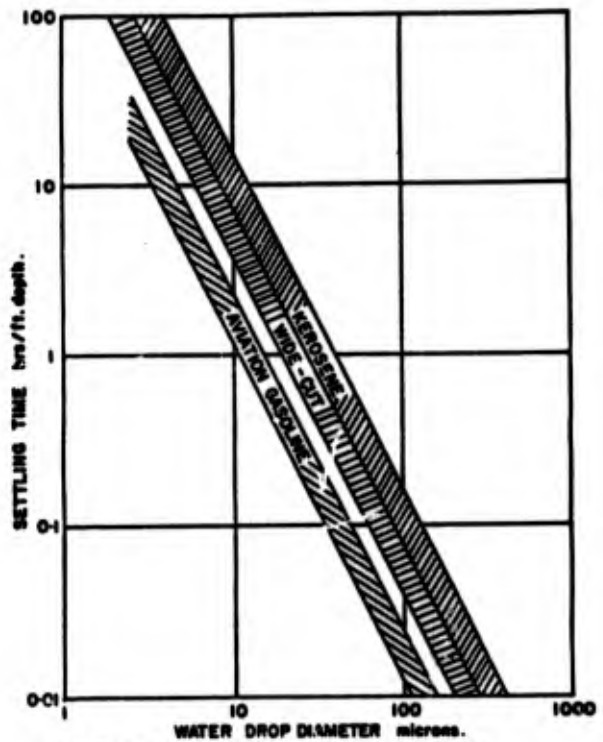


Figure 9. Settling times per foot for water droplets.

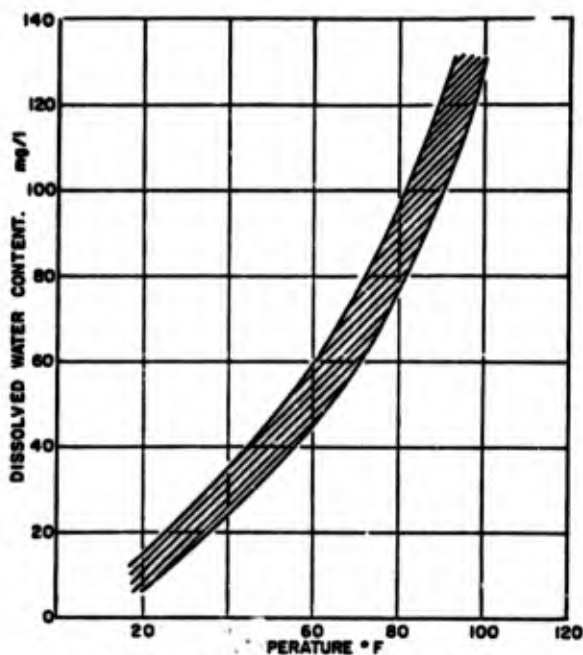


Figure 10. Temperature/Solubility Curve. Water in Jet Fuels.

FIGURE 11

RELATIVE HAZARD ASSOCIATED
WITH
PRODUCT SWITCHING DURING AIRCRAFT FUELLING

		PRODUCT BEING LOADED			
		WIDE-CUT	WIDE-CUT PLUS ASA-350	KEROSENE	KEROSENE PLUS ASA-350
PRODUCTS IN AIRCRAFT TANKS	WIDE CUT	H	M	H	M
	WIDE CUT PLUS ASA-350	H	M	H	M
	KEROSENE	H	M	M	L
	KEROSENE PLUS ASA-350	H	M	M	L
	*COMBINATION WIDE-CUT & KEROSENE	H	M	H	M
	*COMBINATION WIDE-CUT & KEROSENE PLUS ASA-350	H	M	H	M

LEGEND

RELATIVE HAZARD:

- LOW (L) TANK VAPORS NON-FLAMMABLE AND LOW CHARGE LEVELS ON ENTERING FUEL.
- MEDIUM (M) EITHER TANK VAPORS ARE NON-FLAMMABLE OR CHARGE ON ENTERING FUEL IS REDUCED TO LOW LEVEL.
- HIGH (H) FLAMMABLE TANK VAPORS AND HIGH CHARGE LEVELS ON ENTERING FUEL.

*NOTE

FUEL IN AIRCRAFT TANK SHOULD NOT BE CONSIDERED OF ONE TYPE UNTIL THREE SUCCESSIVE FUELLINGS OF SAME TYPE PRODUCT HAS OCCURRED OR AIRCRAFT TANKS HAVE BEEN DRAINED AND ONE FUELLING WITH DESIRED PRODUCT HAS OCCURRED. IF ABSOLUTE ASSURANCE IS REQUIRED A SAMPLE OF PRODUCT FROM AIRCRAFT TANK MUST BE SENT TO A LABORATORY FOR ANALYSIS.

DISCUSSION - PAPERS 1-3

Mr Rekos: What happens to the combustion process using anti-misting fuels? What are the effects on altitude relight and pollution?

Mr Miller: With certain chambers there is a shift of the ignition loop towards richer mixtures but the width of the ignition loop expressed as a percentage does not change significantly. (The question of pollution is discussed under a response to Mr. Tugay which comes later in the discussion.)

Mr Rekos: With regard to the safety problems of jet fuel, what problems do you expect to see from the use of jet fuels refined from tar sands, shale, and oil?

Mr Whyte: No problems were expected or have been experienced using synthetic crude from the Athabasca Tar Sands since hydrocarbon composition is similar to that of the normal crude. Fuels produced from shale or coal could be significantly different depending on the actual processes used.

Mr Glasman: Does the increased viscosity of the anti-misting fuels give more serious ignition characteristics when flames are not present?

Mr Miller: I presume that you are referring to the spontaneous ignition case. The minimum spontaneous ignition temperature of the base kerosine is not affected by the addition of small amounts of anti-misting additives. While it is possible that the increased viscosity might lead to an increase in residence times in certain circumstances, it should be remembered that FM9 modified Avtur is still a low viscosity fluid (about 1.7 - 2 cp at room temperature instead of about 1 cp for kerosine as measured on our apparatus). I feel therefore that the viscosity effect will be a very minor one.

Mr Weatherford: With regard to influences of the antimist additives on ignition and flame spread rates, you are correct. However, for these fuels, the room temperature viscosity is only about two to three times that of neat fuel and the reduction in ignition times and flame speeds is less than 40% in our laboratory flame trough. In the simulated full-scale helicopter crash tests we described, a hot-surface ignition source (at about 620°C) is provided. This source has been observed to ignite neat fuels but has not ignited the candidate antimist fuels. These observations appear to reflect a contradiction, but we believe that, in this case, the neat fuel soaks into the soil adjacent to the hot surface more readily than does the antimist fuel. Hence, a thinner film of neat fuel could remain on the hot surface than would be the case with antimist fuels, and the thinner film could be more readily ignited.

Mr Andrews: Could the author please comment on the effectiveness of typical engine high pressure fuel pumps in degrading fuels prior to combustion?

Mr Miller: Those high pressure fuel pumps we have investigated readily degrade the modified fuel to the point where fire resistance is lost. More severe degradation, however, is required before FM9 modified fuel is compatible with the engine fuel control system and the high pressure pump does not produce this.

Mr Tugay:

- (1) Avez-vous observé une augmentation des fumées de combustion avec les additifs anti-vapeur?
- (2) Y-a-t-il augmentation des oxydes d'azote dans les fumées?

Mr Miller: We have not observed any increase in nitrogen oxides and this is confirmed by Table 5 of Dr. Weatherford's paper. Recent tests on a vaporising chamber have shown that there is no smoke problem under idling conditions.

Mr Weatherford: No significant differences were observed between neat JP-8 and 0.2% AM-1 in JP-8 fuel over the full range of operation in the U.S. Army-sponsored T-63 engine test.

Mr Marriette: Is there a simple means of determining if the safety fuel is still "safe"?

Are there any undesirable side effects from FM9 additives such as aluminium corrosion or degradation of synthetic rubber materials? *

Mr Miller: The most reliable method of determining whether a sample of fuel is still safe is by subjecting it to a small scale fire test.

*This aspect has been answered under the response to Mr.Jackson.

Mr Livermore: The antimist fuel appears to modify the performance of L.P. fuel system components substantially – the constructor relies on gravity feed for ultimate reliability – if a "degrader" component is required, it should not be in the low pressure system, but be on the engine.

Mr Miller: We see this degrader as being immediately upstream of the engine fuel control system.

Mr Wilson: The papers on safety fuels are very encouraging. It seems that good progress is now being made in finding solutions to the many problems associated with the use of antimist fuels. For a safety fuel to be acceptable for civil transport aircraft, a number of points have to be satisfied, including the following:

(1) Fuel costs form a high proportion of the total operating costs of aircraft; any increase in the cost of safety fuel must be small and be justified on a cost-benefit basis.

(2) If safety fuels are introduced, these fuels may not be available at all airfields, particularly if in an emergency aircraft are diverted. It should therefore be possible to use either the current type of fuel in use or the safety fuel, without any adverse effect on the normal operating limitations of the aircraft or the engine, including the re-light envelope and engine fuel filtration elements. The effect on accuracy of the fuel tank contents indicator and reliability of the fuel system must also be considered.

(3) The long term effects, if any, of using safety fuels on the engine and aircraft fuel systems must be established. The compatibility of the additives that reduce fuel mist formation with any other additives or constituents in the fuel needs to be investigated. Adequate flight trials should be made.

On the question of whether kerosine is a safer fuel than wide cut gasoline, the CAA and formerly ARB, have no doubts that kerosine reduces the overall fire hazard in a potentially survivable crash. We have held this view for more than 20 years.

Mr Zimmer: In which time scale can general introduction of safety fuels to operating a/c be expected?

- (1) safety kerosine fuels for turbine engine powered a/c
- (2) safety aviation gasoline for piston engine powered a/c

Or: When can it be expected that the problems mentioned for general introduction will be solved?

Mr Miller: Antimisting kerosine still needs considerable research before its introduction into aircraft and the fuel is not expected to be in use in the current decade. I know of no serious attempts being made to improve the safety of gasoline for piston engine aircraft. Certainly mist suppressing additives will be of no use in this type of fuel.

Mr Weatherford: We have confirmed that none of these antimist additives effectively change the flammability of a volatile fuel such as JP-4 or gasoline. A chemical inhibition mechanism would be required to achieve such changes. Antimist additives would also cause problems relative to completeness of vaporization and uniformity of fuel distribution to cylinders.

Mr Rekos: With the three fold increase in the cost of fuel, the incremental cost for safety additives is now a small percentage and we should be able to go first-class as far as safety additives.

Mr Weatherford: On the other hand, just as momentum was building up for changing over from JP-4 to JP-8 fuels, the energy crisis became serious and halted such considerations (at least temporarily). Hence, the priority for antimist additive research appears to be reduced.

Mr Jackson:

- (a) What is the effect on tank sealants and rubber bag tanks from the antimisting additive?
- (b) If a blender is required to introduce the antimisting additive, is there likely to be a problem logistically in asking small aircraft operators to have a blender at their airfields?
- (c) Will the anti-misting additive give corrosion problems on the blender as happened when blenders were first used for the F.S.J.J. additive?

Mr Miller: While we have no reason to suspect problems of metal corrosion or with rubbers, we have some compatibility testing going ahead at the moment. The results are not yet available. We see no alternative method of introducing the modified fuel other than by blending in the antimisting additive at the aircraft fuelling point.

SYSTEMS PROBLEMS ASSOCIATED WITH THE USE OF SAFETY FUELS

by

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SUMMARY

With the advent of crash-fire-resistant anti-misting aircraft fuels of the visco-elastic class, research has been done into the performance of components in current aircraft fuel systems when using such fuels, and the effect that the systems would have on the fuels. It has been found that the use of safety fuels in a current aircraft system could result in a continual degradation of their crash-fire-resistant properties. Attempts are, therefore, being made to measure the degradation in the major components of a system, and use the results to programme a computer study in order to predict the state of the fuel remaining in aircraft on landing following a full range flight.

SYMBOLS

- a_0 = additive concentration in undegraded fuel
- a_1 = effective additive concentration in collector tank at any instant
- a_2 = effective additive concentration in main tank at any instant
- a_3 = effective additive concentration in additional tank at any instant = a_0
- a_d = effective additive concentration at booster pump delivery
- C_a = correction coefficient
- K = consistency index
- M_1 = ratio of effective additive concentration, following a single booster pump pass, to concentration before the pass (i.e. a_d/a_1)
- M_2 = ratio of effective additive concentration, following a single jet pump primary pass, to concentration before the pass
- M_3 = ratio of effective additive concentration, following a single jet pump secondary pass, to concentration before the pass
- n = flow behaviour index
- Q_1 = collector tank capacity
- Q_2 = main tank capacity
- Q_3 = additional tank capacity
- q = booster pump output flowrate at any condition
- q_{max} = maximum booster pump output flowrate
- T = time taken for fuel to flow from booster pump through jet pump to main tank
- $\dot{\gamma}$ = nominal shear rate
- τ_w = shear stress at pipe wall

1. INTRODUCTION

With the UK development of various anti-misting kerosene (AMK) safety fuels, effort has been devoted to studying their behaviour in typical aircraft fuel systems. Two particular problems have been identified: (i) to prevent undesirable loss of anti-misting properties of the fuel taking place, through degradation of the additive in the tanks and supply lines to the engines and (ii) to achieve desirable and complete degradation of the fuel at the engines, to enable it to be used in the engines' systems without loss of performance.

It has been found that the direct use of undegraded fuel, by an engine, will cause malfunctioning of the engine and its fuel system downstream of the backing pump; to prevent such an occurrence the fuel needs to be thoroughly degraded. Although an effective degrader, suitable for installation on an engine, has yet to be developed, methods are available for degrading the fuel to such an extent that its flow characteristics are almost identical to those of Avtur; safety fuel so degraded has been used by an aircraft engine in a test lasting several hours over a range of thrust levels without either incident or loss of performance. The purpose of this paper, however, is to consider the first of the problems referred to above.

Measurements of the flow characteristics of AMK have shown that both temporary and permanent changes in the fluid's properties can occur. The temporary change is a thickening of the fuel to various levels depending upon shear rate and time of application. The permanent change occurs when a limiting value of shear/time is exceeded, the resulting effect being a thinning of the fuel and a loss of anti-misting properties. The significance of this is the possibility that, in an aircraft low pressure fuel system involving fuel recirculation, the fuel in the tanks could be degraded during flight to a level where it may no longer be effective as a safety fuel, a fact of particular importance at the time of landing.

An attempt has been made to quantify the degradation resulting from the flow of fuel through the critical components in a low pressure fuel system, and the data used to programme a computer study, in which some aircraft fuel systems have been represented by mathematical models, in order to predict the state of fuel at any instant of flight time.

The performances of some components in current aircraft fuel systems, when using either Avtur or AMK, have been compared and the implications of such a fuel change, insofar as retrofit action with present day aircraft or future system design changes may be concerned, are considered.

2. COMPONENT PERFORMANCE EFFECTS

The items in the aircraft fuel system of particular interest concerning flow performance characteristics with AMK fuels are: (i) pipes, (ii) pumps (booster and jet transfer), (iii) filters, (iv) flowmeters, (v) fuel gauges and (vi) heat exchangers. Each of these is considered in some detail below.

(i) Pipes

Pipe flow characteristics of AMK safety fuels have been investigated by measuring the total head pressure loss over a range of flowrates. In a series of tests made with a particular type (FM4) of fuel, in the temperature range +15°C to -40°C using straight pipes (12.7 mm dia), it was shown that in the low shear rate range the equation of flow could be represented by:-

$$\tau_w = K\dot{\gamma}^n$$

The flow index n was found to vary from 0.9, for temperatures above -20°C, to a value of 1.4 at -40°C. In the laminar flow regime the head loss with FM4 fuel was found to be about twice the value for Avtur, whilst under turbulent flow conditions (>0.8 m/s) the head loss of Avtur was 2.5 to 3 times the value found with FM4. Further flow tests using smaller pipes of 2.4-4.45 mm dia showed that, for shear rates greater than 1000 s⁻¹, the simple power law was inadequate. It is expected, however, that a shear rate range of up to 1000 s⁻¹ will be sufficient to cater for most aircraft fuel system design estimates.

Flow measurements made with other versions of AMK safety fuel, over a range of shear rates of from 500 s⁻¹ to 10 000 s⁻¹, have shown these to exhibit a shear/time dependency by way of either a thickening and/or an eventual thinning of the fuel.

A comparison of the flow resistances of Avtur, FM4 and FM9 fuels in 2.7mm pipes is given in Fig.1. These results contrast with those found using the 12.7 mm dia pipes and serve to show the inconsistencies, particularly with FM4, that can be found with such fluids. Further larger scale pipeflow testing is envisaged, together with some basic rheological investigations at a university.

(ii) Pumps

(a) Booster

The type tested was two-staged, comprising an axial flow three-bladed inducer stage followed by a five-bladed radial main stage discharging into a spiral volute. Testing was done over a temperature range from +15°C down to -40°C with the pump using a standard debris guard at inlet (10 mesh per inch). Performance data were obtained over the normal range of flowrates and are presented in Figs.2, 3 and 4.

Pump performance is clearly impaired by the use of AMK. The overall efficiency, compared with Avtur, is reduced by 30% at room temperature, but, in the case of FM9, for a temperature of -25°C, a temperature to which fuel in civil airline use may be expected to attain by the end of a flight, the reduction was 20%. The use of the debris guard was found to have no effect on pump performance.

It is the practice in many pump designs for their motors to be cooled by use of the fuel being pumped. Since the cooling effect of a safety fuel is lower than that of Avtur (see (vi) below) the operating temperature of currently designed motors will be raised by a change to AMK fuel. This effect will be aggravated further by a reduction in the designed cooling flowrate; this is controlled by orifices, the discharge coefficient of which can be reduced to only a proportion (e.g. 70%) of that for Avtur (Fig.5).

A further point of interest is that AMK fuels can be expected to hold contamination in suspension more easily than can Avtur; if so, there will be a need to compare and consider bearing wear, possible sources of ingress of dirt and ways of avoiding this.

(b) Jet transfer

In the evaluation of jet pump performance, interest was centred on a Carter type PN60103 as used in the Lockheed CSA aircraft for inter-tank fuel transfer. Performance figures were obtained with a normal primary supply pressure of 207 kPa for various delivery heads (0.37 m to 1.89 m of fuel); these are presented in Figs.6 and 7.

The performance here, as for the booster pump, is clearly impaired by the use of AMK, the maximum efficiency being reduced from 18% to 8%. The ratio of secondary to primary flowrates necessary to achieve this was reduced by about a half, so that the original design flowrates for the intended installation could not be met. The reason for this loss in performance with AMK is due to suppression of turbulence in the throat, severely limiting the extent of mixing of primary and secondary flows.

(iii) Filters

A feature of undegraded AMK is its inability to flow through an aircraft's fuel system filter of standard porosity (10 μ nominal) without an excessive pressure differential across it. Short term tests with undegraded FM9 at ambient temperature, using both paper and wire gauze filter media, showed that

blockage took place with porosities less than 140 μ . Degradation of the fuel, however, by way of four passes through a high pressure diesel injector, was found to be sufficient to achieve an acceptable filtration performance through a 10 μ aircraft filter (Fig.8). The degree of degradation necessary to reach this condition was found to be 98% (approx) as measured by the orifice flow technique (see below). It was apparent, following the 10 μ filter test with degraded fuel, that the paper had acquired a faint black stain; tests later confirmed that this particulate was wear debris, picked up by the fuel in the injection process, and could have accounted for the small difference in filter performance between degraded FM9 fuel and Avtur. It is not clear why the FM4 did not behave in the same way.

(iv) Flowmeters

Conventional type volumetric flowmeters calibrated for Avtur have been found to be inaccurate when used with non-degraded AMK; in general the indicated rates were about 15% in error. No information is available yet on the performance of a direct reading mass flowmeter which is dependent upon momentum change effects. An alternative and acceptable scheme, for use with either degraded or undegraded fuel, would be the use of a positive displacement-type volumetric flowmeter.

(v) Fuel gauges

Information on the use of tank gauging systems with AMK is limited. There is some evidence, however, to indicate that capacitance type gauging functions satisfactorily, the recorded values maintained accuracies within the requirements demanded by Mil-C-7940A (i.e. 2% of full-scale and 4% of indicated quantity).

(vi) Heat exchangers

It is the practice in civil aircraft to design and fit a heat exchanger in the fuel system, one purpose being to counter any icing resulting from water contamination; reliance upon an icing inhibitor is not accepted by the airlines owing to its uncertain availability in different parts of the world. For this reason comparative evaluation tests have been made between Avtur and AMK (FM4 and FM9). Heat transfer measurements with the undegraded fuel encountered difficulties due to unsteady temperature recordings of both tube and fuel; the taking of an average value of results leads one to assume that the heat transfer coefficient achievable will be only about 60% of that possible with Avtur, under conditions of equal mass flowrate. With degraded fuel, after four passes through a diesel injector, it was found that the coefficients were 90-95% of those obtainable with Avtur and, over the test period of 20 hours, there was no detectable change in either heat transfer coefficient or flow head loss.

It is desirable that an aircraft system should not be affected by a change in type of fuel (i.e. use of either Avtur or AMK). Since it is common practice for equipment such as filters, flowmeters and heat exchangers to be positioned on the engine between the backing pump and the high pressure pump, it is perhaps fortunate that they will be downstream of the intended position for the desirable degrader to be situated. For this reason, the problems found with these items of equipment, when using undegraded safety fuel, would be alleviated if not eliminated.

3. SOURCES OF UNDESIRABLE DEGRADATION

It is a characteristic of an AMK fuel that both temporary and permanent changes in its properties can occur during flow through the pipes and components of a fuel system. The temporary change is a thickening of the fuel to a more viscous state, the extent depending upon the amount of shear (i.e. shear rate/time) to which it has been subjected. Above a limiting value of shear/time, permanent changes occur in the fuel with some loss of anti-misting properties; the effect of repeated exposure to shear/time beyond this limit can be cumulative insofar as the loss is concerned. The significance of this is the possibility that, in the low pressure fuel system of an aircraft, the fuel may be degraded in flight to a level where it may no longer be effective as a safety fuel.

Two major sources of high shear exist in an aircraft fuel system; booster pumps and transfer (jet) pumps - each of which is examined below.

(i) Booster pumps

These are generally of the centrifugal variety operating over a flowrate range ratio of about 4:1 between take-off and cruise requirements, the conditions for optimum overall efficiency being achieved at only one flowrate and this not necessarily matching either of the above running conditions. Many pump motors are designed to be cooled by way of fuel flooding, a portion (about 1%) of the fuel delivered by the pump being by-passed for this purpose; such fuel is subjected to shear in its flow through the motor by way of annular passages and flow controlling orifices. Pumps fitted with inducers, for air separation purposes, can be expected to receive fuel which has had some initial work done on it by the inducer. Furthermore, the flowrate dealt with by the inducer is greater than that catered for by the main impeller and some of the induced flow is recirculated back to the collector box which will, therefore, contain partially degraded fuel. This effect has been demonstrated experimentally, but as yet it has not been quantified. Further shearing of the fuel will also take place within the pump itself by way of normal flow, slip at the impeller tip and leakage through the clearances.

Clearly, the fuel in its passage through a booster pump and motor will encounter a great deal of shear, and in consequence some permanent degradation. The majority of this fuel will be transmitted directly to the engine whilst the remainder may be returned to main tanks and/or collector boxes.

The extent of degradation of AMK fuel in its passage through a pump has been determined experimentally and found to be dependent upon flowrate or residence time within the pump (see Fig.9); this shows a decreasing value of the correction factor C_Q , with reduced flowrate, the product of which with the degradation factor M (see Fig.11) for full flow conditions gives a measure of the effective

concentration per pass at pump delivery. Thus, the lower the value of C_Q , or pump flowrate, the more damaging is the degradation.

(ii) Transfer pumps

The current trend is to use jet pumps for fuel transfer within a system, the desirable feature being simplicity as a 'fit and forget' item of equipment; primary flow for their operation is taken from the booster pump delivery, already partially degraded, and this is used to induce a transfer secondary flow by way of momentum exchange. Experimental evidence has been obtained to show that both primary and secondary flows are degraded in their flow through such pumps, the extent being comparable to that for the booster pumps.

(iii) Other possible sources

These, which have not been quantified yet, are vibration and slosh in tanks, pipe flow and overspill from collector boxes. It follows, therefore, that as the system operation proceeds in the course of a flight, recirculation of degraded fuel must result in a general degradation of the fuel remaining; the true extent may well be more than that being allowed for on the basis of pump degradation alone.

4. MEASUREMENT OF DEGRADATION LEVEL

The method used at RAE to assess the quality of a safety fuel, with respect to degradation, is to pass the fuel through a sharp-edged orifice under a fixed discharge pressure head, the time taken for a given amount to flow being a measure of the state of the fuel. The datum for this assessment has been derived by mixing undegraded AMK and completely degraded AMK (four diesel injector passes) in varying ratios to obtain samples with a constant quantity of additive but with the additive at various levels of degradation. By passing these samples through the fixed orifice, a calibration curve was obtained (Fig.10) showing the effect of percentage degradation on discharge time. Using this technique the extent of degradation for a single pass through a pump when supplied with fuel at different degradation levels, was assessed (Fig.11); these results were obtained at full flow conditions and, as mentioned earlier, need to be used in conjunction with the correction factor C_Q in order to derive a degradation level at pump outlet for various flowrates.

5. SYSTEM EFFECTIVENESS

In view of the foreseeable degradation of the additive, the question arises as to the eventual consequences to AMK fuel in an aircraft in the course of a flight, and whether it will remain in an acceptable anti-misting state. In an attempt to answer this question some typical aircraft fuel systems have been considered for which mathematical models have been compiled, these representing the various stages of flight, and into which fuel degradation constants have been introduced (Appendices 1 and 2), the whole being programmed into a computer. For each analysis the mixing of fuels within tanks, where transfer takes place, was assumed to be instantaneous; also the amount of fuel remaining in the aircraft at the end of flight was taken to be 10% of total tankage capacity, a standard value although some aircraft have been known to extend their flights beyond this limit.

Two aircraft have been considered for analysis; (i) executive jet, and (ii) medium range civil airliner. In each case the normal flight fuel management sequence was followed as well as a variation by way of a small modification, this was introduced in anticipation of achieving an improved fuel condition with respect to its effective concentration. A further extension of the analysis was to examine the effect of successive flights when refuelling with partially degraded fuel remaining in the tanks.

6. DISCUSSION

It should be evident from the above that the acceptance of the fuel as being in a safe state will depend upon whether it exceeds a pre-determined degradation limit at which the fuel is considered to have lost its anti-misting and fire resistance characteristics. The setting of a reliable limit at this stage of development is somewhat premature and obscure; it is stated by the fire hazard specialists that fuels with an additive concentration of 0.3% will satisfy fire resistance safety requirements but that fuels of only 0.2% concentration will not. If the assumption is made that a mean value may be taken as the limit of acceptability, then an undegraded concentration of 0.25% may be taken as corresponding to a fuel of original concentration 0.3% degraded to an effective concentration of 83% of its 'as new' condition. There is some evidence to support this assumption but further confirmation is needed.

The results of model analyses are given in Figs.12, 13 and 14 which indicate, in some instances, that at the end of flight some tanks could contain fuel with a degradation level beyond the stipulated limit and may, therefore, be in a fire risk state. Some situations, however, are considered to have retained their effectiveness whilst minor system modifications have, in some instances, retrieved the situation for those that would otherwise be unacceptable. The extent of the changes in effective concentration, following a single pump pass, will be dependent upon individual pump design and characteristics so that other pumps may well effect concentration changes that are different from those given with the type used in the experimental assessment. The results presented could be optimistic since other sources of degradation, that have not been included, could prevail. Such sources are fuel slosh in tanks, flow through pipes and valves, collector box overflow in some designs and the extent of booster pump inducer usage which recirculates fuel within the collector box.

Increasing the additive concentration above 0.3% has been considered as a possible means of maintaining the effective concentration above the critical limit at all times. It has been concluded that the rheological problems associated with fuel transfer would be worse and the cost increase would not be justified. It is difficult to assess the cost increase accurately at this stage but it is expected that a fuel with an additive concentration of 0.3% would cost about 2% more than Avtur at the present time.

Experimental work on AMK fuel has indicated the main sources where degradation will arise and this, together with the systems assessment, directs attention to such regions where research is needed in order to reduce or eliminate its occurrence. The opportunities for circumventing, or at least easing, the problem would exist in designing a new system but for current aircraft, which are likely to be in service for a decade or two, this could call for some retrofit action. In particular, pump performances can be expected to be impaired and they could fail to meet the original design requirements. Furthermore, any uprating of currently installed equipment to meet any such shortcomings could necessitate an increase in the installed electrical power availability. In any new system design the foremost desire would be to eliminate or curtail recirculation and to select transfer pumps, if required, with a minimum degrading capability, probably powered by a prime mover. They could then be operated at their optimum efficiency where degradation would most probably be least. The use of booster pumps with their changing operating conditions, i.e. take-off and cruise, presents a difficulty since maximum hydraulic efficiency conditions cannot be met for each condition at a constant operating speed and this situation, together with recirculation through jet transfer pumps, enhances the problem. A possible solution using currently designed pumps would be to install two pumps in parallel each of different flow ratings, one matched for take-off flow-rate and the other for cruise. The appropriate pump would be selected to operate at its maximum efficiency keeping electrical loading to a minimum.

As regards a degrader for use on the engine, no satisfactory design has yet been achieved. An engine using mechanically degraded fuel has been run successfully over the full power range, so that there are not expected to be any engine fuel system problems of any major significance when a degrader becomes available.

A point that may yet give rise to an operational difficulty concerns the practice of draining the fuel tanks of water that has accumulated as a result of venting; moist air enters and condenses within the tanks, the water settling to the bottom where it is drained away through fitted drain cocks. Laboratory interaction tests between free water and safety fuel showed that a stable gelatinous emulsion can be formed; this could clog the drains and/or filters. There is evidence to suggest, however, that safety fuel retains more dissolved water than does Avtur and the extent to which this will be effective in practice is being investigated by means of a flight simulation environmental rig, but results have not yet reached a conclusive stage. The problem of restricting the entry of moisture to the tanks by way of the vents would be formidable and one that might only be alleviated by using a gas purging system.

7. CONCLUSIONS

The investigations have indicated that some modifications to current fuel systems may be required before they can be operated on anti-misting safety fuel. It will also be necessary to ensure that the fuel is not progressively degraded by being passed around the system during flight to the point at which it has lost its fire resistant characteristics. It is possible that the application of AMK safety fuels will await a new generation of aircraft which have been designed for their use.

8. ACKNOWLEDGMENT

Mention is hereby made of the fact that some of the experimental data were obtained by Shell Research Limited (Thornton Research Centre) under government contract No. K/A41a/113/CB/A41a.

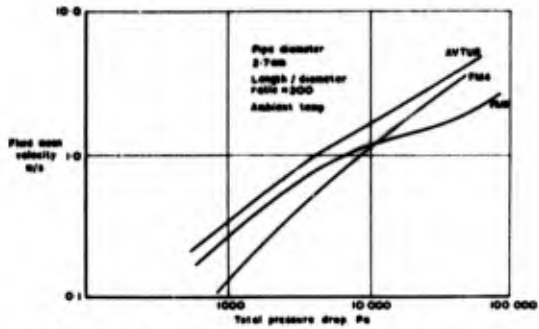


Fig 1 Comparison of pipe flow characteristics between safety fuel and AVTUR

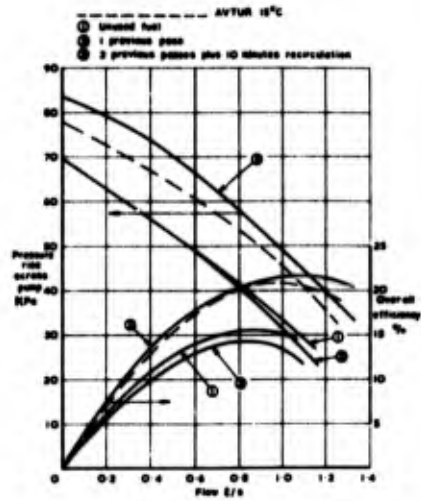


Fig 2 Effect of fuel degradation on pump characteristics with FM9

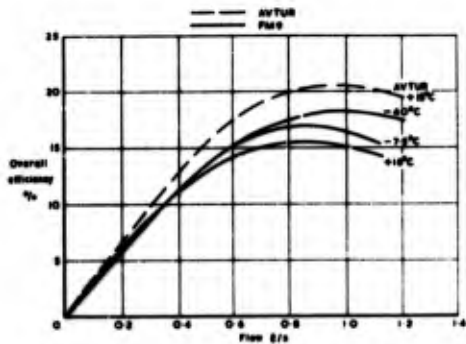


Fig 3 Variation of overall efficiency with flow for FM9

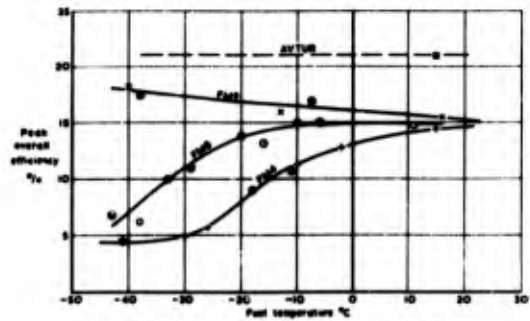


Fig 4 Variation of pump peak efficiency with fuel temperature

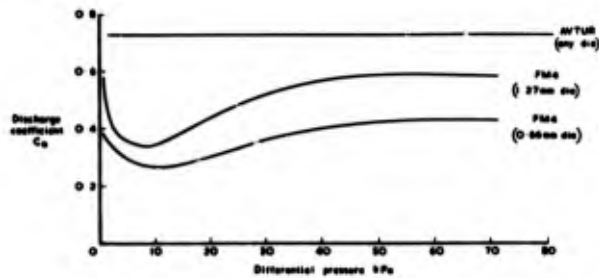


Fig 5 Variation of discharge coefficient - FM4

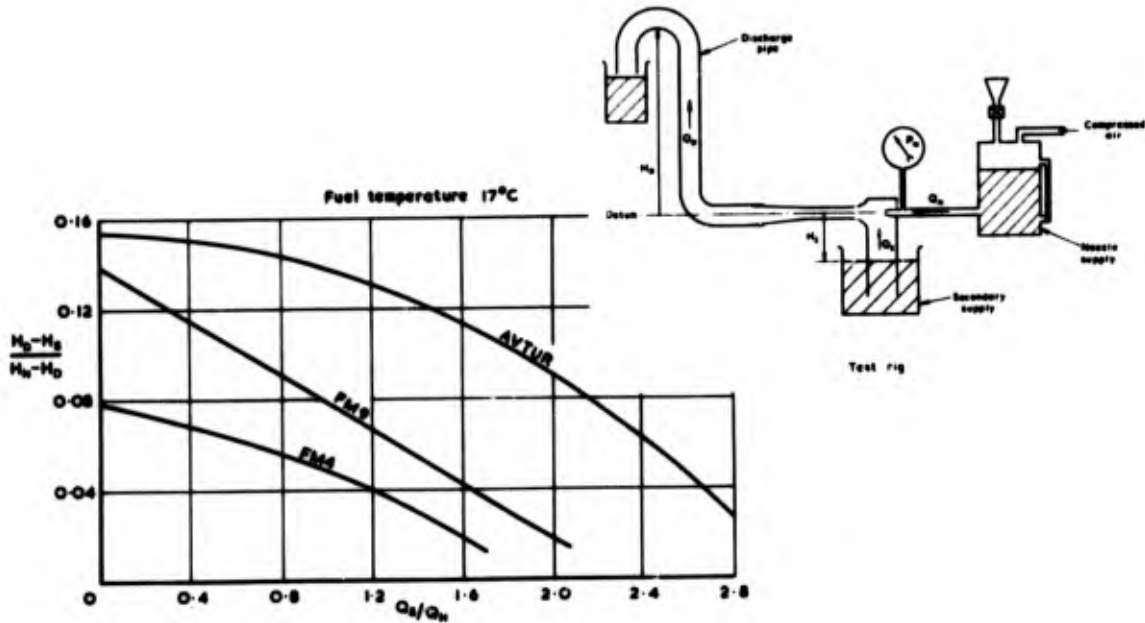


Fig. 6 Variation of pressure ratio with flow ratio

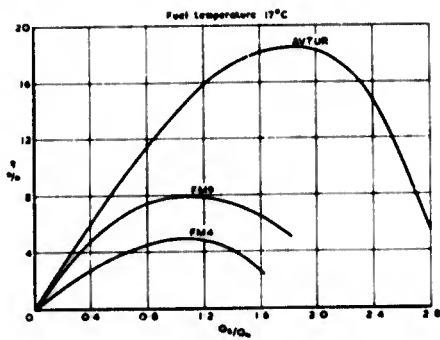


Fig. 7 Variation of efficiency with flow ratio

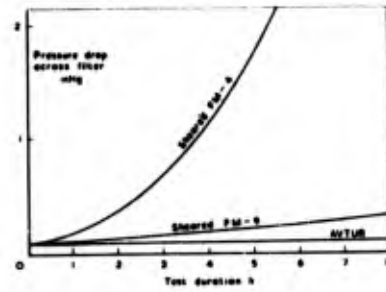


Fig. 8 Filter blocking tendency of AVTUR, FM-4 and FM-9 after 4 shearings

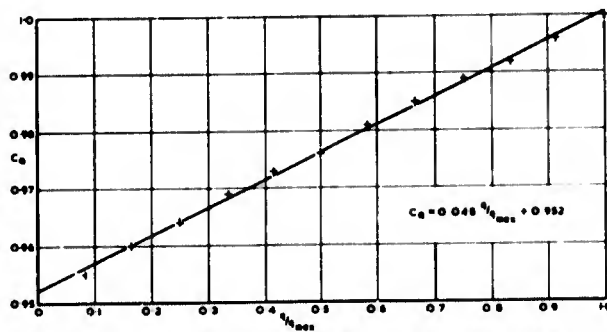


Fig. 9 Plot of pump flow-rate correction coefficient (C_0) against ratio of actual pump flow-rate to max pump flow-rate $\frac{Q_{actual}}{Q_{max}}$

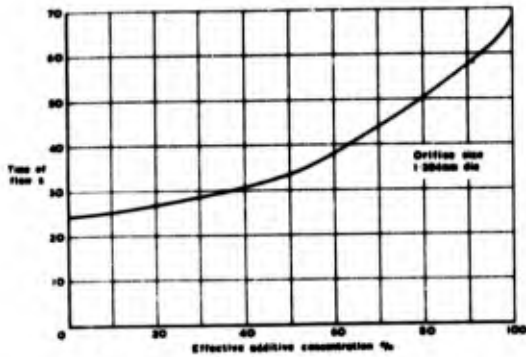
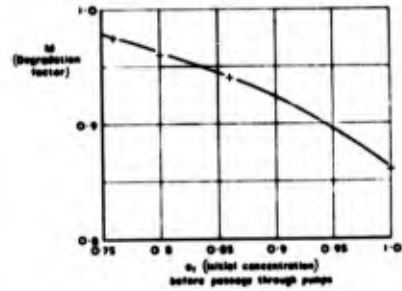


Fig 10 Effective concentration-orifice flow-rate characteristic



Example :-
For the booster pump
 $C_d = M \cdot C_0 = h$

Fig 11 Graph of degradation factor (M) against initial concentration of effective additive (h) before passage through pump

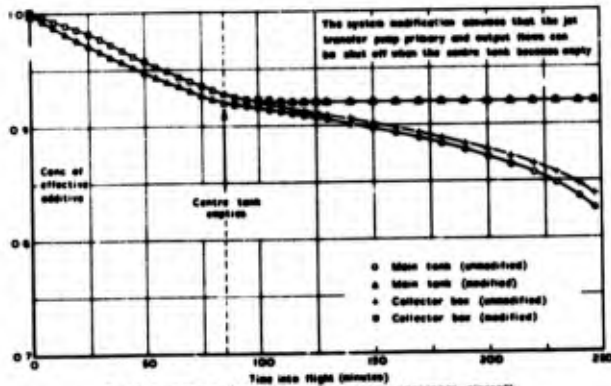


Fig 12 Degradation/time for medium range passenger aircraft (full range flight modified and unmodified)

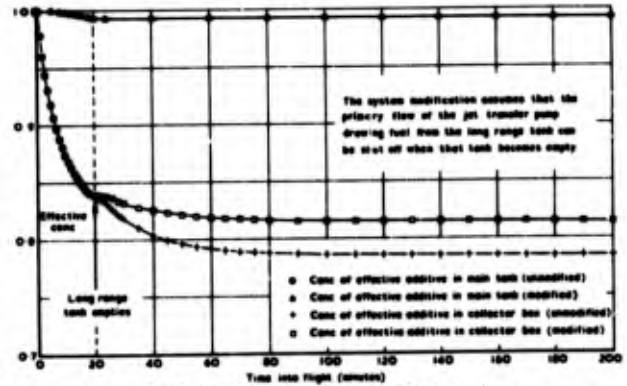


Fig 13 Degradation/time curve for Executive jet (modified system & unmodified system)

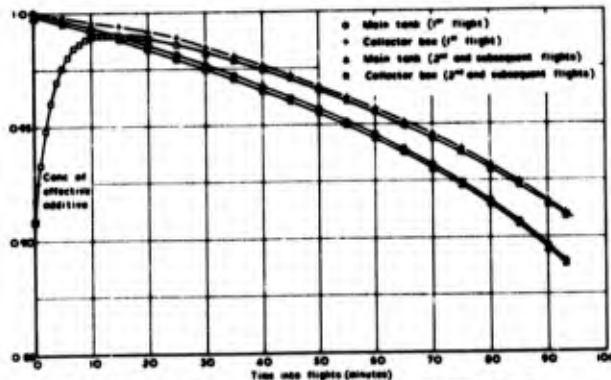
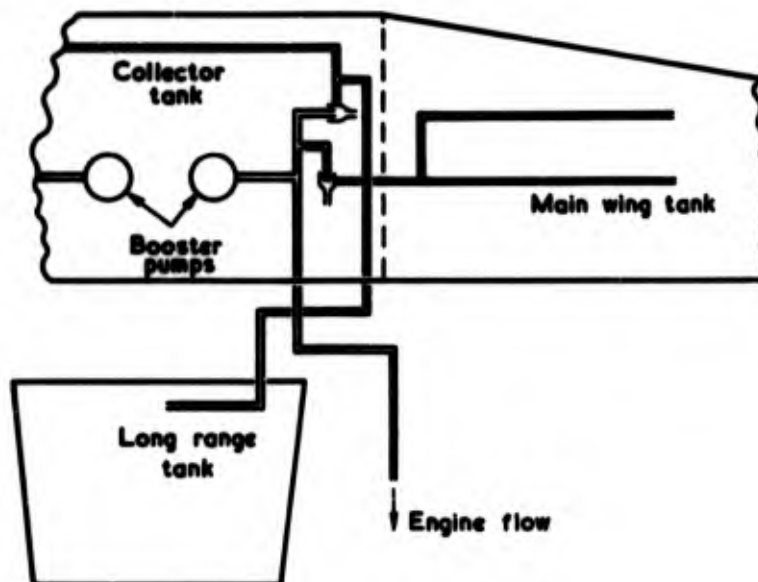


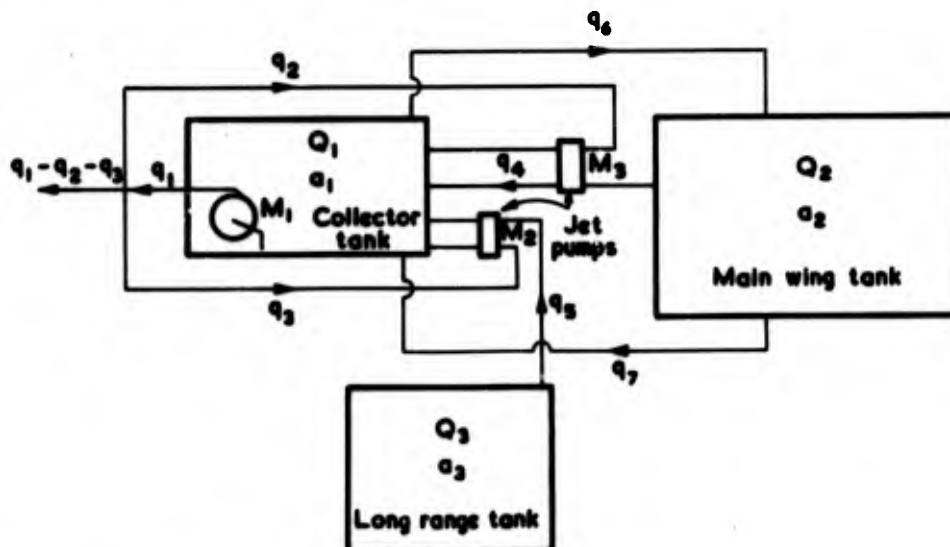
Fig 14 Degradation/time curve for medium range passenger aircraft (series of short range flights tanks filled to 50% max capacity) (unmodified)

Appendix I

Low pressure system layout



Mathematical model



General equations of fuel transfer

Collector tank :-

$$Q_1 \frac{da_1}{dt} = a_1 (M_1 M_2 q_3 + M_1 M_2 q_2 - q_1 - q_6) + a_2 (q_7 + M_3 q_4) + M_3 q_5 a_3$$

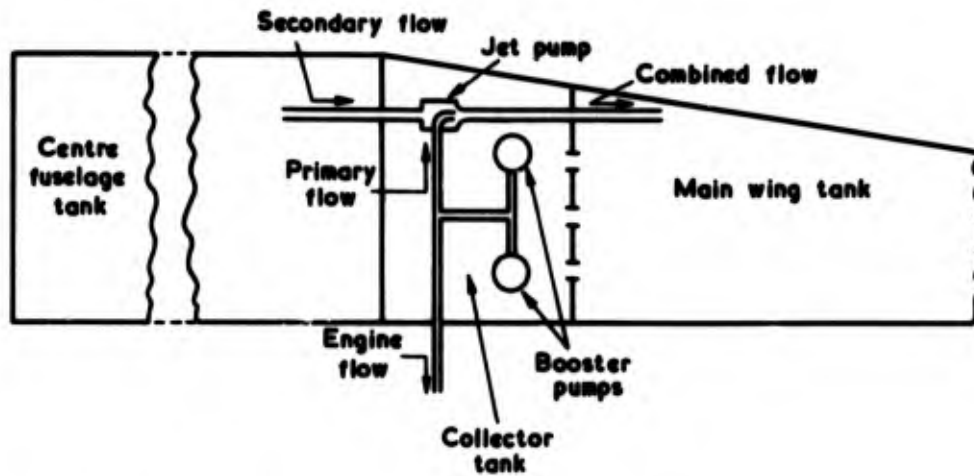
Main tank :-

$$\left[Q_2 + \int_0^t (q_6 - q_4 - q_7) dt \right] \frac{da_2}{dt} = q_6 (a_1 - a_2)$$

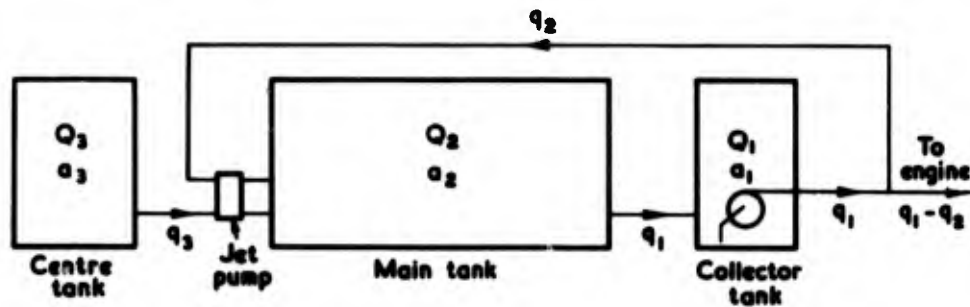
Executive jet

Appendix 2

Low pressure system layout



Mathematical model



General equations of fuel transfer

Collector tank :-

$$Q_1 \frac{da_1}{dt} = q_1 a_2 - q_1 a_1$$

Main tank :-

$$\left[Q_2 - \int_0^t (q_1 - q_2 - q_3) dt \right] \frac{da_2}{dt} = M_1 M_2 q_2 \left(a_1 - \frac{da_1}{dt} T \right) + M_3 q_3 a_0 - (q_2 + q_3) a_2$$

Medium range civil airliner

DISCUSSION – PAPER 4

Mr Jackson: If treated fuel is degraded when circulated through jet pumps, then would the author agree that a similar set of circumstances could exist on aircraft where the fuel proportioning from each tank is controlled by allowing the booster pump to spill back some fuel into the tank and recirculate it.

If this is the case, then an external proportioner would have to be fitted in the fuel delivery pipes, with the penalty of weight, cost, and reliability.

Mr Walsh, Mr Timby and Mr Robinson: We are familiar with the fuel proportioning sequence valve method of controlling fuel flow as mentioned by Mr. Jackson which involves spill off fuel flow through pressure controlled valves. Such a system would be returning fuel to the tank after it had been sheared in both the booster pump and the controlling valve and for this reason would be little different from the situation to be faced with jet transfer pumps, the fuel returned to the tank being partially degraded. It is true that in order to overcome this problem of fuel degradation in the tank then an external proportioner, as suggested by Mr. Jackson, would need to be fitted.

Mr St. John: The adverse effects of the FM9 additive on the fuel system components are much less than those imposed by FM4. A whole series has been investigated, with increasing success, over quite a short period. What are the prospects of even greater success, in a fairly short time, so that the effects become almost negligible? Would it be better to wait before initiating research and development with the necessary modifications to the aircraft fuel systems, which could be nugatory if even further improved additives are developed.

Mr Walsh, Mr Timby and Mr Robinson: This would be the ideal solution to such a situation. In point of fact, reality compels one to evaluate the fuel modifications at each stage of development since it is only from such evaluations that further changes can be made, in the light of any shortcomings found, which will enable one to advance further. I know of no further fuel modifications that are intended beyond that of the current FM9 so it is reasonable, in accordance with your statement, to evaluate this particular type thoroughly at this time as is being done.

Mr Andrews: The effect of antimist additives on in tank boost pump efficiency and head characteristics has been discussed; can the authors comment on any effect of the additives on ability of these pumps to operate under conditions of air and fuel vapour release at the pump inlet?

Mr Walsh, Mr Timby and Mr Robinson: The possibility of effects arising from the use of anti-mist fuel in such circumstances has been considered but to date there has been no effort directed to such an investigation.

Mr Vincent: The early part of the presentation showed that for safety fuels there were problems with:

- (i) orifice discharge coefficients
- (ii) pipe pressure losses
- (iii) pump efficiency decreasing with increased temperature and the plot showed 20°C maximum.

For a military application with higher in flight temperatures, e.g. 80°C, are the system changes not going to be of such a magnitude that safety fuels are not a viable proposition?

Mr Walsh, Mr Timby and Mr Robinson: Pump performance with safety fuel at temperatures higher than +20°C is still an unknown; effort in UK has been devoted to civil aircraft aspects where temperatures would not be expected to reach those encountered with military aircraft. It is true that, on the evidence given, pump performance with FM9 is decreasing with increase in temperature, all the fuel types tending to merge towards a common value. Further effort will be needed to establish the performance beyond the temperature range given whilst a programme of fundamental research into pump design may be needed to try to retrieve some of the lost performance.

Mr Livermore:

(1) The fuel temperature range for civil aircraft should be up to at least +50°C. Solar heating on the ground can give tank temperatures of +70°C.

(2) We rely in the ultimate condition on gravity feed – will safety fuel lead to features such as cavitation of the engine pumps?

Mr Walsh, Mr Timby and Mr Robinson: As regards the first statement, the same comments will apply as those given to Mr. Vincent although the temperatures are higher than we had envisaged. On the question of loss of booster pump action and the reversion to gravity feed this is a further aspect of system operational characteristics which, although not overlooked, needs to be investigated.

INERTAGE DES RESERVOIRS DE CARBURANT

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RESUME

L'intention de cet exposé est de passer en revue l'essentiel des causes d'incendie en relation avec l'inflammabilité du carburant, d'énumérer les principales précautions prises en considération de nos jours pour réduire le risque et de situer la position du constructeur d'avion devant l'attrait de l'inertage des réservoirs, en face de la compétitivité de plus en plus sévère dans le cadre du transport aérien.

1ère PARTIE

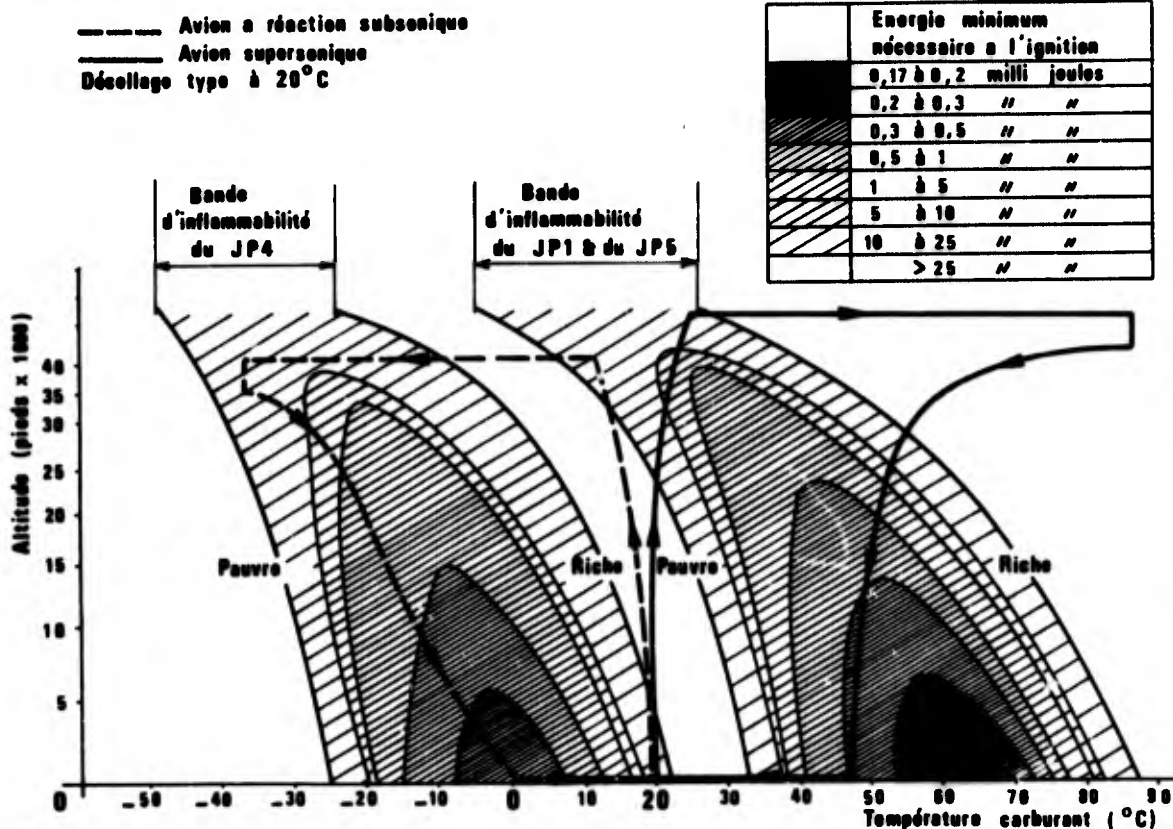
SECURITE DES AVIONS VIS-A-VIS DES RISQUES D'INCENDIE
LIES AUX CARBURANTS UTILISES ACTUELLEMENT POUR LA
TURBO-PROPULSION ET LA TURBO-REACTION (JP1-JP4-JP5)

1 - INFLAMMABILITE DES MELANGES GAZEUX A L'INTERIEUR DES RESERVOIRS

Dans les réservoirs, l'espace libre au-dessus du carburant est occupé par un mélange d'air et de vapeur de carburant.

Au cours des différentes phases d'un vol, ce mélange gazeux présente des risques d'inflammabilité s'il est rencontré des sources d'ignition et si certaines conditions de pression et de température sont en même temps réunies. Ce risque est également lié au niveau d'énergie de la source d'ignition.

Le diagramme ci-dessous a été établi par la BRITISH AIRCRAFT CORPORATION ET LA SOCIETE NATIONALE INDUSTRIELLE AEROSPATIALE dans le cadre des études de sécurité de l'avion CONCORDE.



Ce diagramme montre l'évolution des conditions d'inflammabilité au cours du vol type d'un avion à réaction subsonique et d'un avion supersonique Mach 2.

Le risque est faible sur les avions subsoniques utilisant du JP1 ; le risque est légèrement plus grand sur les avions subsoniques utilisant du JP4 et sur les avions supersoniques utilisant du JP1 bien que ces derniers passent moins de temps dans la zone dangereuse.

Ces causes d'ignition sont essentiellement liées au point éclair du carburant considéré, il existe une autre cause d'inflammation liée à la température d'auto-inflammation qui se situe au-dessus de 230°C.

2 - CAUSE D'INFLAMMATION DES MELANGES GAZEUX

Dans le cadre des risques d'inflammation liés au point éclair, il faut distinguer les sources d'ignition de cause interne et de cause externe aux réservoirs.

Sources d'ignition de cause interne

L'électricité statique :

Pendant le remplissage des réservoirs, en raison de sa faible conductibilité électrique et des vitesses d'écoulement élevées (en particulier dans les filtres à eau des installations d'aéroport) le carburant se charge d'électricité statique.

Les sources mécaniques :

Tous les organes en mouvement peuvent être générateurs d'étincelle ou d'échauffement soit en mettant en contact des éléments de potentiel électrique différent soit par friction sur des surfaces adjacentes.

Les sources électriques :

Courts-circuits entre les câbles électriques et les structures adjacentes à l'intérieur des réservoirs.

Sources d'ignition de cause externe

Les feux moteur :

Communication de l'incendie à l'intérieur des réservoirs à la suite d'un feu non contenu.

L'éclatement des rotors d'un moteur :

Perforation des parois des réservoirs et inflammation du carburant en raison de la température élevée des éclats en provenance des rotors des moteurs.

Les feux extérieurs :

Communication de l'incendie à l'intérieur des réservoirs par introduction de flammes à travers les voies de mise à l'air libre.

La foudre :

Les statistiques montrent que la majorité des coups de foudre surviennent entre 5000 et 12000 pieds et qu'ils sont très peu fréquents au-dessus de 20000 pieds.

Les décharges électriques dues à la foudre peuvent provoquer une ignition dans la mesure où ces décharges se situent dans les zones occupées par des mélanges gazeux explosifs.

Le crash :

La génération importante d'étincelles, associée à des distorsions de la structure des réservoirs entraînant des écoulements de carburant, constitue un risque important de déclenchements d'incendie.

3 - PRECAUTIONS POUR REDUIRE OU ELIMINER LES RISQUES D'INFLAMMATION

Remplissage des réservoirs

- Dimensionnement des circuits de manière à obtenir de faibles vitesses d'écoulement pour réduire le niveau de charge d'électricité statique.
- Circuits entièrement métalliques et parfaitement mis à la masse.
- A l'intérieur des réservoirs, élimination des pointes de manière à éviter les amorçages d'arcs électriques.
- Calibration du circuit assurant un remplissage uniforme de tous les réservoirs.
- Intercommunication appropriées pour que le remplissage soit uniforme à l'intérieur d'un réservoir constitué de plusieurs compartiments.
- Points d'écoulement du carburant dans les réservoirs situés aux points bas et réalisés de manière à éliminer les projections et les formations de mousse ou de brouillard.

Circuits électriques rattachés aux réservoirs

Les circuits électriques de forte puissance (alimentation des pompes) doivent cheminer à l'extérieur des réservoirs ou s'ils cheminent à l'intérieur être installés à l'intérieur de gaines métalliques anti-déflagrantes et parfaitement mises à la masse.

Les circuits électriques de faible puissance (moins de 200 milliampères) doivent comporter des protections de telle manière que dans les cas de panne les plus sévères ils ne puissent constituer une source d'ignition dont l'énergie dépasserait 0,15 millijoules.

Accessoires - Equipements

Tous les organes électriques tels que moteur, solénoïdes, doivent être à l'intérieur d'une enceinte anti-déflagrante et dans la majeure partie des cas, comporter des dispositifs de coupure automatique de l'alimentation électrique (fusibles).

Les éléments mobiles à l'intérieur des réservoirs doivent être parfaitement mis à la masse, en particulier les points servant de butée (possibilité d'étincelles par différence de potentiel électrique).

Réalisation des réservoirs

Les zones de réservoirs pouvant être exposées aux coups de foudre doivent être d'une épaisseur suffisante pour éviter la pénétration de l'arc électrique.

La continuité électrique des panneaux fixes et mobiles doit être capable d'assurer l'écoulement des charges électriques dues à la foudre.

Les points de communication des réservoirs avec l'extérieur (mises à l'air libre) doivent être situés dans des zones non exposées à la foudre ou à des feux extérieurs (feux moteur, incendies au niveau du sol).

Disposition des machines tournantes (moteurs-APU - compresseurs, etc...)

Les dispositions doivent être telles que les projectiles, en provenance des rotors qui pourraient éclater, ne rencontrent pas de réservoir ou de circuit de carburant.

Dans les cas où de telles dispositions ne pourraient pas être réalisées, des blindages sont nécessaires pour contenir les éclats.

4 - MOYENS COMPLEMENTAIRES DE PROTECTION

Dans les cas où les précautions décrites au paragraphe précédent ne seraient pas ou ne pourraient pas être réalisées ou encore pour des objectifs de sécurité spéciaux (par exemple : combats aériens), les protections suivantes peuvent être envisagées.

Additifs anti-statiques

D'un faible dosage : 0,75 part par million, ces produits ne présentent pas d'inconvénients significatifs vis-à-vis des caractéristiques générales des carburants et fournissent une amélioration notable dans la réduction du niveau de charge d'électricité statique.

Ils représentent un accroissement de dépense insignifiant : à titre d'exemple, un jumbo "JET" a besoin de moins d'un dixième de litre d'additif pour chacun de ses ravitaillements.

Dans la mesure où son emploi n'est pas généralisé, son utilisation nécessite la disponibilité d'un doseur ou de citernes spécialement affectées à cet usage, ce qui ne va pas sans poser des problèmes d'ordre pratique sur un grand nombre d'aéroports.

Arrêteur de flamme

Cartouche perméable dans les deux sens, aussi bien à l'air qu'au carburant, mais s'opposant à la rentrée de flammes dans le réservoir.

Ces cartouches sont installées, sans grande difficulté, dans les orifices de mise à l'air libre.

Efficacité vis-à-vis des sources d'ignition de causes externes et en particulier la foudre.

Leur efficacité est permanente pendant toute la durée du vol et au sol.

En raison du risque de colmatage par givrage ou par détérioration mécanique, il est nécessaire d'installer un dispositif de "BY-PASS".

Pénalité de masse : faible.

Pénalité de coût : faible.

Suppresseur de flamme

Dispositif assurant la détection et l'extinction d'un front de flamme dans les orifices de mise à l'air libre des réservoirs.

Efficacité vis-à-vis des sources d'ignition de causes externes et en particulier la foudre.

La durée d'efficacité est limitée en raison de la dilution rapide de l'agent extincteur.

Sauf si on a monté plusieurs cartouches d'agent extincteur, le dispositif ne sert qu'une fois au cours d'un vol et exige une opération de maintenance au sol (remplacement des cartouches usagées).

L'ensemble peut faire l'objet de fonctionnement intempestif et est difficile à tester avant chaque vol.

Pénalité de masse : faible.

Pénalité de coût : modérée.

Mousses anti-déflagrantes

Mousses réticulaires remplissant la totalité du volume de tous les réservoirs ou seulement du réservoir de mise à l'air libre ; ces mousses retardent considérablement ou empêchent la propagation d'une explosion.

Des éléments semi-cubiques sont introduits suivant un ordre chronologique, dans le réservoir à traiter.

Efficacité permanente vis-à-vis des sources d'ignition de causes externes et de causes internes.

Généralement, à base de polyuréthane, des mousses peuvent présenter un certain degré d'altération dans le temps (absorption d'eau).

Poids : 30 kg au mètre cube.

Volume réel : 3 % du volume brut.

Rétention : environ 1,5 % du volume brut.

Pénalité de masse : faible.

Pénalité de coût : modérée.

Inertage des réservoirs

Installation destinée à rendre inerte, dans les réservoirs, l'espace libre au-dessus du carburant.

Efficacité vis-à-vis des sources d'ignition de causes externes et de causes internes pendant toutes les phases normales d'un vol et au sol, pour une durée déterminée.

Ce système est traité dans la deuxième partie.

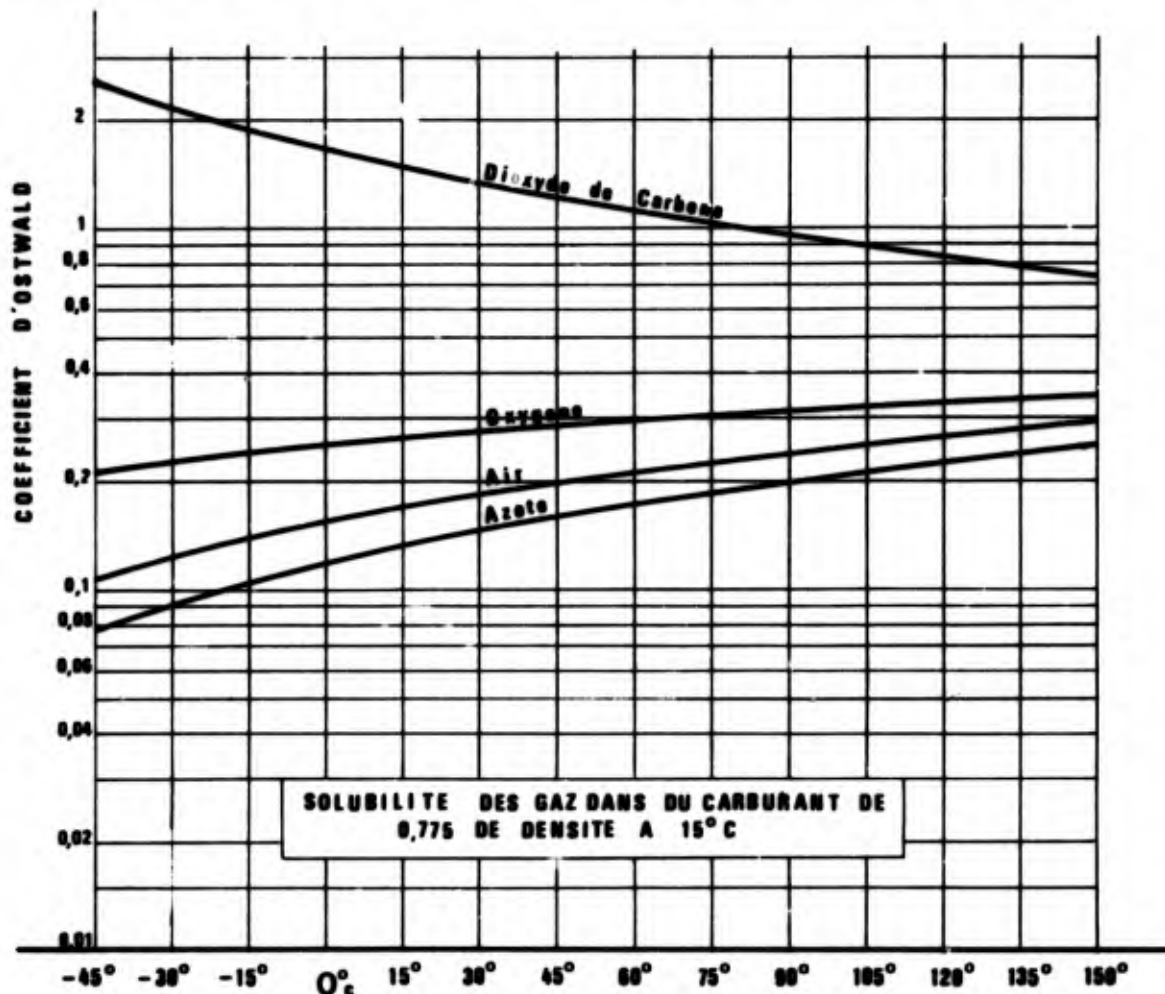
2e PARTIE
INERTAGE DES RESERVOIRS DE CARBURANT

1 - OBJECTIF

Dans les réservoirs, réduction du taux d'oxygène des mélanges gazeux occupant l'espace libre au-dessus du carburant pour que les critères de pression - températures, rencontrés au cours des vols, se situent en dehors des limites d'inflammabilité.
Il est considéré que si le taux d'oxygène est inférieur à 9 ou 10 %, les mélanges gazeux ne sont pas explosifs.

2 - ORIGINE DE L'OXYGENATION DES MELANGES GAZEUX RENCONTRES DANS LES RESERVOIRS

Les réservoirs classiques ne sont pas remplis complètement. Ils sont munis de circuits de mise à l'air libre permettant à l'air de rentrer ou de sortir de manière à maintenir à l'intérieur des réservoirs une pression sensiblement égale à la pression extérieure. Il y a donc de l'air qui rentre en fonction de l'épuisement du réservoir et de l'augmentation de la pression extérieure au cours de la descente ; cet air en provenance de l'extérieur n'est pas la seule source d'oxygénation des mélanges gazeux.
Au niveau du sol, tous les carburants, en contact avec l'atmosphère, peuvent contenir de l'air en dissolution. Cette quantité d'air varie en fonction de types de carburant et de la température. Si le carburant est saturé, il peut contenir 15 à 20 % de son volume d'air à la pression atmosphérique.



Au cours de la montée, et plus ou moins progressivement en fonction du degré d'agitation, l'air dissous se dégage au fur et à mesure que la pression diminue, en outre, cet air est relativement riche en oxygène (24 %) en raison de la bonne solubilité de l'oxygène dans les carburants.

3 - TRAITEMENT POUR RENDRE INERTE L'ESPACE OCCUPE PAR LES MELANGES GAZEUX DANS LES RESERVOIRS

Pour éviter un apport d'oxygène en provenance de l'extérieur, les réservoirs ne doivent pas être en communication avec l'extérieur dans toutes les phases de vol ou de l'air extérieur serait amené à rentrer.

Dans ces conditions, pour assurer à l'intérieur des réservoirs un niveau de pression acceptable et légèrement supérieur à la pression extérieure de manière à empêcher l'air extérieur de rentrer, il faut que :

- lorsque la pression augmente, un système de soupapes de décompression ramène la pression à un niveau normal,
- lorsque la pression diminue, un dispositif assure la pressurisation des réservoirs avec un gaz neutre.

Dans ce domaine, les travaux les plus connus ont été effectués par les firmes suivantes :

- GARRETT et HAMILTON-STANDARD pour un inertage avec de l'air appauvri en oxygène, obtenu par réaction catalytique avec du fuel (remplacement d'une partie de l'oxygène par du dioxyde de carbone),
- INTERTECHNIQUE pour un inertage avec de l'air appauvri en oxygène, obtenu par séparation,
- PARKER HANNIFIN pour un inertage avec de l'azote stocké à l'état liquide.

Les divers systèmes se différencient par le type de gaz utilisé et le mode de production de ce dernier. GARRETT, HAMILTON et INTERTECHNIQUE produisent le gaz à la demande.

Dans le système PARKER HANNIFIN, la quantité d'azote nécessaire est stockée à bord à l'état liquide pour être ensuite délivrée à la demande.

Dans le cas du gaz neutre produit à la demande, les caractéristiques du système sont définies par des critères avion connus :

- consommation moteur,
- vitesse de montée,
- vitesse de descente.

On peut noter, pour situer l'ordre de grandeur des choses, que la quantité de gaz neutre nécessaire est environ 4 fois plus grande pour la descente que pour la phase de vol du décollage à la fin de la croisière.

Dans le cas du gaz neutre stocké à bord, il y a un critère avion connu supplémentaire qui est le volume des réservoirs et un paramètre aléatoire qui est le profil réel du vol.

En effet, s'il est possible de déterminer la quantité de gaz neutre nécessaire pour un profil de vol parfait (une montée, une croisière, une descente et un atterrissage) il n'en est pas de même pour tenir compte des changements de niveau de vol (descentes successives, déroutement, attente, atterrissages successifs). Si la quantité de gaz neutre embarquée est déterminée pour un profil de vol parfait, il s'ensuit une pénalité vis-à-vis de la liberté opérationnelle de l'avion. Si, au contraire, cette quantité est déterminée pour tenir compte d'un vol comprenant plus d'une montée et d'une descente, on pénalise l'avion dans tous les cas d'un profil de vol parfait.

Pour éviter un apport d'oxygène en provenance du carburant, ce dernier doit être traité avant le vol pour que l'air en dissolution ait une basse teneur en oxygène (moins de 10 %). C'est la désoxygénation du carburant.

Il est possible d'envisager que le carburant soit désoxygéné au moment du stockage dans les citernes des aéroports.

Il est également possible de procéder à la désoxygénation du carburant au moment du ravitaillement des avions en utilisant un matériel de servitude au sol s'interposant entre le matériel de ravitaillement classique et l'avion ravitaillé.

Enfin, le carburant pourrait être désoxygéné à bord au moment où il entre dans les réservoirs au moyen d'une installation embarquée appropriée.

Il faut également noter qu'il ne serait pas nécessaire de désoxygéner le carburant à condition que pendant la montée, le système de fourniture du gaz neutre soit en mesure d'assurer un balayage important de l'espace libre des réservoirs de manière à obtenir un mélange dilué avec moins de 10 % d'oxygène.

4 - DEFINITION ET CONSTRUCTION DES AVIONS EN RELATION AVEC L'INERTAGE

Dans la plupart des avions conventionnels, les réservoirs sont mis en communication directement avec l'extérieur par le circuit de mise à l'air libre qui sert également de circuit de trop plein.

Cette disposition d'une simplicité élémentaire offre une grande fiabilité du fait même qu'elle ne fait intervenir aucun équipement.

L'introduction de soupapes de décompression exige soit que ces soupapes soient dimensionnées pour évacuer le débit de trop plein, ce qui en augmente considérablement les dimensions et le poids, soit l'adjonction de vannes de trop plein équipées d'un asservissement à la configuration de remplissage.

L'introduction d'un système de pressurisation doit s'accompagner de l'adjonction de clapets de dépression pour faire face à la défaillance de l'arrivée du gaz neutre, conditions dans lesquelles la fonction d'inertage est perdue.

Si l'avion doit être équipé d'un système à air appauvri par combustion catalytique, il est probable que le générateur devra être installé dans une zone déclarée "zone de feu" comportant en particulier un système de détection et d'extinction d'incendie. Le générateur doit en outre être facilement accessible en raison de l'altération rapide de ses performances.

L'ensemble des mesures de sécurité, dans le cadre de la règle de l'art et de la réglementation, n'apparaissent pas clairement encore à ce jour.

Si l'avion doit être équipé d'un système à air appauvri par séparation, il semble qu'il ne se pose pas de problème de sécurité majeur, le volume des unités de production de gaz représente une difficulté d'installation importante.

Si l'avion doit être équipé d'un système à l'azote liquide, les problèmes rencontrés sont essentiellement liés au stockage et à la distribution d'un liquide (ou vapeur) à très basse température ; il faut citer :

- le givrage important de toutes les surfaces, de circuits et d'accessoires, en contact avec l'air ambiant ;
- la liquéfaction de l'oxygène de l'air ambiant avec risque d'explosion après évaporation dans les milieux gras (voisinage avec circuits hydrauliques).

La réduction de la longueur des circuits par rapport à la structure avion : contraction des circuits de plus de 3 millimètres par mètre pour un avion subsonique et de plus de 4 millimètres par mètre pour un avion supersonique.

Sur les avions qui ne demandent qu'un petit débit d'azote, c'est-à-dire lorsque les tuyauteries de distribution sont d'un petit diamètre, il est facile de réaliser des "Lyres de dilatation" ; si par contre, les tuyauteries sont d'un plus grand diamètre ($\phi > 20$ millimètres), il est très difficile de réaliser de bons joints coulissants ou des soufflets de haute fiabilité.

Des précautions doivent être prises pour que des circuits tels que les circuits hydrauliques ne puissent pas être bloqués par gel dans le cas de projections dues à un éclatement d'un circuit de distribution d'azote.

Dans le cas d'un avion subsonique long courrier, en fin de vol, la température du carburant est souvent au voisinage du point de congélation et l'apport des frigories fournies par l'azote n'améliore pas la situation.

Il est nécessaire de prévoir en outre une prise de parc pour le remplissage du réservoir d'azote liquide.

Si l'avion doit être équipé d'un système permettant de désoxygéner le carburant à bord pendant le remplissage, les précautions du paragraphe 3 ne doivent pas pour autant être négligées pour conserver la disponibilité de l'avion dans le cas d'une défaillance dans la désoxygénation du carburant.

Le système d'inertage ne doit demander aucune intervention de l'équipage si ce n'est la mise en route au début et l'arrêt à la fin du vol. Toutefois, des dispositifs de surveillances doivent permettre de détecter un mal fonctionnement et être raccordés au "MASTER-WARNING".

Alors que la pénalité de masse pour réaliser les précautions du paragraphe 3 s'élève de 10 à 30 kg, l'installation d'un système d'inertage introduit une pénalité de 150 à 300 kg suivant qu'il s'agit d'un avion court ou long courrier, encore que cette valeur doit être augmentée respectivement de 40 ou 80 kg si l'on envisage la désoxygénation du carburant à bord. Cette pénalité de masse est d'autant plus sévère que l'avion a une faible charge marchande comme c'est le cas des avions de transport supersonique actuels. Cette masse représente près de la moitié du circuit de carburant lui-même (tuyauteries, pompes, robinets, etc...).

Le coût du système d'inertage installé à bord représente un montant sensiblement égal au coût du circuit de carburant lui-même (tuyauterie, pompes, robinets, etc...) alors que les précautions du paragraphe 3 n'en représentent qu'environ 1 %.

5 - EXPLOITATION DES AVIONS EN RELATION AVEC L'INERTAGE

Avec le niveau de fiabilité élevé des équipements actuels et en particulier depuis l'introduction sur les avions d'une génération électrique alternative à fréquence régulée, les opérations de maintenance sur les circuits de carburant sont extrêmement réduites sinon nulles.

Suivant le principe d'inertage considéré, et en ce qui concerne l'avion, les opérations de maintenance doivent principalement porter sur la régénération des réacteurs catalytique (toutes les 500 h environ) ou sur l'entretien des groupes de production d'air appauvri par séparation dont la durée de vie est encore mal connue ou encore sur le ravitaillement en azote dans le cas de stockage à bord.

En ce qui concerne les installations aéroportuaires, la désoxygénation du carburant au sol ne devrait pas poser de problème pratique majeur mais représente un investissement non négligeable.

Vis-à-vis du D.O.C., la pénalité de masse d'un tel système peut représenter jusqu'à 2 ou 3 % de la masse des passagers.

6 - CONCLUSION

Il apparaît que pour un gain potentiel en sécurité, l'inertage introduit quotidiennement un ensemble de risques additionnels :

- surpressurisation des réservoirs (conséquences structurales),
- refroidissement excessif du carburant pour les systèmes utilisant l'azote liquide,
- risque de formation de résidus azotés,
- explosion du réservoir de stockage de l'azote liquide ou de tuyauteries de distribution avec des conséquences graves sur les systèmes et la structure (refroidissements brusques, projection de débris, etc...),
- en raison de la pressurisation des réservoirs, augmentation sensible du débit de fuites dans le cas de perforations en particulier dans un crash,
- effets possibles à longue échéance sur l'endurance des réacteurs, la tenue en fatigue des éléments de structures soumis à de brusques écarts de température (système à azote liquide, etc...) et ceci en raison de l'absence d'expérience pratique au niveau de l'aviation civile.

Le rapport d'étude d'octobre 1969, réalisé par l'A.I.A., montre que sur les 6 accidents types examinés, l'inertage n'aurait eu qu'un degré d'efficacité modeste et non exclusif, les précautions et les autres moyens de protection cités plus haut présentant un degré d'efficacité équivalent sinon supérieur.

Dans le cadre de l'aviation civile, on est donc amené à conclure, et ceci à regret, que dans l'état actuel des choses le coût d'un système d'inertage est hors de proportion avec le potentiel net du gain en sécurité apporté. Néanmoins, il est raisonnable de penser que le niveau actuel de développement de l'inertage n'est pas limitatif et que les aménagements et les compromis, qui nécessairement se cristalliseront dans un proche avenir, seront en mesure de modeler un concept industriellement applicable.

INERTAGE DES RESERVOIRS DE CARBURANT AVEC DE L'AIR APPAUVRI EN OXYGENE PAR PERMEATION

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Pour diminuer le danger d'incendie ou d'explosion des réservoirs de carburant d'avions, on a expérimenté l'utilisation d'azote emporté sous forme liquide pour en réaliser la pressurisation et l'inertage.

Intertechnique a développé avec Rhône-Poulenc un système capable de réaliser cet inertage avec de l'air appauvri en oxygène à bord de l'avion par filtration sur une paroi semi perméable ; les essais de laboratoire ont démontré la faisabilité du système et permis d'en calculer les performances qui sont très compétitives.

La réalisation de systèmes avionnables opérationnels exigera la mise au point d'équipements annexes correspondant spécifiquement aux conditions d'emploi de chaque avion : échangeurs de chaleur, compresseurs auxiliaires, dégaseurs de carburant ; elle exigera aussi une profonde modification des systèmes de ventilation et de pressurisation des réservoirs.

Les études en cours aboutissent ainsi au développement de systèmes très différenciés allant des plus simples pour les avions civils légers et les hélicoptères aux plus sophistiqués pour les avions supersoniques civils ou militaires ; tous ces systèmes sont autonomes ; leur masse est généralement compétitive par rapport à la masse des réservoirs d'azote liquide qu'ils remplacent ; ils apportent en outre des avantages annexes intéressants par le dégazage du carburant, la meilleure pressurisation des réservoirs, la suppression des mises à l'air libre individuelles de ces réservoirs.

Le danger d'incendie ou d'explosion

Chaque nouvelle année des méthodes de plus en plus complexes et de plus en plus efficaces sont employées pour la protection des avions contre le feu ; cependant en dépit des progrès considérables réalisés, l'incendie et l'explosion des réservoirs continuent à figurer parmi les causes les plus fréquentes d'accidents ou parmi les principaux motifs d'aggravation d'accidents ayant des causes primaires différentes.

Pourquoi ? Parce que, si l'effort des constructeurs améliore les moyens de prévention, de détection et de lutte contre ces accidents, les progrès de l'aéronautique conduisent ces mêmes constructeurs à construire des avions emportant des quantités de plus en plus grandes de carburant et, pour les avions supersoniques, dans des conditions de température de plus en plus critiques ; dans la construction des avions modernes, on a réussi à éliminer la plupart des matériaux inflammables tels que le bois, la toile, les plastiques combustibles, les alliages à base de magnésium, mais personne n'a encore proposé de se passer de carburant.

La pressurisation des réservoirs en gaz inerte

Le danger principal ne vient pas du carburant liquide mais des vapeurs de carburant mêlées à l'air de pressurisation des réservoirs.

Depuis plus de 20 ans, des recherches persévérantes ont été réalisées, notamment en Grande-Bretagne au Royal Aircraft Establishment de Farnborough et aux Etats-Unis, chez divers constructeurs sous l'égide de la FAA, pour utiliser des gaz inertes à la pressurisation des réservoirs ; ces gaz inertes sont généralement constitués par des mélanges d'air et d'azote ou d'air et de gaz carbonique ; des essais extrêmement poussés ont été conduits notamment en Grande-Bretagne au Collège Aéronautique de Cranfield et aux Etats-Unis à l'Université de Berkeley. Ces essais ont permis d'établir que des mélanges d'oxygène et d'azote à 9 % d'oxygène ou des mélanges d'air et de gaz carbonique à 38 % de gaz carbonique et 62 % d'air étaient complètement inertes avec les vapeurs de tous les carburants aéronautiques usuels.

Les ingénieurs britanniques ont proposé de réaliser de tels mélanges en utilisant les gaz de combustion des réacteurs et ont prouvé que c'était possible ; malheureusement, ce procédé oblige à réaliser le refroidissement des gaz de combustion, puis la séparation de la vapeur d'eau qu'ils contiennent, et ces deux opérations exigent des équipements lourds et encombrants ; de plus, le gaz carbonique se dissout en quantité importante dans le carburant et constitue pour ce carburant une pollution chimique difficilement acceptable.

L'emport d'azote liquide a donc été finalement considéré, ces dernières années, comme le procédé le plus commode pour disposer des gaz inertes nécessaires à la pressurisation des réservoirs de carburant ; ce procédé a été développé, en particulier aux Etats-Unis par la société Parker Hanifin, qui a pu, avec l'aide de la FAA, réaliser une importante campagne d'essais en vol sur DC9 et C 130. Peut-être un procédé analogue a-t-il été utilisé pour la pressurisation des réservoirs de carburant de l'appareil de reconnaissance SR 71 en service depuis plusieurs années avec le succès que l'on sait.

En dépit de performances remarquables obtenues, l'emport d'azote liquide ne constitue pas une solution pleinement satisfaisante au problème de l'inertage des réservoirs, d'abord parce que le ravitaillement des réservoirs en azote liquide pose des problèmes logistiques contraignants, ensuite parce que sur les avions destinés à effectuer de nombreuses montées et descentes entre deux ravitaillements (c'est le cas des avions civils destinés aux étapes courtes ; c'est aussi le cas des appareils militaires de combat), il est nécessaire d'emporter une quantité d'azote liquide d'autant plus grande que le nombre des montées et descentes possibles est plus élevé, et ceci conduit rapidement à des installations d'une masse tout à fait prohibitive.

La production de gaz inerte par perméation

Intertechnique a entrepris depuis le début de 1968, d'abord en coopération avec L'Air Liquide, puis avec Rhône-Poulenc, le développement d'un procédé d'inertage des réservoirs de carburant avec de l'air appauvri en oxygène à bord de l'avion par filtration à travers une paroi semi perméable.

La paroi semi perméable qui a été mise au point est une membrane synthétique produite par Rhône-Poulenc sous la dénomination Iris 4101 ; son épaisseur est de 0,2 micron ; elle est fixée sur une feuille poreuse de même composition chimique de 0,2 mm d'épaisseur qui lui sert de support ; cette membrane est, suivant la température, de 2 à 3 fois plus perméable à l'oxygène qu'à l'azote ; à la température de 20° C, cette perméance est, pour l'oxygène, de 500 litres par heure, par m² et par bar d'écart de pression, ce qui est considérable par rapport aux autres membranes semi perméables connues ; sa perméance à la vapeur d'eau 3 fois plus forte ; le principe de fonctionnement du générateur d'air appauvri est donc très simple : de l'air à haute pression circule lentement d'un côté de la membrane et la majeure partie de l'oxygène qu'il contient traverse cette membrane par perméation et est rejeté à l'extérieur.

En raison de sa minceur, cette membrane est fragile ; elle est soumise à des écarts de pression de plusieurs bars ; il faut donc qu'elle soit appuyée sur un support poreux capable de résister aux pressions extrêmes de fonctionnement du système ; pour obtenir le maximum de rendement du générateur d'air appauvri, il est nécessaire de pouvoir utiliser des pressions atteignant 10 à 15 bars.



Toutes les solutions technologiques habituelles pour la construction des filtres utilisés sur avion se sont révélés très mal adaptées à l'utilisation de cette membrane en raison du poids excessif des supports ; Rhône-Poulenc a finalement utilisé une technologie déjà expérimentée dans la filtration de liquides à forte pression, et qui consiste à disposer les membranes de perméation par paires, dos à dos, de part et d'autre d'un matelas poreux capable d'assurer l'évacuation des gaz à faible pression qui ont traversé les membranes ; membranes et matelas sont ainsi en équilibre de pression et les efforts sur les supports sont réduits au minimum ; cette technologie est maintenant bien au point et les disques de perméation ainsi construits supportent sans mal des écarts de pression atteignant 20 bars ; la photographie ci-contre montre un de ces disques élémentaires de perméation constitué de 2 membranes de part et d'autre d'un matelas poreux ; le disque est percé d'un trou permettant le passage de l'air à haute pression d'une face à l'autre ; les gaz à basse pression qui ont traversé la membrane sont évacués par la périphérie du matelas poreux intercalaire.

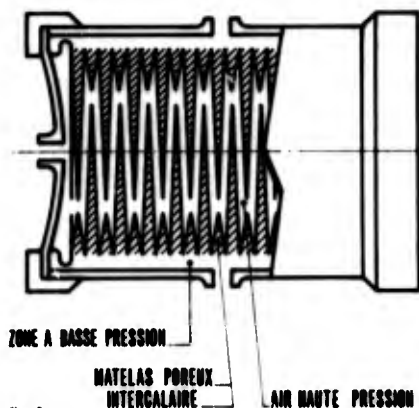
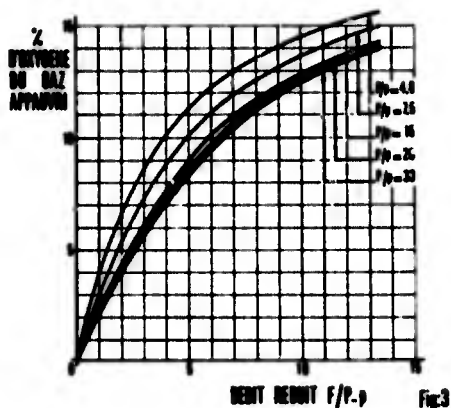


fig. 2

Des cellules de perméation contenant chacune de 2,4 à 4 m² de surface active sont ainsi réalisées par empilage d'une centaine de disques séparés par des joints d'étanchéité ; leur volume est de 6 à 9 litres, leur masse de 2,5 à 4 kg ; il en est donné une coupe schématique sur la figure 2 ci-contre ; on voit que les trous de circulation de l'air à haute pression sont disposés en chicane pour obliger cet air haute pression à circuler sur toute la surface de membrane active ; les gaz basse pression qui ont traversé la membrane (mélange d'oxygène et d'azote très enrichi en oxygène) sont évacués par l'extérieur des matelas poreux intercalaires ; par groupement d'un nombre plus ou moins grand de ces cellules, il est possible de réaliser de manière modulaire le générateur d'air appauvri adapté à chaque avion.

Les performances des générateurs d'air appauvri

Les performances des générateurs d'air appauvri dépendent beaucoup de l'aérodynamique interne des cellules de perméation et du soin apporté à la réalisation des étanchéités ; elles sont toujours un peu inférieures aux performances théoriques calculées à partir des essais de laboratoire mais s'en rapprochent au fur et à mesure des progrès réalisés dans la technologie de leur construction.



Les performances obtenues à ce jour en laboratoire avec une surface de 1 m² de membrane de perméation et à la température de 35° C sont données sur la figure 3 ci-contre. On a porté :

- En abscisse, le débit réduit d'air appauvri $\frac{F}{P-p}$
(on appelle débit réduit d'air appauvri le rapport entre ce débit F exprimé en grammes par minute et l'écart $(P - p)$ entre haute et basse pressions exprimé en bars).
- En ordonnée, le pourcentage d'oxygène dans l'air appauvri (rapport entre la pression partielle d'oxygène et la pression totale).

On voit que le pourcentage d'oxygène dans l'air appauvri dépend essentiellement du débit demandé ; des appauvrissements excellents peuvent être obtenus à faible débit ; réciproquement on pourra obtenir un débit d'air appauvri très important si l'on peut utiliser des mélanges à 10 ou 12 % d'oxygène ; c'est ainsi que dans les phases de descente où un débit important est demandé, on se contentera d'un appauvrissement à 10 ou 12 % d'oxygène, ce qui suffit en pratique à éliminer tout risque d'explosion ; en croisière avec des débits 3 à 4 fois plus faibles on pourra obtenir moins de 5 % d'oxygène.

On voit aussi que pour un même écart de pression, l'efficacité du générateur d'air appauvri dépend du rapport entre haute et basse pressions ; cette efficacité est meilleure quand ce rapport est grand à cause de la meilleure évacuation des gaz enrichis en oxygène qui ont traversé la membrane.

Comme la quantité d'oxygène extrait par perméation est à peu près proportionnelle à la différence des pressions partielles d'oxygène entre les deux faces de la membrane, l'efficacité de l'appauvrissement dépend de la nature des écoulements amont et aval, de la rapidité d'évacuation des gaz extraits à basse pression ; on peut même améliorer sensiblement en laboratoire l'efficacité du système en assurant une ventilation énergique avec de l'air de la face basse pression des membranes, ce qui a pour effet, pour une même pression totale, d'abaisser la pression partielle de l'oxygène aval, et par conséquent d'en améliorer l'extraction.

Mais la caractéristique pratique probablement la plus importante du système proposé est que le fonctionnement du générateur peut être réglé très simplement en contrôlant la pression amont (par exemple à l'aide d'un détendeur) et le débit d'air appauvri utilisé (à l'aide de gicleurs calibrés ou d'un robinet asservi) ; en jouant sur ces deux paramètres, on peut obtenir à la fois le débit et le taux d'appauvrissement désiré.

Il suffit donc, en pratique, de calculer les dimensions du générateur d'air appauvri en fonction du cas de fonctionnement le plus critique : c'est toujours le cas de la descente la plus rapide à laquelle on exige d'assurer l'inertage des réservoirs ; si le générateur d'air appauvri est capable de fournir un débit suffisant dans ce cas critique, son fonctionnement peut être réglé dans tous les autres cas de vol simplement en réglant la pression amont et le débit de sortie de l'air appauvri.

Les systèmes avionnables d'inertage des réservoirs

Les systèmes avionnables d'inertage des réservoirs devront être beaucoup plus complexes que les systèmes de laboratoire décrits ci-dessus en raison des contraintes particulières du vol et des problèmes annexes que constituent le dégazage du carburant et la pressurisation des réservoirs : à cet effet, ils devront comprendre des échangeurs de chaleur, un compresseur auxiliaire, des dispositifs d'inertage et de dégazage du carburant.

Pour alimenter le générateur d'air appauvri, l'air haute pression sera prélevé sur la prise de pression P2 des compresseurs des réacteurs ; comme la température de cet air au prélèvement est beaucoup trop élevée pour la membrane, un échangeur de chaleur doit être interposé entre le prélèvement et l'entrée du générateur pour assurer sa protection thermique ; cet échangeur de chaleur pourra être en vol subsonique refroidi à l'air ambiant ; en vol supersonique élevé, il devra être refroidi par de l'air de température inférieure à 50° C, par exemple, l'air de sortie de cabine.

La pression P2 donnée par les réacteurs est suffisamment élevée en montée ou en croisière pour l'alimentation du générateur ; mais pendant la descente, il est nécessaire d'augmenter beaucoup le débit d'air appauvri au moment précis où la pression P2 du réacteur est la plus basse ; sur les avions à hautes performances, un compresseur auxiliaire sera donc nécessaire ; il sera entraîné par une turbine de détente utilisant cette même pression P2 du réacteur. Dans les différents avants-projets étudiés tant pour les avions de transport civils que pour les appareils militaires, il est apparu qu'en général un seul étage de compresseur d'un rapport de pression voisin de 2 était suffisant ; dans des cas exceptionnels, deux étages donnant un rapport de pression total de l'ordre de 4 sont nécessaires.

L'emploi d'un compresseur auxiliaire constitue pour le système proposé un incontestable inconvénient : ces machines tournantes sont fragiles ; leur entraînement exigera le prélèvement sur les réacteurs de débits P2 non négligeables. Pour obvier à ces deux inconvénients, on a prévu de n'utiliser le compresseur auxiliaire que pendant la descente, c'est-à-dire à un moment où les performances des réacteurs ne sont généralement pas critiques, et pendant un temps très court à chaque vol (moins d'un dixième du temps total de vol) ce qui limite l'usure des machines tournantes.

Sur les avions civils subsoniques et sur les hélicoptères, il ne sera en général pas nécessaire de prévoir de compresseur auxiliaire, le bilan d'ensemble de l'installation étant beaucoup plus favorable en raison, notamment, des moindres performances demandées.

Un problème annexe important est d'assurer le dégazage du carburant pendant la montée ; en effet, le carburant contient normalement au sol une assez grande quantité d'air dissous (jusqu'à 15 % de son volume) ; cet air est de l'air enrichi en oxygène en raison de la plus grande solubilité de l'oxygène dans le carburant ; en montée, il dégaze, soit progressivement, soit brutalement, et il se forme dans les réservoirs des poches de dégazage hautement inflammables à 25 % d'oxygène ; le dégazage permanent du carburant et l'évacuation des gaz produits hors du réservoir sont donc absolument nécessaires ; ceci est effectué très aisément par injection d'air appauvri dans la masse même du carburant à l'aide d'émetteurs de dégazage constitués par des coiffes poreuses d'où l'air appauvri s'échappe en nombreuses bulles.

Ce système qui assure en permanence le dégazage du carburant pendant la montée évite donc aussi les phénomènes de dégazage brutal qui ont été constatés quelques fois à haute altitude à la mise en marche des pompes de carburant.

Les performances d'inertage espérées

Le procédé de production d'air appauvri Rhône-Poulenc-Intertechnique n'a été l'objet à ce jour que d'essais de laboratoire et toutes les performances indiquées ci-dessous sont des performances calculées à l'occasion des études d'avant-projet faites pour l'application du procédé à différents avions.

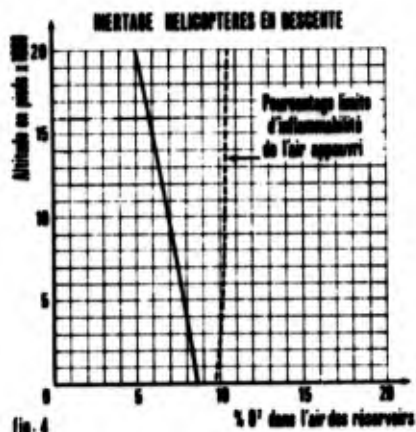


Fig. 4

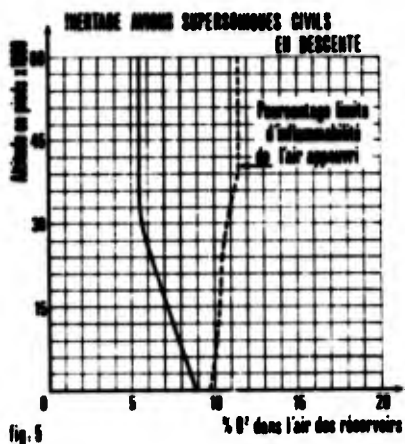


Fig. 5

Ces études aboutissent à la conception de plusieurs systèmes très différents suivant le type d'avion à protéger ; ils vont, d'ensembles très sophistiqués pour les avions supersoniques civils ou militaires à des systèmes très simples, sans même de compresseur auxiliaire, pour les avions légers et les hélicoptères.

Dans toutes ces applications le générateur d'air appauvri est utilisé à faible débit et avec des taux d'oxygène très bas, inférieurs à 5 %, pendant les phases de montée et de croisière ; en descente, on demande par contre un très fort débit d'air faiblement appauvri (de 12 % à 14 % d'oxygène), en sorte que le pourcentage d'oxygène dans les gaz de pressurisation des réservoirs croît au cours de la descente ; tout l'art de l'ingénieur est d'optimiser le régime de fonctionnement du générateur pour que, en fin de descente, le pourcentage d'oxygène dans les gaz de pressurisation de tous les réservoirs reste inférieur au pourcentage d'environ 9 % généralement considéré comme le seuil de sécurité.

On trouvera figure 4 ci-contre l'évolution du pourcentage d'oxygène en descente rapide dans les réservoirs de 900 litres de volume total d'un hélicoptère équipé d'un système très simple comprenant simplement un générateur, un échangeur de chaleur et un régulateur d'une masse totale de 13 kg.

Figure 5 on a reproduit les performances d'inertage calculées en descente rapide dans le cas d'un avion supersonique d'une capacité totale de 110 000 litres de carburant ; la masse totale de l'installation d'inertage est de 220 kg ; on voit que les performances obtenues sont sensiblement équivalentes avec une pénalisation de poids beaucoup plus faible relativement au volume des réservoirs à protéger ; ce gain très important n'a pu être obtenu qu'en acceptant un système beaucoup plus sophistiqué avec un compresseur auxiliaire à deux étages pour le gavage du générateur en descente.

Les performances comparées d'un autre système d'inertage par perméation

Au mois de juillet dernier, la société américaine Garrett a publié les résultats d'une étude originale réalisée à la demande de la FAA, sur un système d'inertage des réservoirs d'avion par air appauvri tout à fait analogue à celui étudié par Intertechnique ; il est très intéressant de constater que Garrett a abouti, sur la conception d'ensemble du système d'inertage, aux mêmes résultats qu'Intertechnique : nécessité d'un compresseur auxiliaire pour la descente, nécessité de modifier l'installation de ventilation de l'avion pour tirer le meilleur parti du système d'inertage, même disposition des échangeurs de chaleur, etc ...

L'étude menée par Garrett diffère essentiellement de celle conduite par Intertechnique en ce qui concerne le choix de la membrane perméante et le mode d'utilisation de ces membranes à l'intérieur des cellules de perméation ; disposant d'un matériau de base dont les caractéristiques propres de perméation étaient moins bonnes que celles des membranes Iris 4101, la société Garrett a réalisé des membranes tubulaires de tout petit diamètre, technologie délicate mais qui a permis d'atteindre pour le générateur les mêmes performances que celles obtenues par Intertechnique malgré le handicap d'un produit de base moins performant.

En dépit de cette différence dans la conception interne du générateur d'air appauvri, il est extrêmement encourageant que des études menées de manière complètement indépendante aient abouti ainsi à la même conception d'ensemble du système avion et à des estimations de performances globales très voisines.

Les performances comparées des systèmes d'inertage à l'azote liquide

Dans les systèmes d'inertage utilisant de l'azote liquide, le devis de masse de l'installation dépend beaucoup du nombre de descentes pour lequel le système d'inertage doit être calculé ; pour les avions long-courriers effectuant une descente en fin de croisière plus, éventuellement, une descente après déroutement, les deux solutions concurrentes : emport d'azote liquide ou production d'air appauvri aboutissent à des systèmes de masse et d'encombrement sensiblement égaux ; pour les avions qui doivent effectuer plusieurs descentes entre deux ravitaillements les systèmes de production d'air appauvri par perméation sont beaucoup moins encombrants et moins lourds.

Comme pour toute technique nouvelle, le gros handicap des systèmes d'inertage par perméation est leur prix : les estimations d'Intertechnique conduisent à des prix presque deux fois plus élevés que ceux des systèmes à l'azote liquide ; ceci ne représente encore cependant qu'environ 2/1000 du prix total de l'avion ; ces estimations sont parfaitement cohérentes avec celles de Garrett, si l'on tient compte de la technologie plus onéreuse choisie par Garrett pour le générateur d'air appauvri.

Sans chercher à minimiser cet inconvénient, il est nécessaire de rappeler l'immense avantage logistique qu'apporte à l'utilisateur un système complètement autonome et qui ne nécessite aucun traitement préalable du carburant ; alors que l'emport d'azote liquide entraîne un ravitaillement particulier à chaque escale (ou toutes les 3 ou 4 escales si l'on accepte un système plus lourd) et exige l'utilisation de carburant préalablement inerté au sol ; dans les systèmes à azote liquide l'inertage du carburant en vol exigerait en effet de doubler, à peu près, la quantité d'azote emportée.

Le système proposé par Intertechnique et Rhône-Poulenc, comme le système Garrett, sont complètement autonomes sur le plan logistique ; ils ont les avantages annexes d'éviter les accidents de dégazage brutal à haute altitude constatés quelquefois avec du carburant saturé d'air, notamment à la mise en marche des pompes ; ils entraînent la suppression des mises à l'air libre individuelles des réservoirs, dont chacun connaît les inconvénients ; et les essais en cours laissent espérer que ces systèmes auront une endurance aussi satisfaisante que celle des équipements de climatisation les plus récents.

DISCUSSION - PAPER 6

Mr Marriette: The necessity to eliminate dissolved O₂ in the fuel has been ignored. How is this accomplished without airport ground scrubbing facilities? If scrubbed in flight, what additional weight has to be included with those quoted?

Mr Tugay: Dans la solution proposée, nous prévoyons pendant toute la montée d'injecter de l'air appauvri dans la masse du carburant et nous avons mis au point à cet effet des injecteurs composés d'une tuyère avec une coiffe poreuse qui permet de dégazer suffisamment le carburant pendant la montée. En fait, en partant d'un carburant saturé au sol, la quantité maximale d'O₂ dans l'air au dessus du carburant atteint 8,5% à 30.000 pieds et ensuite redécroit jusqu'à 5%. C'est un des avantages de la solution proposée: elle permet sans autre pénalisation d'utiliser du carburant ordinaire.

Flame Propagation in Aircraft Vent Systems
During Refuelling

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Summary

An investigation has been made to determine if ignition at the fuel system vent box of a large commercial aircraft during refuelling could result in flame propagation through the vent system and cause an explosion inside one of the fuel tanks. The program was initiated as the result of an explosion during a commercial refuelling and was confined to investigating the type and series of aircraft involved utilizing a simulation of part of the vent system leading to the tank where the explosion originated. The ability of the flame to propagate was demonstrated using wide-cut fuel and a 50/50 mixture of wide-cut fuel and kerosene. No propagation occurred with kerosene nor with wide-cut fuel that had lost 5% of its light ends. Flame propagation and explosion intensity were found to depend on mixture temperature, fuel/air ratio, mixture flow velocity and oxygen content of the air.

1. Introduction

During pressure refuelling of a Douglas DC-8, Series 53 aircraft an explosion occurred that blew off a section of top plating from the right wing and started a fire. At the time of the explosion the aircraft was being fuelled with wide-cut type aviation turbine fuel, although the aircraft tanks contained kerosene type aviation turbine fuel remaining from a previous refuelling.

One possible cause of the explosion considered during the subsequent investigation was that ignition occurred at the exit of the aircraft fuel system vent, which is located towards the wing tip, and after ignition the flame propagated back through the vent system to the #3 alternate tank (see Figure 1) where the explosion was believed to have originated. Brenneman (Reference 1), from measurements made during actual refuellings, detected flammable mixtures right at the vent exits of certain aircraft when wide-cut fuel was being loaded at ambient temperatures similar to that when the DC-8 explosion took place i.e. 76°F. Based on his evidence it was considered possible that a flammable mixture could have been present at the vent exit of the DC-8 at the time of the refuelling.

Examination of the design of the vent system, shown in simplified form in Figure 2, shows that if flame propagation occurred its preferred path might be straight down the 4" diameter main vent pipe into the 3" diameter branch vent pipe leading to #3 main tank, rather than into #3 alternate tank where the explosion occurred.

One of several experimental programs initiated during the course of the accident investigation was therefore aimed at determining the following:

- (a) If ignition occurred at the vent exit could the flame propagate back through the vent system against the fuel vapour/air mixture being expelled out of the vent system as the fuel was entering the tanks.
- (b) If propagation can occur what are the most favourable conditions.
- (c) Would it be possible to produce an explosion in #3 alternate tank by flame propagation through the vent system.

The results of this investigation are presented in this paper.

2. Simulation of Fuelling Operation

Due to the urgent nature of the investigation and since it was impossible to use an actual aircraft vent system or reproduce the full scale refuelling (which involved a fuel flow rate of approximately 350 IGPM) a simulated system had to be assembled as rapidly as possible. A simulated system was therefore designed and assem-

bled to include the following requirements:-

- (1) A reproduction of the aircraft fuel vent system from the vent exit to the #3 alternate and #3 main tanks, using full scale dimensions for length and pipe diameter.
- (2) Small scale fuel reservoirs to represent the #3 alternate and main tanks.
- (3) A system to represent the refuelling, without actual addition of fuel, such that fuel vapour/air mixtures could be expelled through the vent system at velocities equivalent to those obtained in practice during a refuelling.

Note: At the time of the incident a fuel flow rate into the right wing was approximately 350 IGPM. The linear velocity of the mixture in the vent system is related to the fuel flow rate and in the 4" diameter vent system pipe the following relationship between fuel flow rate and linear velocity exists:-

<u>Fuel Flow Rate</u> IGPM	<u>Mixture Velocity</u> (fps)
200	6.1
300	9.2
400	12.3
500	15.3
600	18.4
700	21.5

- (4) An ignition source at the vent exit of sufficient energy to ensure that ignition would occur if a flammable mixture was present.

The simulated system that was assembled is shown in Figure 2 and consists of:

- (A) A five gallon container at the vent exit to simulate the vent box in the aircraft wing.
- (B) An electric spark generation unit capable of providing 60 sparks per second, each spark having an energy of 3.3 Joules.
- (C) Sixty-five feet of 4" diameter main vent pipe. The initial twenty feet of pipe was made from aluminum the rest being plastic (polyvinyl chloride).
- (D) Two branch lines approximately twenty-five feet long and 3" in diameter. These two branch lines are spaced ten feet apart and lead into the simulation of #3 main and #3 alternate tanks.
- (E) Two five gallon tanks, one connected to each of the 3" diameter branch pipes, to simulate the #3 main and #3 alternate tanks. The size of the tanks were limited to five gallons to minimize the effect of any explosions that might occur.
- (F) Two air blowers, one for each branch of the vent system, whose outputs were regulated separately by Variac controllers. The air from the blowers was blown over the fuel surface before entering the vent system.
- (G) Two aerators, one for each fuel tank using compressed air from a standard cylinder. The air was passed through the aerators which were set below the fuel surface. This air generated the required amount of fuel vapour which then mixed with the main air stream flowing through each tank from the air blowers.
- (H) A hot water bath for heating the compressed air entering the aerator system. Initially attempts were made to vaporize the fuel without pre-heating the air. However, it was found that since the latent heat of vaporization needed to generate the required rate of fuel evaporation could only come from the small amount of fuel in the tanks, its temperature dropped significantly. The hot water bath was therefore necessary to replace this heat in order to maintain the fuel temperature at ambient.

Note: Since the ratio of blower air to aerator air was about 10 to 1 and the heat input was approximately equal to the heat of vaporization of the fuel, the air/fuel vapour mixture temperature can be considered equal to the blower air temperature i.e. ambient.
- (I) An anemotherm air meter was used to measure the mixture velocity in the 4" diameter vent pipe near the vent box. A commercially available hot wire catalytic explosimeter was used to measure the vapour concentration expelled at the vent exit.

3. Experimental Program

3.1 Fuels Used in the Program

The initial fuel used in the program was wide-cut aviation turbine fuel taken from the hydrant cart being used to refuel the left wing of the DC-8 at the time of the incident. This is the same fuel that was being added to the right wing. Distillation characteristics and the Reid Vapor Pressure of the fuel are shown in Table 1. These and other properties meet the requirements for ASTM D1655, Jet B and US Military Specification Mil-T-5624, Grade JP-4. Later runs were made with another source of wide-cut fuel which also met the requirements of the above specifications.

Table 1: Volatility Characteristics of Wide-Cut Fuel Before and After a Test Run

<u>Property</u>	<u>New Test Fuel</u>	<u>After Test</u>	<u>Specification Requirement</u>
(a) Distillation Characteristics			
Initial Boiling Point, °F	146	180	Report
5% recovered, °F	183	208	-
10% recovered, °F	196	220	Report
20% recovered, °F	210	239	290 max.
50% recovered, °F	274	301	370 max.
90% recovered, °F	422	430	470 max.
Final Boiling Point, °F	494	505	Report
(b) Reid Vapor Pressure			
lb.	2.97	1.43	2.0-3.0

Fresh fuel was used for each run because it was found that the light ends of the fuel were consumed in a test changing its distillation characteristics and reducing the vapor pressure. This loss of light ends occurred whether or not flame propagation took place and it was impossible to obtain a flammable mixture at the vent exit, under the test conditions, with the "used" fuel. Typically losses of 5% light ends were observed and this is shown in Table 1. Other fuels used were a 50/50 mixture of wide-cut fuel and aviation kerosene conforming to ASTM D1655, Jet A-1. The distillation characteristics and flash point of the kerosene are shown in Table 2. Although not part of the program a limited number of tests were also made using the kerosene on its own.

Table 2: Volatility Characteristics of Kerosene Fuel

<u>Property</u>	<u>Test Fuel</u>	<u>Specification Requirements</u>
(a) Distillation Characteristics		
Initial Boiling Point, °F	346	-
10% recovered, °F	378	440 max.
50% recovered, °F	407	450 max.
Final Boiling Point, °F	478	550 max.
(b) Flash Point, °F	137	105 min.

3.2 Experimental Procedure

Before each experiment the velocity of the main air flow from each of the two blowers was set and balanced. One gallon of fuel was then added to each of the two fuel tanks. The secondary air was then turned on through the aerators. The total mixture flow rate and the vapor concentration was then measured at the 4" main vent exit. When, and if a combustible mixture was detected, the ignition source was turned on. The results of the ignition were then observed visually and by photography.

When ignition occurred at the vent box without propagation the flame was cut off by stopping the flow of secondary air and increasing the blower air to produce a lean mixture below the lower flammability limit.

Flame propagation tests were conducted at the conditions listed in Tables 3 and 4. The variable parameters were mixture velocity in the 4" main vent pipe and the mixture temperature, which as already stated can be considered as ambient temperature. Due to the weather conditions at the time of the program, ambient temperatures were limited to approximately 45°F and 70°F.

3.3 Oxygen Enrichment

Since the solubilities of oxygen and nitrogen in fuel are different the composition of air dissolved in fuel is different to normal atmospheric air. Values of oxygen contents of 30-33% have been reported for a series of typical aviation fuels (Reference 2). On ascent, fuel in an aircraft tank can become supersaturated with air and fuel agitation, such as produced by the operation of a boost pump, can promote air release. The problems associated with air release at altitude have been studied pre-

viously (Reference 3). Air released from fuel will be oxygen enriched and the effect of this on the ignition characteristics of the vapour/air mixture in the vent was considered. Although not supersaturated with air, the fuel entering an aircraft tank during refuelling may possibly release oxygen enriched air into the tank due to agitation. Although not a part of the main program a limited number of tests were made using oxygen enriched air. This enrichment was achieved by passing a mixture of air and oxygen through the aerators instead of pure air. Flame propagation tests were conducted at the conditions listed in Table 5.

4. Results

4.1 Flame Propagation Using Wide-Cut Fuel

The results obtained using wide-cut fuel on its own are presented in Table 3. In summary the following observations were made:-

- (1) Flame propagation upstream against a combustible mixture flow velocity of 12 fps to 18 fps in the 4" diameter main vent pipe was possible when the mixture temperature was 70-75°F. Propagation did not occur at 21 fps.
- (2) At the higher flow ranges flame propagation in the initial 40 feet of main vent pipe was slow and tended to oscillate. This was confirmed by the high temperature of the pipes immediately after the test and the heat damage suffered in this area.
- (3) Flame propagation upstream was accompanied by a muffled rumbling noise prior to the final explosion.
- (4) When flame propagation occurred the flame tended to pick up speed as it moved up the vent pipe and an explosion occurred in the vent pipe between the two branch pipes and in the fuel tanks. The low temperature of this portion of the vent system immediately after a test and the absence of heat damage to the 3" vent pipes confirmed that the flame moved very fast in those sections. However, on several occasions the branch vents pipes along with the fuel tanks were blown up by the explosion.
- (5) Mixture temperature played an important role in flame propagation against flow in the vent system. At 48°F, even though a combustible mixture was detected in the vent system, the flame failed to propagate upstream against a relatively low mixture flow velocity (6 fps). Instead, a blowtorch phenomena resulted at the vent box.

4.2 Flame Propagation Using 50/50 Mixture of Wide-Cut Fuel and Kerosene

The results obtained using a 50/50 mixture of wide-cut fuel and kerosene are presented in Table 4. The results were essentially the same as with wide-cut fuel on its own. In summary therefore:-

- (1) Mixing kerosene with wide-cut fuel did not have any noticeable effect on the production of a combustible mixture compared with using wide-cut on its own.
- (2) Flame propagation upstream against a combustible mixture flow velocity of 12 to 14 fps in the 4" main vent pipe was possible when the mixture temperature was 72°F.
- (3) At 46°F, the flame did not propagate upstream when the mixture flow velocity in the vent was as low as 4 fps.

4.3 Flame Propagation Using Kerosene

Flame propagation was not possible nor were flammable mixtures present at the vent exit when kerosene was used at ambient temperatures of approximately 70°F. This was not unexpected since the flash point of the kerosene (see Table 2) was 137°F, which is above typically encountered values.

4.4 Flame Propagation with Wide-Cut Fuel and Oxygen Enrichment

The results obtained with oxygen enrichment using wide-cut fuel are presented in Table 5. In summary the following observations can be made:-

- (1) Flame propagation upstream against a combustible mixture flow velocity of 18 fps was possible when the mixture temperature was 40°F and the air contained 3% added oxygen.
- (2) Flame propagation was much more rapid in the presence of oxygen enriched air with ignition and explosions being virtually simultaneous.
- (3) The explosions produced were much more violent in the presence of oxygen enriched air. The 3" vent pipes disintegrating rather than blowing apart as occurred with normal atmospheric air.

5. Conclusions

From the experimental results obtained, using the simulated refuelling system described previously, it may be concluded that:

- (1) Flame propagation upstream in the simulated fuel tank vent system was possible with wide-cut fuel and a 50/50 mixture of wide-cut fuel and kerosene and was dependent upon mixture flow velocity and mixture temperature.
 - (a) At a mixture temperature of approximately 70°F propagation was possible when the mixture velocity in the 4" vent pipe was at or below 18 fps (Equivalent to a fuelling rate of 600 IGPM).
 - (b) At a mixture temperature of 48°F flame propagation was not possible even at a mixture velocity in the 4" vent pipe as low as 6 fps (Equivalent to a fuelling rate of 200 IGPM).
- (2) Flame propagation in the initial section of the vent system was slow, but picked up speed as it moved up the system. The time taken for propagation from the vent box to either, or both, fuel tanks varied between two and fifteen seconds.
- (3) Flame propagation caused explosions in both the simulated #3 main and alternate tanks and/or in the branch pipes close to the tanks.
- (4) Both flame propagation and explosion intensity depend on the mixture temperature, fuel vapour concentration and fuel to air ratio, the combustible mixture being formed mostly from the light ends of the fuel.
- (5) Flame propagation was not possible using kerosene under the conditions used.
- (6) Enrichment of the air in the fuel vapour/air mixture with 3-6% oxygen enabled flame propagation to occur at temperatures as low as 40°F, with mixture velocities up to 18 fps.
- (7) With oxygen enrichment the rate of flame propagation and the intensity of resultant explosions were greatly increased. The ignition and explosion occurred virtually instantaneously.

6. References

1. Brenneman, J.J., "A Study of the Fuel Vapor Envelope at Aircraft Tank Vents during Fuelling Operations" United Air Lines, Dec. 1963.
2. Ross, K., "The Solubility of Air in Aviation Turbine Fuels" Shell Research Ltd., Thornton Research Centre, England. Report No. K.186, Sept. 1970.
3. Timby, E.A., and Wells, R.F., "Fuel Overflow and Tank Differential Pressure due to Air Release from Fuel at Altitude" Royal Aircraft Establishment, Farnborough, England, Technical Report 72007, Feb. 1972.

**Table 3: Flame Propagation Through Wide-Cut Fuel Vapour
and Air Mixture Inside a Simulated Aircraft
Vent System**

Run No.	1	2	3	4	5	6	7	8	9	10	11	12
Mixture Temperature (°F)			70			75			70			75
Mixture Velocity in 4" pipe (ft/sec)			12			12			15			15
Flame Propagated back to tanks			Yes			Yes			Yes			Yes
Explosion in tanks			Yes			Yes			Yes			Yes
Remarks	3" branch vents blown apart at slip joints; relatively mild explosions; no structural damage. Flame moved back comparatively fast.					Taped 3" branch vents blown to pieces. Very fast flash back; less than two seconds.		Untaped 3" branch vents blown apart at slip joints; stronger explosions; no structural damage.			Taped 3" branch vents blown to pieces; violent explosion. Very fast flash back (approximately 2 seconds)	
Run No.	13	14	15	16	17	18	19	20	21	22	23	
Mixture Temperature (°F)			70			75			70			
Mixture Velocity in 4" pipe (ft/sec)			18			18			21			
Flame Propagated back to tanks			Yes			Yes			No			
Explosion in tanks			Yes			Yes			No			
Remarks	Flame propagated slowly in the first 40' of main vent pipe. Oscillation phenomena observed from the continuous change in shape of the P.V.C. pipes. Damage due to heating of this pipe section always resulted. Flame propagated very fast in the rest of the system resulting in violent explosions. However, temperature of this section of the system remained close to the ambient temperature					Taped pipes blown to pieces; violent explosion. Fairly fast flash back; approximately 3-4 seconds.		Blow torch phenomenon at the exit of the vent box.				
Run No.	24	25	26	27	28	29	30	31	32	33		
Mixture Temperature (°F)			48					48				
Mixture Velocity in 4" pipe (ft/sec)			12					6				
Flame Propagated back to tanks			No					No				
Explosion in tanks			No					No				
Remarks	Blow torch phenomenon at the exit of the vent box.					Blow torch phenomenon at the exit of the vent box.						

Table 4: Flame Propagation Through Vapour From A 50/50 Mixture of Wide-Cut Fuel and Kerosene and Air

Run No.	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Mixture Temperature(°F)			72					72					72		
Mixture Velocity in 4" pipe(ft/sec)			12					15					18		
Flame propagated back to tanks			Yes					Yes					Yes		
Explosion in tanks			Yes					Yes					Yes		
Remarks	3" branch vents blown apart at slip joints;mild explosion; no structural damage to system.					3" branch vents blown apart at slip joints; stronger explosions;no structural damage to system.					The twenty feet 4" pipe next to the vent box was damaged by heating.				
Run No.	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
Mixture Temperature(°F)			72					45					46		
Mixture Velocity in 4" pipe(ft/sec)			22					10					6		
Flame propagated back to tanks			No					No					No		
Explosion in tanks			No					No					No		
RemarksBlow torch phenomenon at vent box.....														

Table 5: Flame Propagation Through Wide-Cut Fuel Vapour and Oxygen Enriched Air Mixture in Simulated Vent System

Run No.	A	B	C	D
Mixture Temp. (°F)	42	40	46	50
Mixture Velocity (fps)	18	18	15	12
Oxygen Added (%)	5	3	6	3
Flame Propagated back to tanks	Yes	Yes	Yes	Yes
Explosion in tanks	Yes	Yes	Yes	Yes

Remarks

In all cases flame propagation was extremely rapid and in Runs B, C and D ignition and explosion were virtually instantaneous. Explosions produced were very violent frequently disintegrating the 3" branch pipes. In Run D external fire produced from fuel scattered by the explosion.

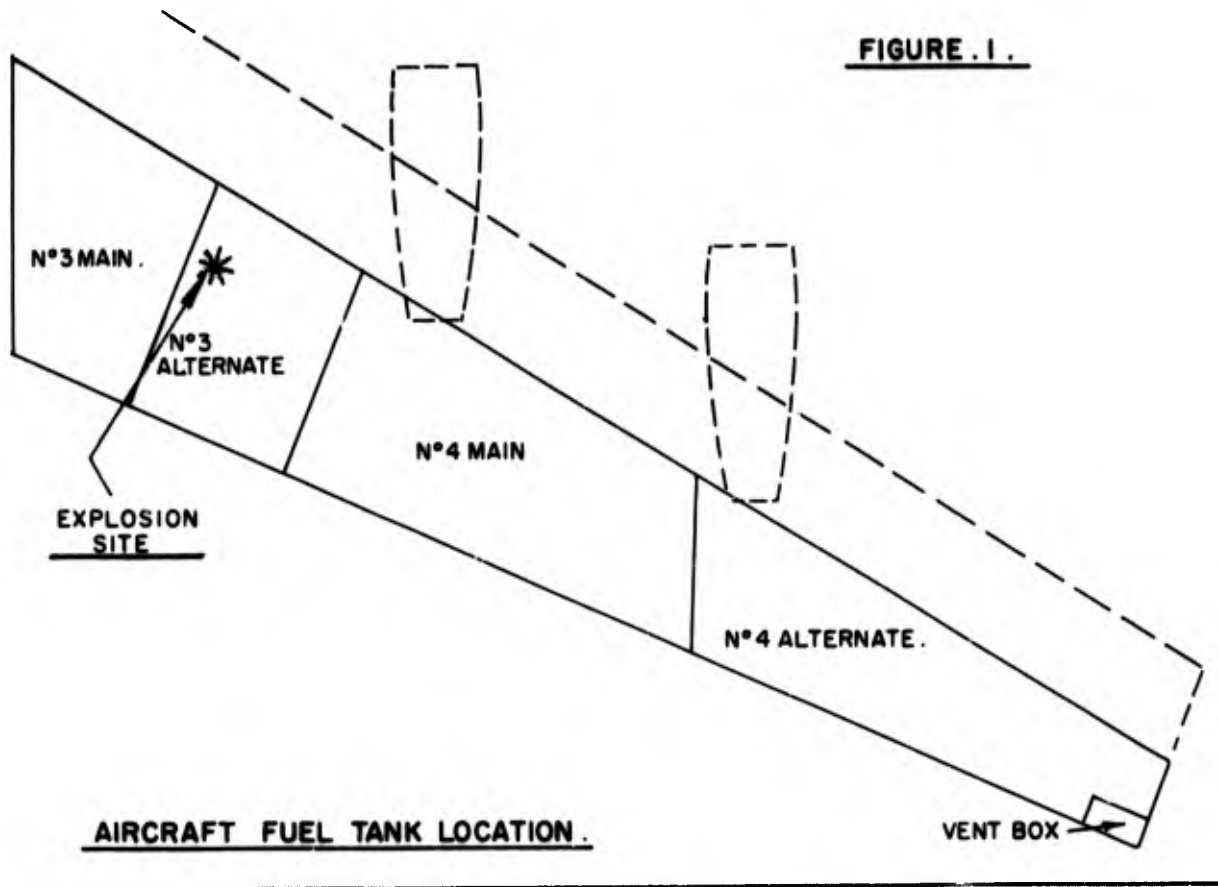
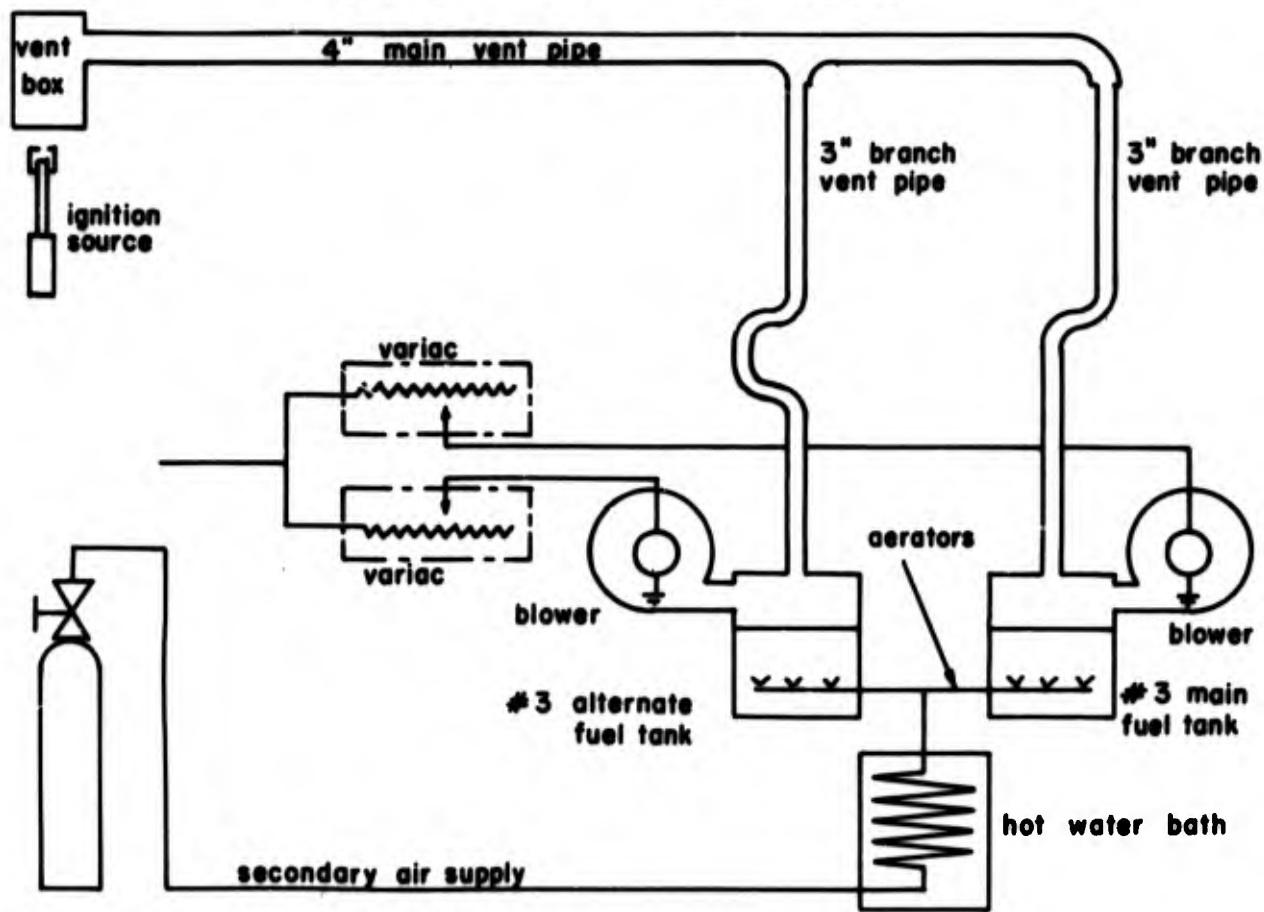


FIGURE 2. Experimental Apparatus.



DISCUSSION -- PAPER 7

Mr Jackson:

(a) When the tank exploded in the DC8 during refuelling at 300 GPM, was the source of ignition known?

(b) From the presentation of the paper it was noted that to prevent the flame at the vent outlet from propagating back into the tank, the velocity of the mixture from the tank had to exceed 18 ft/sec. From an aircraft designer's point of view he has to design a vent system which will accept a specific flow of fuel which will not create a back pressure which will overpressurise his tanks (this assumes failure of the tank shut off device). To keep the velocity of the tank mixture above 18 ft/sec, he may have to design a smaller vent pipe which could increase the permissible pressure in the tank in the event of an overflow from the tank.

Mr Gardner and Mr Wong:

(a) The investigation did not reveal the source of ignition.

(b) Certainly a smaller vent pipe, hence higher velocity, would prevent flash back in the vent system. However, it would probably be better to include a flame arrestor or suppressor in the vent system rather than using smaller pipe sizes which could lead to the risk of outpressuring the fuel tanks.

Mr Sirignano: Your flame propagation speeds are greater than the pre-mixed laminar flame speeds. Presumably, turbulent flames are occurring. Therefore, I suggest that you should measure parameters, such as intensity and scale, which characterize the turbulence in your vent. Without these measurements, it would be difficult to correlate your data.

Mr Gardner and Mr Wong: The experiments performed were for the specific purpose of duplicating conditions in the particular vent system concerned and time did not allow a more fundamental study.

DYNAMIC MODELING OF AIRCRAFT FUEL TANK ENVIRONMENTS AND VULNERABILITY

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SUMMARY

This paper summarizes development work currently underway to more precisely define and assess the environments, hazards, and vulnerability of regions adjacent to and within aircraft fuel tanks. It presents the importance and difficulties of developing fuel tank environment models which are accurate enough for confident assessment of aircraft combat vulnerability and operating safety. Three approaches to modeling the flammability of the ullage of an aircraft fuel tank are discussed, including the one currently being developed. Examples illustrate various ways that dynamic effects radically alter equilibrium vapor conditions in the ullage. Finally, the method of applying the fuel tank ullage environment model to computerized aircraft vulnerability programs is presented.

BACKGROUND

This paper summarizes development work that is now being performed at Falcon Research and Development Company, in Denver, Colorado, for the Fire Protection Branch of the Air Force Aero Propulsion Laboratory at Wright-Patterson Air Force Base, Ohio. This program is sponsored by the Joint Technical Coordinating Group for Aircraft Survivability, an organization with members from all three military services of the United States Department of Defense. We are in the tenth month of the two year program. Completion is scheduled for June, 1976.

The basic purpose of this program is to more precisely define and assess the environments, hazards, and combat vulnerability of regions adjacent to and within aircraft fuel tanks.

This need for more precision is based on three facts. First, damage to the fuel tanks often results in quick destruction of the aircraft. Second, the proportionately high volume and surface area of the airplane's fuel tanks make them relatively large targets for the enemy threats. Third, the interactions of the threat, aircraft tanks, and combustion phenomena are extremely complex and often not well defined. Hence, improving analysis related to fuel tank fire and explosion can significantly increase the accuracy of the total aircraft's survivability values.

This is particularly important during design. Here, the large volume and area of the fuel tanks often lead to very significant weight, cost, and performance penalties for adding passive defense measures. Thus, adding protection must be well justified, preferably by quantitative methods.

More precise measures of fuel tank hazards may be valuable for non-combat aircraft safety as well. Although fuel tanks and systems are isolated as much as possible from ignition sources, improbable natural events or human or mechanical failures can cause loss of hundreds of lives at a stroke. Hence, aircraft fire safety is an attempt at perfection, regardless of the statistics. It is subject to difficult tradeoffs with aircraft efficiency that are strikingly similar to those for combat survivability, and may require similar precision.

PROGRAM SCOPE

The analysis technique being developed is broad and general. It provides values of vulnerability of the total aircraft and its individual fuel tanks for any point on a given mission profile. With input of the results (i.e., "hit distribution") of dynamic engagement models between the aircraft and its combat threats, the probability of survival of the aircraft may also be determined for a given point in the mission. The analysis applies dynamic physical models to detailed data on the properties of the aircraft, its environments and missions, impacting threats, and contained fuel. Particular

emphasis is placed on defining the regions of flammability in the ullage of fuel tanks prior to a hit, and the dynamics of the penetrators as generators of fuel spray and as ignition sources.

The analysis follows the chain of physical events until they culminate in either sustainable damage or system failure. Failure is assigned various levels of severity, expressed in "Kill Categories". The analysis techniques are as compatible with existing aircraft vulnerability methods and models as practical.

This study is concerned with the full spectrum of United States military aircraft, from the smallest to the largest. Emphasis is on military turbine fuels, with flash points from below zero to above one-hundred degrees Fahrenheit.

The hazards are primarily non-nuclear combat threats, particularly incendiary and high-explosive projectiles, and fragments from nearby warhead detonations. Single, independent encounters between a given projectile or fragment and the aircraft are analyzed. For contact-fuzed explosive projectiles, we are most concerned with the smaller ones which cannot destroy the aircraft's structure solely with their own blast and fragmentation effects.

The analysis is also to be adaptable to hazards such as lightning strikes upon fuel tanks, and electrical shorts and hot surfaces within tanks or encountered by leaked fuel or vapors.

APPROACH

Our fundamental approach is to couple existing vulnerability analysis computer programs with dynamic computer models of fuel tank ullage flammability, threat-induced fuel spray and ignition, and the system responses to the combustion phenomena. Great care is being taken to avoid excessive growth in the size, complexity, and run time of the final computer program.

The role of the computer in our analysis technique is strictly as a tool of the systems analyst. Human experience and judgment are essential for correct selection of the input data, and proper application of the optional dynamic models.

The program is applicable to both large, complex models of fully designed aircraft, and to very simple problems limited in input detail, time, or funds. The program is modular, so that more refined or simpler models developed in the future may be easily substituted in the general program.

We are often limited in the development of the dynamic physical models by inadequate analytical tools and insufficient data. In such cases, we include the apparent physical variables in the models. In this way, future refinements in the analytical tools or data base may more likely be accommodated by revising the inputs rather than discarding the entire model.

The focal point of our analytical technique is the "shotline". This is computer-generated data detailing individual impacts along straight paths through the aircraft of parallel penetrators originating from a given attack direction. Alternately, the shotlines represent fragment paths from a point of detonation of a projectile exploding near or within the aircraft. The computer generates thousands of these paths covering all the threat attack directions specified. All of the relevant dynamic models are applied to each and every shotline involving fuel tank impacts. The program sums the contribution of each shotline for a given view presented to the threat, and obtains both fuel tank and total aircraft vulnerable area.

Many existing models and computer programs are applicable to the shotline analysis of fuel tank and adjacent void space vulnerability. Computerized aircraft configuration models are highly refined, and dozens of them have been prepared. They define in detail hundreds or even thousands of components in complex modern aircraft. They output the encounters as shotline information, directly applicable to our fuel tank analysis program.

Extensive models also exist on the penetration and other interaction of projectiles and fragments with the aircraft components. These are also directly applicable. Some improvement is needed and is being made in the accuracy of incendiary projectile activation and fragment impact flash/ignition models.

Vulnerability analysis programs accept the shotlines and other input data, then compute and print out vulnerable areas for each attack direction. Models have been

developed in the past for predicting fuel tank ullage flammability, but none have been integrated with vulnerability analysis programs. This is a major area of innovation for this program.

FUEL TANK ULLAGE FLAMMABILITY MODELS

In the past, a prevalent approach to fuel tank ullage flammability has been to assume equilibrium conditions and homogeneous vapor/air mixtures. The Well-Stirred Fuel Tank Ullage Flammability Program is an example of the latter assumption. It was developed by Kosvic, Zung, and Gerstein under the technical direction of the Air Force Aero Propulsion Laboratory (Reference 1) with partial funding by the Federal Aviation Administration. It combined experimental and analytical research, and was concerned particularly with dynamic effects and elevated temperatures in supersonic aircraft fuel tanks.

The Well-Stirred Model is particularly applicable to the ascent and level flight modes for shallow (e.g., wing) fuel tanks. The model analyzes mass and energy transport rates due to fuel evaporation, vent system flow into or out of the tank, heat transfer, and outgassing of dissolved air from the liquid fuel. Provisions were made in the model for fuel droplet formation in the ullage due to condensation and liquid slosh and vibration.

The Well-Stirred Model includes the dynamic effects of changes in altitude, bulk fuel temperature, skin and structure temperature, ullage volume, and liquid fuel/ullage interface area. The program computes the vent velocity, ullage gas temperature, and fuel vapor/air concentration for a given point in the simulated mission.

The assumption of well-stirred ullage was found to be significantly in error for cruise conditions at constant altitude, particularly for "deep" tanks where the ullage volume is high in relation to the liquid fuel/ullage interface area. Hence, a Distributed Fuel/Air Model was developed for conditions where significant fuel vapor concentration gradients are encountered. The model was applied to a one-dimensional case which was directly compared with experimental data.

This program uses a derivation of the continuity equation. It numerically integrates pressure and temperature time histories and a prescribed velocity flow field in the ullage in order to obtain fuel vapor concentration values for each node point in the vapor space. The computer program uses a resistance-capacitance electrical analog finite difference method, similar to that used for a general heat transfer program (Reference 2). This Distributed F/A Model cannot be directly applied to our Fuel Tank Vulnerability Program because it requires input of a precise vent and ullage gas flow field which is generally unknown. In addition, the program is complex and costly to run for the more complicated cases, and the many iterations needed for "shotline-by-shotline" analysis.

Hence, as an integral part of our research program, Breen, Bartz, Helgeson, and others at K.V.B. Incorporated, Tustin, California, are refining and modifying the Well-Stirred Model to provide fuel vapor concentration gradient data. This Fuel/Air Gradient Model superimposes non-homogenous conditions as perturbations upon the Well-Stirred Model. The extent of perturbation depends primarily upon the dynamic conditions involved, such as climb or dive rate, and/or fuel transfer rate. The "relaxation times" for these perturbations depend on the relative strength of the factors that tend to drive the ullage mixture to equilibrium, including fuel temperature and vapor pressure, ullage gas mixing, liquid fuel/ullage interface area, and ullage height. The primary output is a one-dimensional fuel/air gradient from the liquid surface to the top of the tank. This model is semi-empirical, and test data in this same form will be applied for the appropriate dynamic conditions.

Figure 1 illustrates the three ullage flammability models applied to the same tank.

A one-dimensional fuel/air gradient may not be adequate for some cases. In Figure 2, a shallow wing fuel tank is shown with hypothetical flammable regions for dive and cruise conditions. The tank is symmetrical, with identical vents at each end. Here, a lateral variation is induced as well as the vertical gradient. The subdivided ullage in the lower drawing illustrates how vertical and lateral gradient information may be approximated for simplified input into the Fuel Tank Vulnerability Program. Of course, the accuracy of the model may be increased by increasing the number of subdivisions of the ullage.

FUEL TANK VULNERABILITY PROGRAM

A schematic to illustrate the Fuel Tank Vulnerability Program's combination of shotline information, pre-impact ullage flammability models, penetration models, activation/

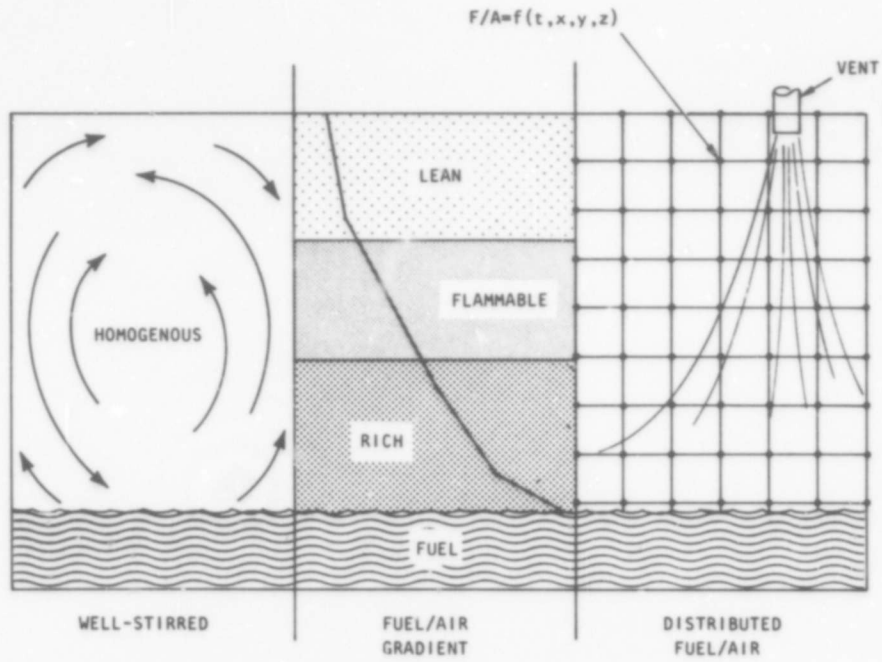


FIGURE 1. Fuel Tank Ullage Flammability Models

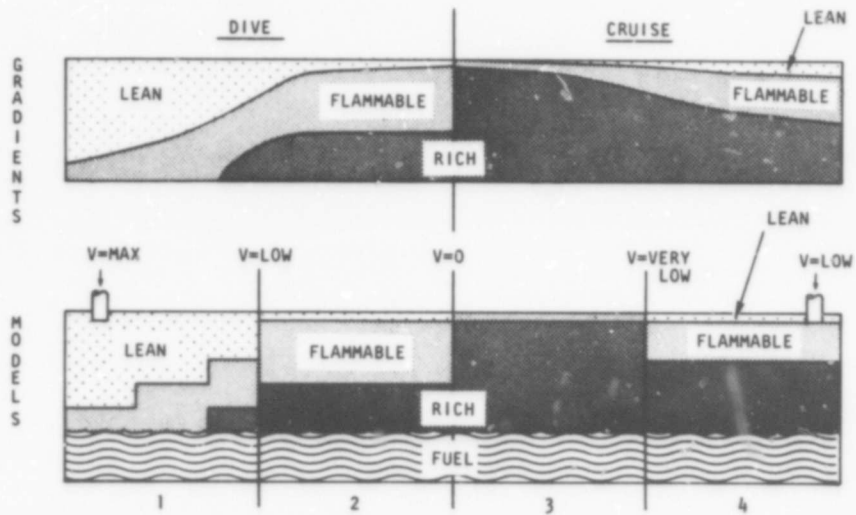


FIGURE 2. Application of F/A Gradients to Shallow Tank Ullage Components

flash ignition source models, spray models, and combustion responses is shown in Figure 3. This is a partially-filled fuel tank with a void space between it and the structure on the left, and slipstream-wetted integral structure on the right. The tank is vented, and the vapor space contains regions which vary in flammability.

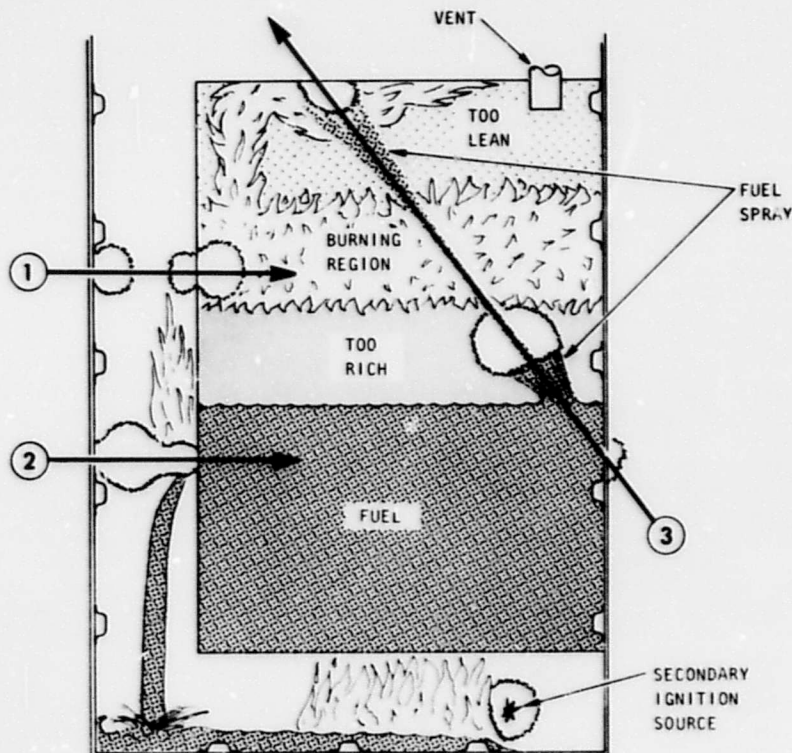


FIGURE 3. Typical Fuel Tank Shotlines

In this example, fresh air has entered the vent due to aircraft descent and fuel transfer from the tank. The incoming air has driven the fuel vapor concentration in the upper region below that necessary for combustion. The middle region is flammable. The lower region is overrich because of its proximity to the low flash point fuel. The three vectors represent trajectories of individual penetrators, our "shotlines".

Shotline Number 1 shows the direct encounter of a penetrator with flammable vapor in the ullage. The small clouds along the shotline are typical ignition sources. For incendiary projectiles, these flashes represent burning incendiary mixture deposited by the bullet as it strikes various solid components. These may also be locations of flashes caused by the high-speed impact of a projectile or fragment upon metal surfaces. For high-explosive (HE) and high-explosive-incendiary (HEI) projectiles, the location of each detonation and flash is determined by the fuze employed and impact conditions. For this particular shotline, the flammable region is ignited and an explosion occurs.

For Shotline Number 2, the flashing external to the tank is similar to Shotline Number 1. Of course, no fuel vapor explosion can occur in the liquid. However, the impact and penetration of the liquid fuel by a bullet or fragment at high velocity can grossly compound wall damage and fuel leakage.

In this case, the fuel has been released and ignited by the penetrator. An independent hazard is shown by the lower fire, where leaking fuel and vapor have found an on-board ignition source. These "primary" and "secondary" fires by Shotline 2 are considered the most prevalent means by which the smaller incendiary projectiles cause fuel-system-related aircraft kills. Hence, these void spaces around fuel tanks are critical areas for analysis and protection.

Shotline Number 3 is an impact upon a fuel tank wall that is integral with primary airframe structure. Even though fuel is present on the inside, the slipstream that is assumed present on the outside combines with the liquid escaping from the hole to prevent

a sustained fire on the tank wall. The second flash along Shotline 3 locates the delayed detonation of an explosive round or the delayed activation of an incendiary round. The third flash is caused by projectile or fragment impact with the tank top at exit.

Figure 3 depicts fuel spray caused by the penetrator exiting the liquid surface. In-house gunfire tests conducted for this case by the Air Force Aero Propulsion Laboratory confirm that; (1) a substantial spray is generated, (2) fuel spray follows the shotline, and (3) the spray can reach an incendiary flash at the exit before "burnout".

This is an extremely important phenomenon. In this case, overpressures can occur in the vapor space of fuel tanks containing high flash point fuels, whose very lean ullage might otherwise be considered "safe" (i.e., no appreciable concentration of fuel vapor is present prior to impact). A high-explosive projectile detonating in similarly "safe" ullage is also capable of generating combustible spray, in addition to providing an extremely energetic ignition source.

In the case of a low flash point fuel, this spray could also serve to connect an exit flash with a large region of flammable vapor (e.g., the region penetrated by Shotline 1). Shotline 3 may be reversed to consider another possibility, travel through the ullage and into the liquid fuel.

To illustrate the final step in the shotline analysis, consider the case where flammable vapor in the ullage has been ignited by Shotline 1. The pressure rise in the ullage is computed based on the volume of ullage burned, total ullage volume, the absolute pressure, and the pressure rise ratio given combustion (e.g., 8 to 1). This quasi-static pressure is reduced by a venting factor and then compared with the pressure capability of the tank. A "Kill Category" (severity) is assigned to each shotline's vulnerable area contribution, depending upon whether the explosion was capable of structural failure and immediate loss of the aircraft ("K Kill"), all the way down to a "Mission Available" Kill. In this latter case, the consequence is only to require inspection and possible repair or cleaning of the tank after landing. There are more sophisticated Internal Blast Models which may be applied to this problem, if further improvements prove necessary for this particular response model.

This shotline analysis technique is very rigorous. It effectively isolates the elements of a complex problem. It is a means by which many variations in aircraft configurations, threat effects, and component and fluids responses can be studied in detail. It can suggest relationships between physical and chemical phenomena for semi-empirical modeling. It is an effective method of applying simple replica target gunfire test data to appropriate complex impact events. This very detailed deployment of the kill mechanisms can inspire methods for defeating the hazard. It provides a means for analyzing how much the passive defense measures improve combat survivability.

SAFETY APPLICATION

The detailed model necessary for fuel tank combat survivability determinations has a potential application to safety analysis of the same aircraft. This is mainly possible because a means has been found to define regions of flammability, ignition sources, liquid fuel, and other zones with distinct characteristics within the fuel tanks which are totally independent of the original computerized aircraft description. That is, we do not now have to define these regions as hard, fixed components in the original target description (as if they were fuel pumps, structure, or other actual components).

Thus, the safety analyst is free to define regions of ignition sources spatially within an aircraft's fuel tank. For example, hot spots due to lightning strikes may be identified on areas of integral tank skin which are thin enough for them to be a hazard. Each ignition region could be identified by the source of the hazard, and a probability of ignition assigned as a value from zero to one.

As envisioned, shotlines may represent turbine blades which have separated from a jet engine and are penetrating a fuel tank. Even if there are no penetrators, the shotlines would be used to "interrogate" the model and determine where ignition sources and flammable regions intersect.

All the various hazards could be incorporated in each run, provided that the ignition regions did not overlap.

The flight profiles, pre-impact ullage flammability models, and overpressure and secondary fire hazard response models used for the combat analyses should be applicable to the safety analysis as well. Safety-related dynamic models could as effectively be incorporated in the tank analysis program as the threat-related ones.

Enough views would be selected to insure interaction of all ignition sources with combustible regions. The various views would be summed and/or averaged for an overall measure of the probabilities of the various failures for a given point in a simulated flight.

The values would generally be separated by the hazard which provided the ignition source. Severity of the response could be measured in time to failure, or some other criterion besides "Kill Category".

As this development program progresses, the potential application and value of this analysis technique to fire safety will be further studied.

CONCLUSION

The Dynamic Fuel Tank Vulnerability Program greatly increases the physical realism and accuracy of combat survivability/vulnerability analyses. The more detailed and realistic threat effects and fuel tank response models included effectively complement the existing fidelity of computerized aircraft configurations, penetration models, and dynamic aircraft/weapons engagement analyses.

The demand for test data by this program exceeds the supply. The hotline analysis technique is a powerful tool for defining what we do not know. It should be applied in the design and data formats of gunfire tests and other dynamic fuel tank environment and combustion experiments.

The highest levels of aircraft fuel tank and system survivability can best be achieved by closely coupling advanced analytical methods, such as the Dynamic Fuel Tank Vulnerability Program, with relevant and closely controlled experiments.

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ACKNOWLEDGMENTS

Mr. Gregory W. Gandee of the Air Force Aero Propulsion Laboratory is the United States Air Force Project Engineer monitoring this program. As principal author of the technical statement of work for this program, his contribution to its basic approach and his continuing technical guidance are gratefully acknowledged. Messrs. Benito P. Botteri and Robert G. Clodfelter of the same organization have also provided valuable technical information and perspective.

The direction provided by the Falcon Research and Development Program Manager, Mr. George H. Custard, is also gratefully acknowledged.

DISCUSSION - PAPER 8

Mr Sirignano: The duration associated with the ignition source has not been mentioned as a pertinent parameter in your studies. Do you believe that it is important? If so, how might it be included?

Mr Mahood:

(1) It is true that the duration of the ignition source is one of the most important physical parameters involved in the ignition of fuel spray by incendiary threats. However, for fires in void spaces around fuel tanks (a most prevalent kill mechanism), the duration and/or ignition energy of activated incendiary projectiles can be from several times to orders of magnitude greater than the minimum necessary for igniting fuel spray. Distances between these flashes and the fuel tank walls can be on the order of inches or a few feet, whereas the initial fuel spray velocities are generally in the hundreds of feet per second. In such cases; the duration of the threat-related ignition source is not a highly sensitive variable in the computation of probability of sustained fire.

The critical factors in obtaining a destructive "sustained" fire are whether the incendiary threat can deposit its ignition energy in the right place for it to be encountered by the fuel spray liberated by tank wall/liquid fuel penetration, and the success of this transient "flash" fire in igniting the stream of leaking fuel as it develops. The application of a complex, time-dependent model tracing every physical step from threat impact to sustained fire or burnout would not be justified in the above circumstances, even if such a model existed. Such an application would be wasteful, considering that for a 26-view vulnerability analysis of a moderately sized and complex aircraft with wing and fuselage tankage, this ignition/fire model may have to be applied individually to 20,000 to 30,000 shotlines for each distinct type of threat being analyzed. The emphasis upon evaluation of a large number of shotlines is justified considering the often radical difference in the ignition potential of the same incendiary threat following separate paths from the outer skin of the aircraft to the fuel tanks. Thus, semi-empirical models are used in the Fuel Tank Vulnerability Program which include only those independent variables to which the final sustained fire probabilities have proven sensitive.

That is not to say that ignition source duration is not to be included in any ignition models incorporated in the vulnerability program. For example, the "effective" ignition source duration of an incandescent fragment traveling through flammable fuel tank ullage may be a critical parameter for that ignition case. This particular sub-model has not yet been selected. Selection is hampered by a lack of applicable test data.

The development of detailed, complex physical models of all the events related to ignition of fires by combat threats within aircraft would be very beneficial to the Fuel Tank Vulnerability Program, even though they could not all be integrated in the computer program. The complex models could be used to (1) develop simplified "approximate" relationships suitable for the vulnerability program, (2) produce a body of appropriate input data, and (3) provide a standard for comparison with the simpler models to calculate their accuracy.

(2) The ignition source duration parameter may be included in the fuel tank vulnerability program by substituting a model with this parameter for an existing "spatial" model. The modular nature of the computer program facilitates this replacement.

As envisioned, the incendiary source locations would still be defined along the shotline, based upon impact conditions. Their size and ignition potential would vary with time. The fuel spray travel as a function of time would also be simulated. The probability of flash-fire ignition would be directly related to the degree of co-mingling of the fuel spray and the igniting region of the flash. This simulation would be incomplete without the further evaluation of the probability of ignition of a sustained fire by this flash fire.

The development of such a model is hampered by a lack of full understanding of the phenomena involved, and dearth of test data.

Mr Woof:

(1) Could you advise how you integrate in your programme the fire raising characteristics of the numerous combat threats, i.e. API and H.E.I. rounds, secondary fire sources etc.?

(2) Have you considered modifying your programme to cover the effects of hydraulic fires etc.?

Mr Mahood:

(1) Three distinct methods are employed. The first applies to all "kinetic energy" penetrators, including API projectiles and fragments from warhead detonations somewhat removed from the aircraft. In this case, the ignition sources are located along each shotline for each type of penetrator and impacting conditions on the outer skin of the aircraft. The ignition source locations are based on the sequential analysis of the penetrator's impact with each

item along the shotline. (NOTE: This determination is made only for shotlines which include intersection with a fuel-containing component.)

Semi-empirical penetration and incendiary projectile activation or impact flash models are applied in each case, as appropriate. This penetration analysis proceeds to the location of flammable spray, liquid fuel, or vapor. The relative locations of the ignition sources and flammables, characteristics of the projectile functions or impact flashes, and number and spacing of intervening surfaces are determined and applied to another semi-empirical relationship to determine probability of sustained fire.

Certain types of incendiary functions vary significantly and unpredictably in their location under identical impact conditions. In such cases, the program randomly selects locations from within the extreme range of location values determined experimentally. The relatively large number of shotlines evaluated permits this technique.

The dynamics of the penetrator impact on the tank surface define the response of any self-sealing material, if present, and the rate of sustained leakage. For void space fires and "primary" ignitions, the rate and duration of sustained leakage determines the severity (e.g. "kill level") of the fire. The paper describes the ignition of flammable vapors in tank ullage.

For High-Explosive Incendiary (HEI) Projectiles, the Point Burst Ray Generator Program is being adapted. The detonation point is determined by present means, employing a fuzing model and consideration of the target materials impacted. From the detonation point, a blast zone is defined which gives specific blast damage/failure effects which vary with tank wall construction. The next zone outward approximates the near-simultaneous interaction of fragments relatively close together. As with the blast zone, the damage to the tank wall is based on the weights of selected classes of fragments typical for the given projectile, the number per unit tank area, their velocities, and the properties of the tank wall. The last zone is beyond the interacting fragments, where spacing between fragments has increased to the point that they may be considered as acting alone. Again, the program is defined so that test data may be incorporated in terms of projectile detonation, blast and fragmentation effects, and observed responses of the wall materials. The responses to massive leakage and fires that result are modeled similar to that for the kinetic energy projectiles.

The modeling of the secondary ignition hazard, given fuel tank leakage, is severely hampered by lack of data. Liquid and vaporized fuel paths are difficult to define, and subtle air-flows and pressure relationships between semi-closed compartments before and particularly after penetration by threat effects are poorly defined. Hence, the secondary fire hazard is characterized by the general ignition hazard of the compartments to which leakage is assumed to apply. The compartment ignition hazard is modified if components which constitute more severe ignition sources when damaged, such as electrical wiring bundles, are damaged by the same shotline which released fuel and provided a primary ignition source. The probability of secondary ignition is applied as an input for each compartment, along with interconnecting factors between compartments. Shotlines traversing that compartment and inducing fuel leakage are assigned a "secondary" fire kill value, based on amount and rate of fuel leakage and the probability of secondary ignition. The primary and secondary fire kill probabilities and/or vulnerable areas may be output distinctly or by some specified rule of combination.

(2) The present program was limited in scope to fuel tank system vulnerability simply to maintain the effort at a practical size. There is no reason why the same principles and similar models could not be applied to hydraulic fire analysis as well. Care must be taken, however, to keep the overall program size, complexity, and run time within reasonable bounds.

**Les MATERIAUX d'INTERIEUR CABINE
DANS les AVIONS de TRANSPORT CIVILS**

par

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Le transport aérien commercial est entré dans sa phase de réel développement au cours des années qui succédèrent au second conflit mondial. Les premiers avions de transport pour passagers étaient, pour la plupart, issus d'avions de transport militaires, développés principalement aux Etats-Unis. Leur propulsion était assurée par moteur à piston entraînant une hélice. Puis vinrent les avions à turbopropulseurs et enfin les premiers avions à réaction : COMET, CARAVELLE et BOEING 707.

La technologie des matériaux non métalliques prit son essor dans le même temps. Les matériaux plastiques offraient de toutes nouvelles possibilités et certaines de leurs qualités, telles que leur légèreté, étaient du plus grand intérêt. Un des premiers matériaux qui furent employés était le tissu enduit. La variété d'aspect qui pouvait en être obtenue permettait de l'utiliser pour décorer les parois de cabine et de le substituer au cuir pour le garnissage des fauteuils. La chimie offrit également des résines plastiques d'imprégnation dont une large gamme d'emploi donna naissance à de nouveaux produits. Avec ceux-ci furent conçus des panneaux composites d'une grande légèreté. L'imprégnation de papier collé et expansé permit de disposer de pains alvéolaires très légers appelés "nids d'abeilles" qui sont encore largement utilisés de nos jours. Ces matériaux servent à constituer l'âme de panneaux sandwichs que l'on revêtait alors, par collage, de contreplaqué de faible épaisseur. La décoration de ces panneaux sandwichs s'obtenait en appliquant des matériaux lamifiés ou des tissus enduits. Une autre formule de panneaux de parois consistait à réaliser des éléments emboutis, en feuilles d'alliage léger calandré avec un film plastique de décoration. Dans le domaine de l'éclairage, l'utilisation de matériau plastique transparent en lieu et place du verre permettait de réaliser un gain de masse notable. Les possibilités de transformation étaient relativement aisées. Rappelons que le marché potentiel de matériaux que présente l'Industrie Aéronautique est extrêmement faible, comparé à d'autres industries telles que l'automobile ou le bâtiment; les éléments fabriqués en nombre relativement modeste ne donnent guère l'occasion de développer un matériau d'usage spécifiquement Aéronautique. C'est ainsi que, grâce à l'industrie des plastiques, il devient possible de mener à bien des aménagements d'intérieurs d'avions, d'aspect assez luxueux, sans qu'il soit trop sacrifié à la perte de masse. Le souci de rentabilité d'un aéronef civil est en effet directement lié à l'importance de la charge marchande, autrement dit la masse disponible en cabine et en soute pour les passagers, leurs bagages et le fret.

Au temps des premières conceptions, les Règlements d'inflammabilité que devait respecter le constructeur étaient directement issus des méthodes d'essai en usage dans l'industrie des textiles ou de la Réglementation couvrant les locaux recevant du public. Le problème permanent auquel le constructeur d'avion est confronté est la surveillance de l'accroissement de masse. Il fallut donc considérer avec circonspection ce qui était appliqué aux autres industries, car la recondaction, in extenso, de leurs exigences, aurait à tout jamais barré la route aux possibilités d'utilisation sur avion. Soulignons que, en compensation, la haute fiabilité des systèmes d'un avion est garantie par des exigences draconiennes. La probabilité de défaillance est minime. Certes, la qualité des matériaux plastiques, au début, n'était pas comparable à celle atteinte aujourd'hui. Il fallut faire appel à des traitements par agents d'ignifugation, bain ou pulvérisation, afin d'obtenir une qualité de tenue au feu satisfaisante. Malheureusement ces procédés n'étaient pas systématiquement applicables à tous les produits. Le genre d'additifs dont on disposait jusqu'alors n'étaient pas d'une grande stabilité et, migrant dans le temps, n'assuraient pas une permanence de l'ignifugation. La tendance nouvelle est orientée sur la recherche d'ignifugeants spécifiques de grande stabilité qui font partie intégrante de la composition du matériau.

Ce n'est que récemment qu'il devint possible, par exemple, de disposer de matériaux transparents d'une qualité acceptable. Chaque fois qu'on le pouvait, on sélectionnait le produit le meilleur. On aboutissait ainsi à un compromis qui permettait d'atteindre le meilleur niveau possible de sécurité.

Toutefois, un compromis, dicté par les circonstances, ne s'avère jamais pleinement satisfaisant. Des recherches furent donc entamées pour trouver par quelles voies, de notables améliorations pourraient être obtenues. Des rencontres eurent lieu au niveau International. Une confrontation de l'expérience acquise se fit entre les grands Constructeurs d'avions, en collaboration avec les Autorités de Certification de divers Pays d'Europe et des Etats-Unis. Une comparaison fut faite entre les diverses méthodes d'essai au feu des matériaux. Ces méthodes étaient assez dissemblables quoique les résultats obtenus en fussent similaires, sinon comparables. Du fait de la nécessité de certifier des avions que l'on exportait, et compte tenu de l'origine diverse des matériaux, il apparut nécessaire d'établir une méthode d'essai unique afin que des résultats obtenus en des lieux différents soient répétitifs. Au fur et à mesure de l'avancement des conversations ayant pour but d'aboutir à l'établissement de ces méthodes internationales, la technologie de matériaux progressait. Il devenait ainsi possible de relever en même temps le niveau des exigences.

C'est alors que quelques accidents spectaculaires, et en particulier celui d'un avion de ligne américain, à Salt City, le 11 Novembre 1965, apportèrent des éléments nouveaux à la situation. L'étude des conséquences de cet accident révéla que de nombreux passagers avaient péri du fait de la présence de fumées opaques et de gaz toxiques dégagés par les matériaux non métalliques qui constituaient le garnissage de cabine. Cet événement stimula les recherches, et l'on chercha à évaluer quelle était l'influence de la fumée sur les conditions d'évacuation rapide d'un avion, et dans quelle mesure la toxicité des gaz des matériaux soumis à la chaleur ou à la flamme pouvait être dangereuse. Des essais se multiplièrent, tant à l'échelon de laboratoire qu'en vraie grandeur. Des incendies furent provoqués dans des cellules d'avions désaffectées, et leurs effets furent observés et analysés. Le National Aviation Facilities Experimental Center à Atlantic City, dans le New-Jersey, ainsi que plusieurs autres Centres Américains, effectuèrent de nombreuses expérimentations. En Europe, les années passées furent principalement consacrées à des tests de laboratoire, notamment au Laboratoire Central de la Société Aérospatiale, en collaboration très étroite avec le Bureau d'Etudes des Aménagements Commerciaux d'avions. Maintenant des essais en semi-grandeur sont conduits au Centre d'Essais Aéronautiques de Toulouse. Notre propos n'est point de nous étendre sur ce type de recherche que M. AUVINET dirige au C. E. A. T. et qu'il vous exposera avec davantage de compétence.

Différents résultats de laboratoire révélèrent des phénomènes liés aux caractéristiques des produits testés. Par exemple, dans beaucoup de cas, un matériau de bonne tenue au feu émet davantage de fumée qu'un matériau brûlant facilement. Une des raisons peut en être la présence des produits d'ignifugation.

Comme il fut fait pour les essais d'inflammabilité, les recherches relatives à l'émission de fumées sont conduites dans un esprit de large coopération, et une standardisation déjà avancée des matériels de mesure permet de penser à l'élaboration, également en ce domaine, d'une méthode d'essais commune.

Nous disposons donc actuellement d'une Réglementation concernant les essais d'inflammabilité. Celle-ci, adoptée par l'O. A. C. I., a été incorporée dans son Manuel de Navigabilité. Quoique ne faisant pas encore l'objet d'une Réglementation Officielle, une méthode commune de mesure est suivie pour évaluer le taux d'émission de fumée. Le troisième stade des recherches porte sur la toxicité des gaz dégagés par pyrolyse ou combustion. Là encore de nombreux essais et l'étude des conséquences directes découlant du feu à bord conduisent à estimer que l'un des principaux dangers d'intoxication est le dégagement d'oxyde de carbone. Le plus grand nombre de matériaux d'essence organique se prête en effet à l'émission de ce gaz qui s'assimile rapidement à l'hémoglobine du sang et tue un être humain en quelques minutes. La production de l'oxyde de carbone est favorisée à la fois par l'ignifugation qui, par définition, entrave la combustion complète du matériau, et par l'appauvrissement en oxygène dû au feu dans l'enceinte confinée de la cabine. A l'oxyde de carbone s'ajoutent d'autres gaz très toxiques, tels que le gaz cyanhydrique et les halogénés.

On voit que la prise en considération de tous ces paramètres ne rend pas la tâche facile, et que la solution idéale est encore loin d'être trouvée. Comme nous le disions plus haut, les recherches se poursuivent avec opiniâtreté, mais il faut malgré tout, pendant ce temps, mener à bien les constructions en cours. La méthode actuellement en vigueur consiste à vérifier en priorité la tenue au feu de chaque matériau, et à prohiber l'emploi de ceux qui ne remplissent pas les conditions de la norme. En second lieu, une comparaison est faite entre divers matériaux pouvant remplir les conditions d'emploi d'un cas déterminé : on effectue des mesures d'émission de fumée sur chacun des matériaux en compétition afin de sélectionner le meilleur. Notons enfin que les matériaux connus comme étant les plus toxiques sont écartés de l'utilisation. Disons franchement que des exigences rigoureuses ne peuvent pas toujours être suivies à la lettre par manque de disponibilité de produits meilleurs ou d'un coût par trop élevé. Ajoutons que, lorsqu'un matériau nouveau apparaît, il n'est pas possible de le substituer immédiatement, en cours de production, aux matériaux usuels. Cela conduirait à la perte de stocks importants de pièces primaires et de rechanges, à remplacer des outillages souvent très coûteux. L'amélioration ne peut principalement se faire qu'au travers de la conception d'éléments nouveaux. Lorsque les Autorités Aéronautiques des Etats-Unis rendirent plus sévères les conditions de réception des matériaux d'intérieur cabine, leur première intention était d'imposer une rétro-activité d'application sur les avions déjà construits ou en cours de production. Compte tenu de l'énorme dépense que cela aurait provoqué, ce projet fut abandonné. Cela est navrant, mais les Constructeurs et les Compagnies Aériennes n'auraient pas pu supporter des dépenses d'une telle ampleur.

L'apparition de matériaux nouveaux, au cours de ces dernières années, a aidé à la progression des études. Des recherches laborieuses ont été entreprises pour déterminer des procédés optima de mise en oeuvre et trouver l'application possible de ces matériaux, compte tenu des facilités inhérentes aux besoins. A quelques exceptions près, la quantité de pièces communes utilisées dans l'aménagement d'un avion ne permet que rarement de passer par des solutions faisant appel au moulage ou à l'extrusion. Le coût d'outillages de ces types de transformation est difficile à amortir. L'extrusion, quant à elle, impose l'utilisation de longueurs de profilés suffisantes pour que le prix de revient au mètre courant soit profitable. C'est donc plus vers le thermoformage de plaques, disponibles en stock, que s'oriente souvent le Bureau d'Etudes. Lorsqu'un matériau en plaque est choisi, il faut en étudier les possibilités d'assemblage : collage ou autres procédés, tels que soudure par haute fréquence. L'accrochage des peintures de décoration pose souvent des problèmes difficiles à résoudre. Lorsque le matériau est utilisé en raison de sa transparence, on doit aussi s'assurer de sa stabilité aux rayons ultra-violets et au vieillissement.

L'apparition des fibres nouvelles a permis de remplacer le papier constituant les nids d'abeilles et de les substituer graduellement aux classiques tissus de verre imprégnés de résine, avec lesquels on réalise

les revêtements des sandwiches. Les résines ont fait l'objet de nombreuses recherches comparatives. Traditionnellement époxydiques ou polyester, elles assuraient rarement à la fois la bonne tenue de l'assemblage aux critères d'inflammabilité, et une émission de fumée de niveau suffisamment bas. L'ingénieur s'est alors tourné vers de nouvelles résines plus élaborées. Le souci de maîtriser en cours de fabrication, avec une relative précision, la masse des pièces construites, l'a amené à utiliser des tissus préalablement imprégnés à la machine possédant un taux de résine relativement constant. Mais, comme pour obtenir des avantages il faut souvent sacrifier à des inconvénients, ces résines nouvelles exigent des précautions de stockage à basse température, des procédés de mise en oeuvre différents des résines usuelles. Une température de polymérisation plus élevée a provoqué une évolution du type d'outillage. Il est par ailleurs nécessaire d'obtenir un fini de surface très soigné sur le côté décoré des sandwiches. En effet, la légèreté recherchée pour les éléments d'habillage ne permet l'emploi que de revêtements décoratifs très légers se présentant sous forme de film imprégné et grainé. Celui-ci, appliqué par collage, ne possède pas une épaisseur suffisante pour masquer les irrégularités de surface. Outre une souplesse de fabrication permettant de varier le décor en fonction du choix des Compagnies clientes, le film doit, après pose, être insensible aux salissures et au dépôt de la nicotine. Sa face apparente doit être capable de recevoir un nouveau film en surépaisseur afin de satisfaire aux opérations de maintenance. Sur la face arrière, en contact avec le panneau support, le film doit être enduit d'un adhésif réactivable à chaud. Une faible adhérence à froid doit permettre l'accrochage en cours de mise en place, mais laisser la possibilité de déposer et de répéter l'opération si la mise en place a été mal exécutée. Ajoutons qu'une certaine formabilité est exigée pour ce film. Le collage du décor s'applique, dans certains cas, à des panneaux comportant des zones galbées, comme par exemple les panneaux entourant les hublots de cabine. Le film doit se prêter à la mise en forme sur des surfaces quelquefois non développables, sans que son aspect final en souffre. Le grainage ne doit pas être affecté dans ces zones, causant un préjudice au bon aspect de la pièce terminée.

Afin d'illustrer cette fastidieuse description, permettez nous de vous soumettre quelques vues diapositives. Ces images vous montreront quelques exemples de pièces types fabriquées pour des aménagements d'avions.

CONCLUSION

Notre but a été de vous faire voir la complexité de la tâche que nous devons assumer. L'antagonisme des exigences : auto-extinguibilité, faible émission de fumée, facilité de transformation, conduit à adopter une formule de compromis. Les nombreuses recherches conduites tant aux Etats-Unis qu'en Europe, ont montré que :

- les matériaux de bonne extingüibilité émettent généralement plus de fumée,
- les produits ignifugeants émettent souvent des produits toxiques,
- l'appauvrissement en oxygène et la qualité d'auto-extingüibilité des matériaux favorisent la production d'oxyde de carbone, principal danger d'intoxication.

La tâche n'est pas aisée, et la solution idéale ne nous paraît pas pouvoir être atteinte à court terme. Nous pensons que tous les efforts doivent principalement tendre à permettre de maîtriser rapidement un début accidentel d'incendie. Une possibilité de détection rapide, alliée à une résistance des matériaux à la flamme, doivent, avec l'aide de moyens d'intervention et de protection rapide et efficaces, permettre de gagner du terrain sur les risques encourus. Pour notre part nous poursuivons, avec foi et opiniâtreté, la recherche de matériaux nouveaux et plus sûrs. Son succès nous permettra d'élever le niveau de la Réglementation, en d'autres termes d'améliorer encore et plus loin la sécurité.

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FIRE DYNAMICS OF MODERN AIRCRAFT FROM A MATERIALS POINT OF VIEW

by

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SUMMARY

A general approach for selecting polymers to increase fire safety in aircraft is described. It will be shown that polymer flammability and thermal protection capability are related to the molecular structure of the polymer and its thermochemical properties. These criteria are used to develop advanced fire-resistant materials which can achieve increased survivability in both post-crash and in-flight fires. The degree of fire hardening of materials depends greatly on the available heat load and fire threat present. It will be shown that improvements in fire safety can be achieved by the use of polymers possessing certain basic thermochemical parameters such as high char yield.

1. INTRODUCTION

Enhancement of human survivability and reduction of aircraft vulnerability to accidental or ballistically initiated aircraft fires are the objectives of aerospace fire research, and related studies for the development of fire-resistant materials, components, and structures. Losses of life and aircraft have resulted from recent disasters representative of the principal kinds of fires encountered in aircraft operations: the in-flight fire, the ramp fire, and the post-crash fire. Analysis of these events has called attention to the potential threat to survivability produced by the combined effects of heat of combustion, smoke, and toxic gases that can be generated by most of the polymeric materials so commonly used in all modern aircraft construction. However, to improve aircraft fire safety replacement materials should be cost effective, comparably functional, and timely. For these reasons aircraft fire safety must be considered a complex systems problem that requires trade-offs between kinds of materials, design parameters, reduction of ignition sources, early fire detection, extinguishment, and fire isolation. Only a partial solution can be obtained from use of fire hardened materials and structures; this paper emphasizes this particular aspect of aircraft fire safety.

Although there are many laboratory test methods for evaluating the flammability of materials, they cannot, at present, be used to qualify materials for fire safety in a real fire environment. (ref. 1). The same assessment must also be made about the excellent basic studies on smoke and toxic gas production (ref. 2). There are no reliable analyses that relate material properties to survivability in aircraft fires. Only full-scale component testing gives meaningful answers to survivability assessments of specific systems. What is needed for long-term improvement is the definition of survivability criteria to guide the evolution of aircraft fire safety.

The objective of this paper is to present a methodology for assessing the effects of fire threats to aerospace vehicles by first considering an appropriate fire dynamics logic and to point out, with specific examples in the case of both military and domestic aircraft, reasonable opportunities to break the fire dynamics chain to increase the probability of survival by the application of new materials and structures. Criteria for developing new materials and test methods for materials selection will also be presented.

2. FIRE THREAT VERSUS FIRE HARDENING

A general approach for specifying fire survivability is shown in Fig. 1 in which the fire threat level is plotted as a function of the degree of fire hardening for aircraft structures. The size of the imposed ignition source and flashover time have been plotted as a fire threat criteria and for a given system such as a contemporary interior aircraft wall paneling. This fire threat is compared to the degree of fire hardening required in a full scale component test.

Figures 2 and 3 indicate the effect of ignition source size on flashover. The effect of a 1 kg and 2 kg hydrocarbon ignition source on a prototype, wide-body jet aircraft lavatory fitted with state-of-the-art lavatory wall paneling is shown. It can be seen that the larger ignition source produces catastrophic flashover in 2.3 minutes, whereas the smaller ignition source produces a fully contained fire which was observed to burn itself out in 10 minutes. It was observed that even the small ignition source caused the wall panel to produce considerable smoke and gas. In this study smoke and gas production was not considered in the fire hardening criteria.

The limit of the degree of fire hardening for the structure indicated in Figs. 2 and 3 can be designated in Fig. 1 as an allowable fire threat level produced by an ignition source between 1 kg and 2 kg. It is also indicated in Fig. 1 that by the application of the advanced materials technology that will be available by 1978 a four- to tenfold improvement can be achieved in the degree of fire hardening for this particular system. From this simplistic example it is evident that the specification of survivability in terms of the interaction of the thermal environment with the materials system, requires specific information about the interaction of anticipated fire threat levels with aircraft subsystems such as unattended modules, (lavatories, cargo bays, and galleys), interiors of passenger compartments, fuselage structure, engine bays, and fuels. In order to establish an allowable threat level as shown in Fig. 1 it remains to obtain an agreement among aircraft manufacturers, airline operators, and regulatory agencies, through appropriate risk assessment studies.

3. AIRCRAFT FIRE DYNAMICS LOGIC TREE

A general fire dynamics logic tree is shown in Fig. 4 which may be used to identify opportunities to improve aircraft fire safety. It is shown that fire safety depends on two principal functions: namely, prevention of ignition and management of the fire impact. Overall fire safety and survivability for both

military and civilian aircraft can be substantially improved by prevention of ignition. This is the major factor in considering the survivability and vulnerability of close support combat military aircraft. Survivability has been achieved in some instances by ignition suppression of the ballistic incendiary threat and by protection of the fuel system with low density foams and composites.

In the case of military aircraft, management of the fire impact after ignition has occurred has received less attention. Analysis of most fire scenarios in all aircraft fire disasters indicates that more than 95 percent of the fires could have been prevented by taking positive action to prevent ignition. The remaining fraction of aircraft fire disasters might have been controlled by adequate management of the fire impact. Since it is practically impossible to predict an accidental fire threat level accurately, both ignition and fire management must be considered together in fire hardening of aircraft components in order to address both threat mechanisms. For example, ballistic foams prevent ignition by controlling the energy heat source, and also control thermal energy transfer by virtue of their excellent insulation qualities. Certain foams can act through ablation mechanisms, by managing the fire, controlling the fire, and defending in place to manage the areas exposed. Low density foams, composites, unsupported films and coatings can be modified by including components which produce volatile species under the fire-impact to suppress fire and control combustion processes.

Energy sources can be isolated and energy transfer prevented by inorganic insulation, reradiation and dissipation by conduction. The total thermochemical energy of potential energy sources can be managed by the judicious selection of materials that are essentially noncombustible in the fire environment: for example, silica, silicates, magnesium oxides, and high char yield organic polymers, such as the aromatic heterocyclics, polyimides, polyquinoxalines. Design modifications of components and special structural configurations to control ventilation, to limit convection, and reduce radiant energy transfer are also important considerations in managing the fire impact. Although it is technically possible to fire-harden the structural and functional materials which are an integral part of the aircraft, at present there is little hope of eliminating the fuel contribution from sources in cargo bays and passenger carryon materials. The latter alone can amount to between 2500-5000 kg in a wide-body jet with a fuel load contribution of 4000-7000 Btu/kg. Unlike the aircraft fuel itself, which with the exception of the engine fire (in-flight) and post-crash fire is well managed, the passenger carryon materials and frequently the aircraft cargo, are not controlled. For these reasons the probable fire threats must be anticipated accurately, and the system must be designed and tested with a clear understanding of the fire impact if the fire is to be managed at all.

In examining the logic tree, it is clear that the first line of defense against any fire threat is fire suppression. This action generally involves the concerted functions of detection and extinguishment. In the occupied areas of the aircraft it is believed that the passengers and crew are the best detectors, and fire fighting procedures are adequate. But when the fire starts in inaccessible areas, for example, in the plenum volume or unattended modules such as lavatories, cargo bays, and galleys, this human response to fire control is of little value (as was the case in the Varig Boeing 707 disaster). The same concern applies to the external fuel fed fire associated with the post-crash case where survival depends on external fire fighting and assistance in egress. For these reasons, it appears that the largest short-term payoff for enhancing aircraft fire survivability is in the area of fire hardening of unattended, inaccessible aircraft modules to cope with the in-flight and ramp fire, and fuselage fire hardening to provide protection against the impact of the external fuel fire. The use of fire hardened, nonsmoking, nontoxic materials and structures offers an effective fire management tool.

Aerospace research and development have yielded a large number of high-strength low-density composites, fire-suppression and fire-resistant coatings, ablative foam insulation, and char-forming transparent polymers, in the form of unsupported free films and glazings for both space vehicles and military applications. Most of these new polymers, materials and derivative components are now limited in commercial volume, and for this reason are relatively high in cost. They all provide extremely high efficiency as ablative thermal protection materials; that is, they resist burn-through and minimize back-face temperature rise under both aerodynamic heating and fire impact. Unlike most nonmetallic contemporary aircraft materials, these newly developed polymer systems and component derivatives provide resistance to ignition, limited flame spread to prevent flashover, maximum thermal protection to isolate fires, prevent burn-through, and produce little or no toxic gas or smoke when exposed to a sustained ignition source. These new polymers and their component derivatives may be ideal candidates from a fire safety point of view in the development of fire barriers to replace conventional aircraft materials and in providing new kinds of construction materials to prevent ignition and manage fire impact.

4. FIRE-RESISTANT MATERIALS TECHNOLOGY BASE FOR AIRCRAFT APPLICATIONS

The technology base provided by NASA-Ames to design, fabricate, test, and select new polymeric materials for enhancing aircraft safety has evolved from two basic requirements for manned space vehicles: (1) char-forming polymers for materials for entry technology, and (2) ignition suppressing materials for protection of crew members from fires. Both of these technologies are unique in a thermochemical sense. The high-char yield polymers such as phenolics, imides and imidazoles, have provided a basis for applying the concepts of thermal protection for reentering spacecraft to aircraft fire containment and isolation (ref. 3). Thermally stable fluoro polymers, such as teflon and vinylidene fluoride derivatives, have provided materials especially suited to the prevention of ignition in aircraft fire accidents (ref. 4). Both of these definite polymer classes of aerospace materials require considerable modification and assessment to be applied in a cost effective manner to improve aircraft survivability. Both classes of materials are presently relatively expensive. A one-to-one replacement of contemporary materials with these advanced aerospace materials could result in a three- to tenfold increase in cost.

The char forming materials are generally cross-linked polycyclic aromatic polymers (ref. 5); this molecular structural constraint places limitations on processing and limits application to relatively stiff, high modular structures. The fluoro substituted polymers are limited to ignition suppression and may pose a serious toxic threat due to the toxicity of the pyrolytic gases produced from a sustained ignition source. This result is generalized in Fig. 5. The flammability, including ignition resistance and flame spread are compared to the estimated toxic threat. It can be seen that the conventional use of effective fire suppressant additives and the fluoro substitution of polymers to achieve reduction in flammability may increase

both the toxic and smoke threat; whereas the char-forming polymer can reduce flammability and at the same time reduce toxicity and smoke production. There are opportunities to apply both of these new classes of advanced state-of-the-art materials to aerospace vehicles with appropriate systems constraints and safeguards.

5. HEAT REJECTION MECHANISMS OF CHAR-FORMING POLYMERS

Figure 6 represents the principal heat rejection mechanisms characteristic of char-forming ablative polymers. These involve the response of a low density foam or composite to an externally applied heating environment. The figure shows the extent of char formation produced by one dimensional heat transfer to the surface at a heating rate q , applied for a fixed length of time. When the heat is applied convectively, it is blocked in part by aerodynamic blowing in the boundary layer by diffusive coupling of the pyrolytic gases formed from the decomposition of the constituent polymers (which also produces residual char). The amount of char formed under steady state conditions is bounded by a surface temperature, T_s , and a decomposition temperature of the char-forming polymer. Heat is rejected at the surface by radiation, which for a black char with an emissivity approaching unity, is at a rate proportional to the fourth power of the temperature.

In the fire environment where there is a large radiative component of the heat load, the thermal reradiation from the hot char surface is one of two principal modes of heat rejection. The other principal mode depends on low thermal conductivity of the virgin substrate to provide heat blockage in the mass and energy balance relationship of this process. Additional heat is absorbed by the pyrolytic gases as they are heated from the decomposition temperature to the wall temperature as the gases pass through the char layer. It is the objective of this ablative application of char forming material to maintain as low a back-face temperature as possible for the largest period of time under an impacting heat load with a minimum weight of ablative material per square foot of protective surface. For heat loads that are mainly radiative—those encountered in most fuel fire environments—it was found empirically that low-density organic foam insulation with a density of 40-60 kg/m³, provided optimum fire thermal protection from fuel fires when the constituent polymer exhibited 30-50 percent char yield in an anaerobic environment as measured by thermogravimetry.

6. THERMODYNAMIC ANALYSIS OF ONE DIMENSIONAL CHAR-FORMING PYROLYSIS

This correlation with thermal performance was further examined analytically as shown in Fig. 7. The net heat rate applied to the surface results, at steady state, in an equilibrium surface temperature T_s , and a constant vapor production rate q_{va} . This vapor production rate results from the pyrolysis of the amount of polymer bounded by T_s and T_p , the pyrolytic temperature required to form a stable char from the virgin polymer. The amount of char formed, Y_c , that is, the polymer converted to stable char, is proportional to the linear rate of char production \dot{Y}_c acting through time t , as given by:

$$Y_c :: \int_0^t \dot{Y}_c dt :: \int_0^t \dot{q}_{app} dt \quad (1)$$

which is also proportional to the applied heating rate acting for the same time, t , as given by:

$$\dot{Y}_c :: \frac{1}{q_{va}} \quad (2)$$

In this linear mass and energy transfer process the linear rate of char production is evenly proportional to the rate of vapor production. It follows that the rate of vapor production q_{va} is evenly proportional to the amount of char produced in the interval, t , as given by:

$$\therefore Y_c :: \frac{1}{q_{va}} | t \quad (3)$$

It has been found that the char yield, Y_c , obtained from the anaerobic pyrolysis in a simple thermogravimetric analysis of a char-forming polymer is identical with the carbonaceous debris layer obtained by the one dimensional pyrolysis in both the fire and other radiation environment. It has been shown (ref. 5), that in the absence of significant char removal from the surface by oxidation, spalling, or carbon sublimation processes do not occur in the fuel fire environment. This correlation is true for all char-forming polymers and is independent of the heating rate over a range of three orders of magnitude in a radiation-only environment.

The char yield obtained anaerobically is a definite reproducible thermochemical property which can be obtained simply by thermogravimetric analysis carried out at modest heating rates to 800°C in pure nitrogen. A typical thermogram for an isocyanurate foam plastic is shown in Fig. 8. It can be easily estimated at 800°C and for the polymer amounts to about 45 percent. It can be seen that this polymer begins to decompose at approximately 200°C, and has essentially completed its decomposition by the time a temperature of 700°C has been reached.

In order to evaluate this char yield of char-forming ablative polymers as a correlation parameter for both flammability properties and their efficiency as thermal protection systems for fire containment, a number of different polymers were obtained in foam form with densities in the range of 30-60 kg/m³ and char yields in the range of 20-80 percent. These were evaluated by standard tests methods, by measuring ignition, smoke obscuration and flame spread. The relative toxicity of the pyrolytic gases was assessed by using an in situ enzyme preparation (ref. 6). The thermal efficiencies were determined in a T-3 burner (ref. 7). Costs were estimated as of 1973 and are based on published monomer costs processes. The results are plotted in Fig. 9.

It can be seen that all the flammability properties decrease monotonically, and almost linearly with increasing char yield or with decreasing vapor production rate at the wall (Eq. 3). The thermal protection efficiency appears to go through a maximum 40-45 percent char yield. This may be explained by the contribution of the enthalpic contribution of the transpiring gases which would be expected to decrease with a decreasing rate of vapor production at higher values of the char yield. Due to the difficulty in processing

and unavailability of monomers for systems with high char yield values (>65 percent), the costs presently become very unfavorable.

It can be seen from the results indicated in Fig. 9, that the best combination of properties and costs for selecting char-forming polymers for the development of aircraft material systems lies in a range between 40 and 60 percent. It should be noted that the use of the char yield index as a selection criterion for materials also sets the limits on the values of the flammability tests to be expected. These values have yet to be correlated with full-scale component test data, a final requirement for completing general materials selection criteria. It also should be pointed out that unlike the high temperature fluoro substituted polymers, which have limited applications as thin coatings on fire sensitive substrates, the char-forming polymers exhibit both ignition suppression and hardening with regard to fire penetration and are intended to be applied as primary structures rather than thin overlays for flammable substructures.

7. PREDICTION OF THE CHAR YIELDS OF POLYMERS FROM MOLECULAR STRUCTURE

Each macromolecule has a unique pyrolysis mechanism. For high-temperature stable, char-forming polymers, however, it is possible to predict these characteristic thermochemical parameters stoichiometrically, from the polymers' known molecular structure, with sufficient exactness to be extremely useful in selecting polymers for development as fire-resistant materials. The thermochemical processes characteristic of the anaerobic pyrolysis of a number of char-forming polymers is shown in Fig. 10. It is sufficient to point out that for the most part it is the aromatic rings—which are either inherently multiply bonded or become so during the early stages of the thermoanalysis process—which ultimately donate their carbon atoms to the final stable char. The dominant mechanistic features of these processes are the existence of very stable aromatic - carbon levels which are sufficiently stable to persist during the elimination of substituent hydrogen atoms, followed by ring coalescence, to yield, polycondensed ring systems with graphite-like structures. This general reaction mechanism makes it possible to correlate the primary thermochemical char yield with the molecular structures of polycyclic aromatic polymers as shown in Fig. 11. The experimentally determined anaerobic char yield is plotted as a function of the calculated number of multiple bonded aromatic ring equivalents initially present in the polymer. It can be seen that this relationship is surprisingly linear over a wide range of useful polymer types. Consequently, in accordance to Figs. 9 and 10, it is possible having a knowledge of molecular structure of polymers to predict the flammability and thermal protection properties of polymers. In general the epoxy resin systems and polyurethanes do not meet the flammability selection criteria established above. The isocyanurates at 40 percent or more char-yield give the best combination of fire isolation properties and flammability characteristics. Polymers like the phenolic, polybenzimidazoles and polyphenylene are extremely hard to the impact of fuel fire ignition although they are less efficient as thermal ablaters.

8. APPLICATION OF POLYCYCLIC AROMATIC POLYMERS AS BASIC MATERIALS FOR AIRCRAFT FIRE PROTECTION

Applying the aforementioned selection criteria, a semirigid closed-cell polyisocyanurate foam at a density of 30-60 kg/m³ was selected for evaluation for fuselage protection in a large scale test using the airframe of a C-47 (ref. 3). This foam was applied internally against the skin of the aircraft. The aircraft fuselage was divided into two sections. One section was protected with the foam and the other section was of standard aircraft construction. The entire fuselage was subjected to a fire environment produced from 18,500 lit. of JP-4 fuel. Figure 12 depicts the result at the end of the test after approximately 13 minutes showing the fuselage section protected by the isocyanurate foam, charred but still intact, while the unprotected section has melted and flowed out on the ground. Also included in Fig. 12, is a plot of the cabin interior temperatures for both the unprotected and protected section. It can be seen that the interior temperature for the unprotected section is in the order of 250°C in less than 2 minutes and has gone off scale in 3 minutes. The interior cabin air temperature of the protected section shows little or no change for up to 6 minutes, with little smoke or gas evolved in the interior. This protection may permit time to put the fire out. It can be seen that as the fire burns itself out, the cabin interior temperature is still at a survivable level. Complete details and results of this test are given in reference 3.

It can be concluded from these results that it is possible to make a reasonable prediction of the performance of aircraft fire performance from laboratory test methods and extrapolate these to full-scale test conditions in the case of providing fuselage thermal protection from the action of a fuel fire in a simulated post-crash scenario.

It is evident from this test result that the materials selection criteria based on correlation of laboratory thermal protection efficiency data with predictable basic thermochemical parameters can be reasonably extrapolated to full-scale tests. It remains to be demonstrated that similar agreement can be achieved in the case of flammability tests related to aircraft fire safety.

9. APPLICATION OF HIGH CHAR-YIELD POLYMERS FOR THE DESIGN AND CONSTRUCTION OF AIRCRAFT MODULES

To determine the relationship between laboratory flammability tests—and the capacity of char-yield materials selection criteria for predicting the performance of aircraft interior materials including ignition, flame spread, smoke, and toxic threats to full-scale components testing—the opportunity of increasing the level of fire hardening of unattended aircraft modules such as lavatories, cargo bays, and galleys has been considered. In these cases two dominant failure modes, flashover and degree of fire containment or fire endurance, have been considered and wall panels have been selected for fire hardening. The construction details of these load-bearing, lightweight wall panel construction comprising state-of-the-art and advanced materials is shown in Fig. 13. The state-of-the-art panels were evaluated against two fire threat levels as shown in Figs. 2 and 3. In these tests, it was established that flashover occurred with this wall paneling in 2.3 minutes and apparent burn through in about 5 minutes from a 2 kg hydrocarbon fuel source placed against the base of the wall panel.

Each of the polymeric materials comprising the state-of-the-art composite were evaluated by both conventional flame spread, limiting oxygen index and smoke generation. With the exception of the phenolic impregnated polyimide paper honeycomb, none of these polymeric components met the flammability criteria established for char-forming polymers with thermochemical char yields of more than 40 percent. The

thermochemical char yield of all of the polymer components, with the exception of the high char yield honeycomb, were found to be less than 25 percent.

A group of advanced polymeric materials was selected to increase the degree of fire hardening of the total composite panel on the basis of thermochemical parameters and the fire test criteria established above. All of the candidate replacements gave thermogravimetric char yields in excess of 40 percent. The transparent polyvinyl fluoride film, which gave a char yield of 10 percent and a corresponding limiting oxygen index of 20, was replaced by a phenophtalein polycarbonate transparent free film (ref. 8) with a char yield of 40 percent and limiting oxygen index of 38. The highly flammable acrylate adhesive was replaced with a fire retardant chlorendic anhydride epoxy adhesive. The low char yield laminated epoxy resin was replaced with a high char yield bismaleimide resin with a char yield of 50 percent and a limiting oxygen index of 50. The honeycomb structure which met the flammability criteria was further hardened to heat penetration by filling the honeycomb cells with a high char yield, low density (20 kg/m^3) polyquinoxaline foam formed from the in situ polymerization of p-nitroaniline bisulfate (ref. 10).

Table I indicates the properties of this new prototype aircraft interior structural panel fabricated from advanced materials selected for evaluation by the thermochemical criteria set forth in this paper. Panel properties are compared with the properties of contemporary panels found on most domestic transport aircraft. It is shown that at equivalent density the fire containment or fire endurance capability of this panel has been improved by a factor of five. This improvement is believed to be due to the thermal protection efficiency of the high char yield foam filling the honeycomb structure. It may also be seen in Table I that these panel modifications have resulted in a great reduction in the specific optical smoke density. Examination of the smoke density values for the constituent components of these composites clearly shows that the principal contributor to smoke is the epoxy resin laminating resin in the contemporary panel. This is predictable from the materials selection criteria set forth above. Replacing the epoxy with the high char yield bismaleimide resin effectively reduces the total smoke evolved to the low value of 16. It is interesting to note that with the two composites the specific optical density is also an additive property of the individual component values.

Figure 14 compares the fire endurance or containment capability of the advanced aircraft interior panel B which is compared with the state-of-the-art panel A under the conditions of the T-3 test (ref. 7). In this figure, the backface temperature rise is plotted as a function of the time in minutes under the impact of front face heat flux of $11 \times 10^4 \text{ W/m}^2$ which is a reasonable simulation of a full-scale fuel fire. It can be seen that the backface temperature of the conventional composite reaches an arbitrarily chosen survival temperature of 200°C in 2 minutes whereas it takes as long as 9 minutes to reach a comparable backface temperature with the advanced material B. By extrapolating the results obtained from the T-3 test facility to a full-scale fuselage burn-through test it is to be expected that similar fire containment capability can be expected in full-scale component testing of interior panels fabricated from these high char yield polymer systems.

The assessment of the full-scale component flammability, including time to flashover, toxic threat assessment, and ignition characteristics from high energy ignition source, must wait full-scale component testing of these new panels in aircraft structural configuration.

10. CONCLUSIONS

It has been shown that it is possible to predict the values of laboratory flammability tests and the thermal protection capability of char-forming polymeric materials from basic thermochemical parameters. Two examples—fuselage hardening and fire hardening of interior aircraft modules—have been presented in which materials selection and design employed these materials selection criteria. In the case of fire isolation and containment these examples demonstrate the effectiveness of this methodology in improving fire safety in aircraft fires. Further full-scale component testing is required to apply this methodology to flashover and toxic threat predictions based on laboratory test methods now available.

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Table I. Comparison of Thermophysical properties of aircraft interior panels.

<p>• COMPOSITE PROPERTIES</p> <p>DENSITY (ASTM D 71)</p> <p>FLATWIDE TENSILE STRENGTH (ASTM C207), 24 C</p> <p>FIRE ENDURANCE, BASF AMES T-3 THERMAL TEST FACILITY, TIME (min) TO REACH BACKFACE TEMPERATURE OF 37°C. FRONT FACE HEAT FLUX $11 \times 10^4 \text{ W/m}^2$</p> <p>SMOKE DENSITY (MSD, 10g 4 second) SPECIFIC OPTICAL DENSITY</p> <p>FAR 25.83 (VERTICAL TEST METHOD STANDARD 191, METHOD 2002)</p>	<p>PVF, EPOXY GLASS, POLYAMIDE HONEYCOMB, EPOXY GLASS</p> <p>99 kg/m³</p> <p>8.82 GPa</p> <p>2</p> <p>87</p> <p>PAGES</p>	<p>PHENOL POLYCARBONATE, BISPHENOL A GLASS, POLYAMIDE HONEYCOMB FILLED WITH POLYBIPHENOLIC FOAM, BISPHENOL A GLASS</p> <p>99 kg/m³</p> <p>-</p> <p>18</p> <p>16</p> <p>PAGES</p>
<p>• COMPONENT SMOKE DENSITY</p> <p>MAXIMUM SPECIFIC OPTICAL DENSITY (MSD SMOKE CHAMBER)</p>	<p>POLYVINYL FLUORIDE 7</p> <p>POLYAMIDE 2</p> <p>EPOXY RESIN 99</p> <p>GLASS -</p>	<p>PHENOL POLYCARBONATE 5</p> <p>POLYAMIDE 2</p> <p>BISPHENOL A RESIN 9</p> <p>-</p>
<p>• COMPOSITE MATERIAL BALANCE</p> <p>% BY WEIGHT</p>	<p>POLYVINYL FLUORIDE 7.8</p> <p>POLYAMIDE 20.5</p> <p>191,120 GLASS 41.9</p> <p>EPOXY RESIN 30.8</p>	<p>PHENOL POLYCARBONATE 5.0</p> <p>POLYAMIDE 20.5</p> <p>191 GLASS 38.0</p> <p>BISPHENOL A RESIN 35.0</p> <p>POLYBIPHENOLIC 14.5</p>

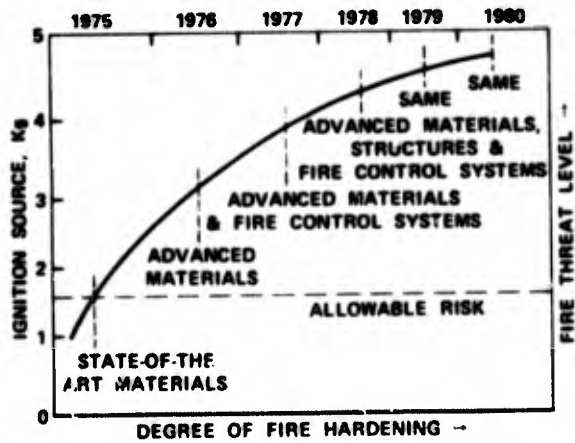


Fig. 1 Comparison of fire threat level and fire hardening.

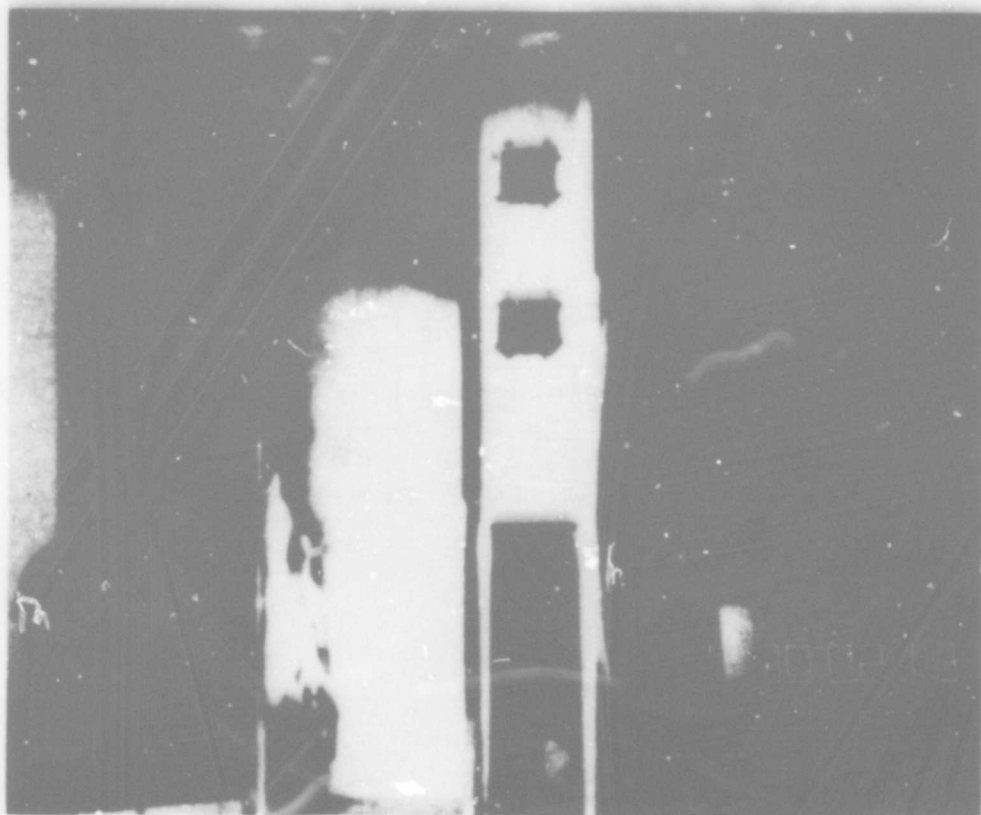


Fig. 2 Fire resulting from 1 kg ignition source.

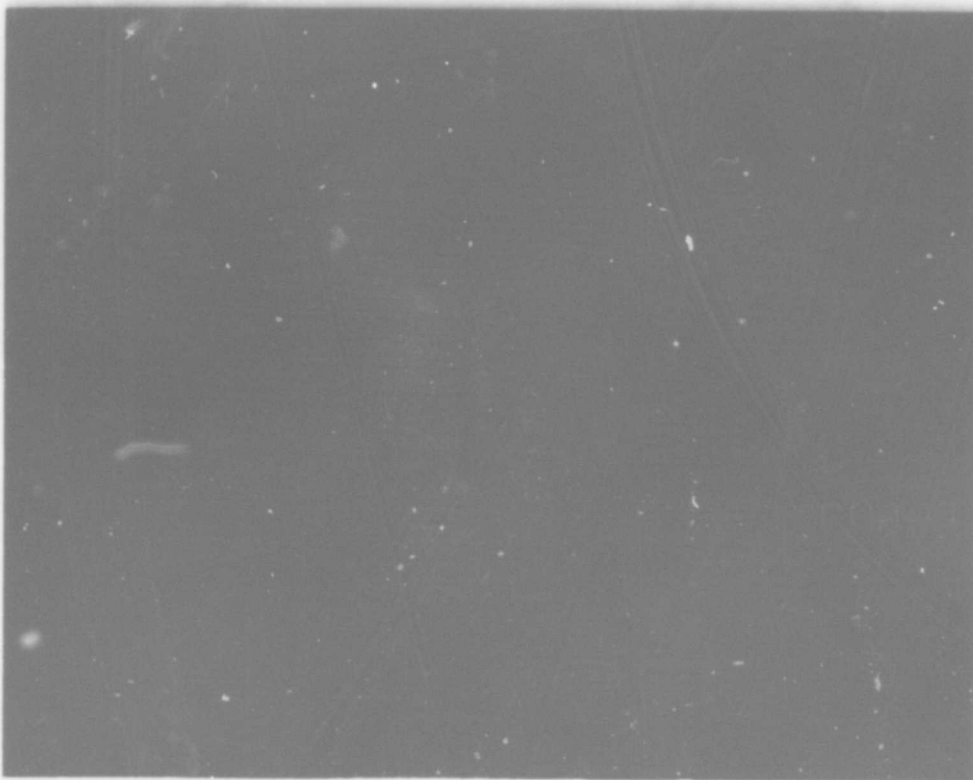


Fig. 3 Fire resulting from 2 kg ignition source.

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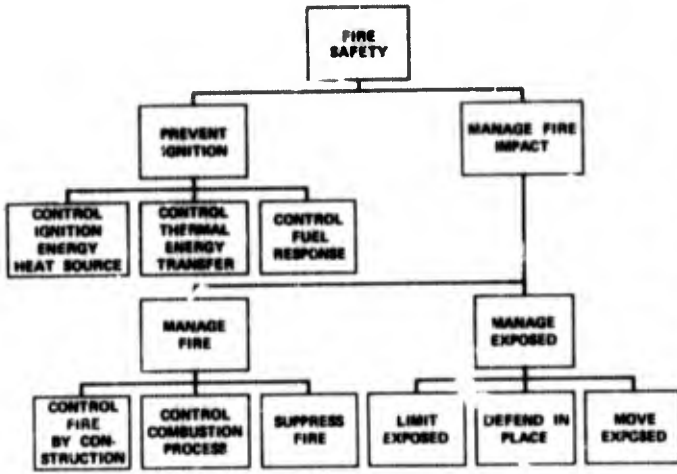


Fig. 4 Fire dynamics logic tree.

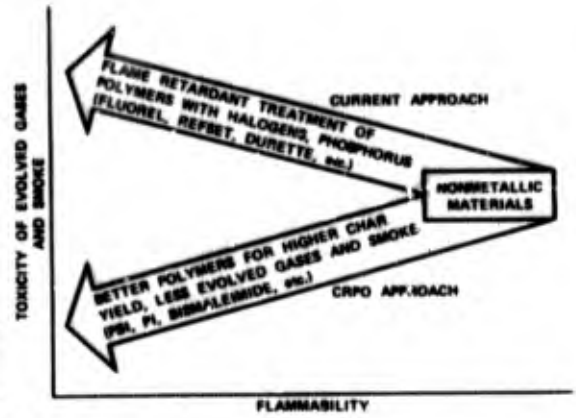


Fig. 5 Contrasting methods of reducing flammability of nonmetallic materials.

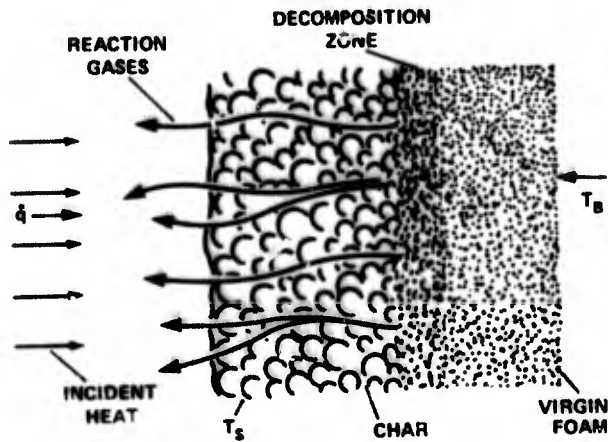


Fig. 6 Typical reaction of char-forming foams due to thermal loads.

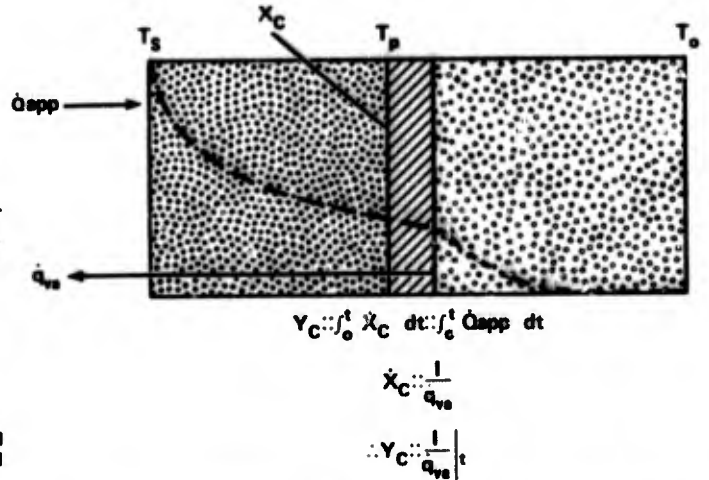


Fig. 7 Thermodynamic analysis of one-dimensional char-forming pyrolysis.

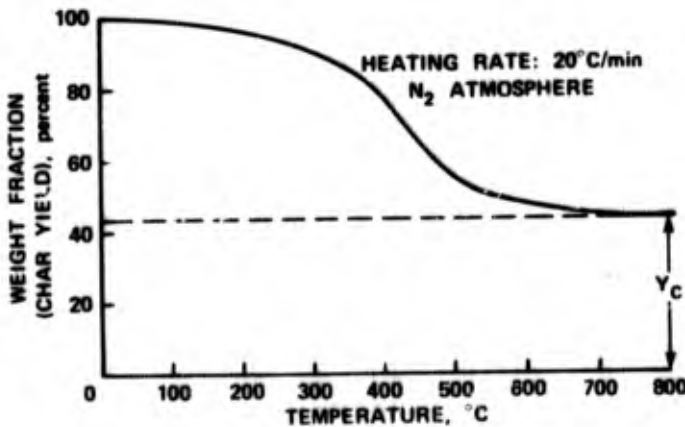


Fig. 8 Dynamic thermogram for polyisocyanurate foam.

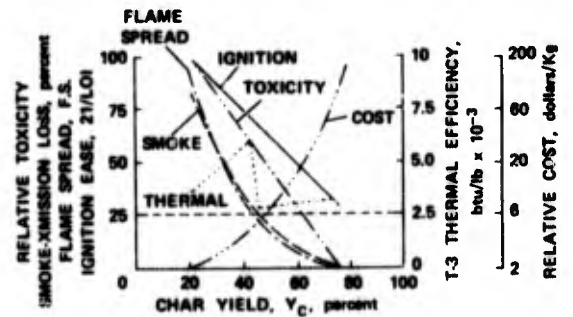


Fig. 9 Summary of properties of char-forming foamed polymers.

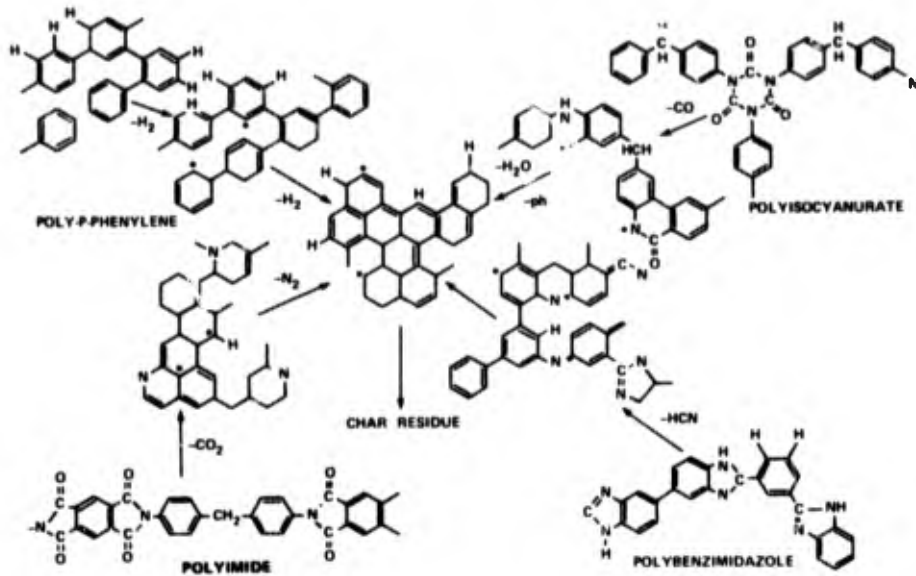


Fig. 10 Thermal degradation of high temperature polymers.

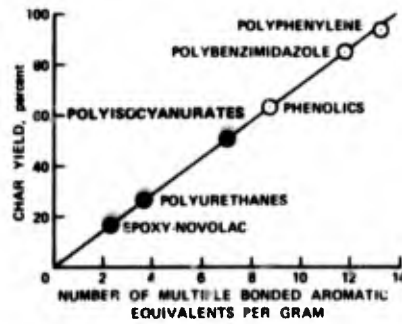


Fig. 11 Correlation of primary thermochemical char yield with molecular structure.

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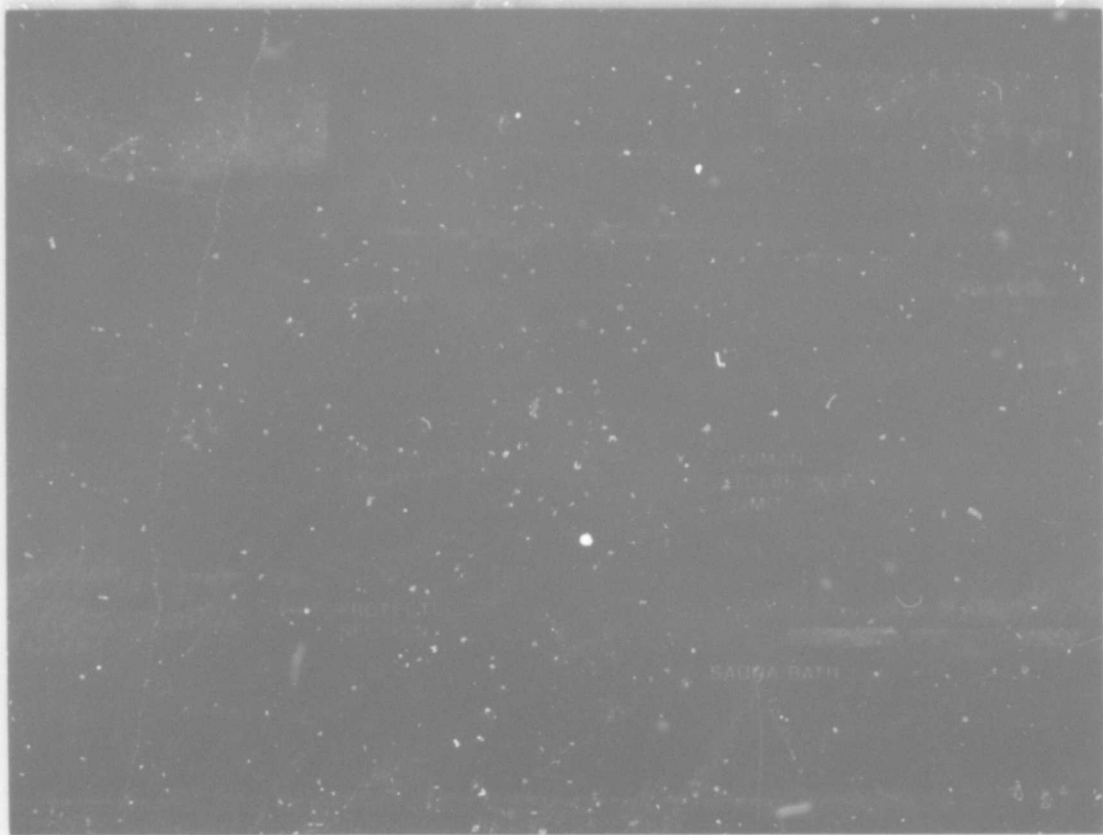


Fig. 12 Thermal history of C-47 aircraft test.

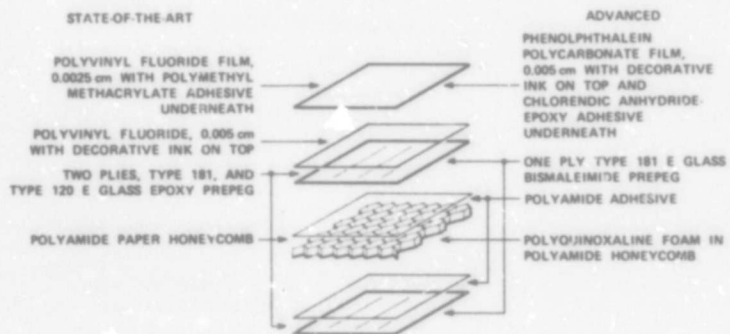


Fig. 13 Composite configuration of aircraft interior panels.

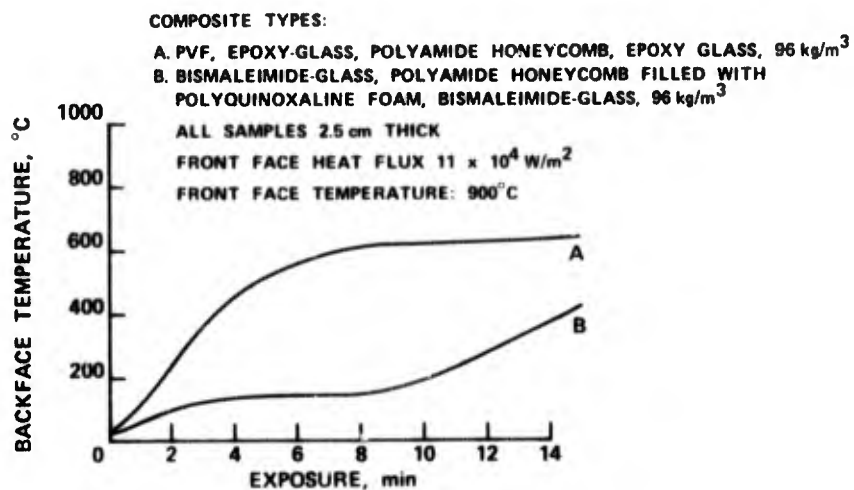


Fig. 14 Comparison of fire containment capability of aircraft interior panels.

CRITICAL EVALUATION OF TODAY'S FIREPROOF TESTING OF AEROSPACE MATERIALS

by

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SUMMARY

In the past years an international standardization effort became active to find an agreement on rules giving the answer to the question: "To which requirements the aerospace industry shall comply with respect to Fire Safety inside an aerospace vehicle?" Many aerospace industrial countries contributed with proposals and test results from their industries and governments to answer this question in an absolute way. The laws, specifications and rules issued by the Federal Aviation Administration (FAA) of the USA were taken as a basis for further discussions, and finally after various modifications the present FAR 25-853, 25-855 and 25-1191 with Appendix F were internationally accepted. After 4 years of practical experience with the application of these chapters of the FAR, a critical evaluation will be presented. The usefulness of the requirements and methods of tests for the judgement of materials or materials combinations in applications, will be specifically discussed here. It will be shown that the application, test requirements, and test methods criteria for materials, sometimes provide questionable fire safety.

PREFACE

This contribution of the conference is not intended to upset anyone or to set a fire under the existing well intentioned safety rules.

1. INTRODUCTION

Based on test results evaluated in various industrial and governmental laboratories, many aerospace countries proposed test methods to determine flammability properties of materials. Many of these tests had to serve for demonstrating fire safety of materials. The outcome should be decisive upon use in an aircraft compartment. Proposed new laws, specifications and rules based on these new methods of tests were issued by the Federal Aviation Administration (FAA) of the USA for discussion and study. Finally after various modification the present FAR 25-853, 25-855 and 25-1191 with Appendix F were internationally accepted. All methods of tests and their criteria will be presented and briefly explained in the following. Combining these test methods with the FAR requirements for the judgement of application of materials or material combination in an aircraft cabin, will be specifically discussed.

2. METHODS OF TESTS

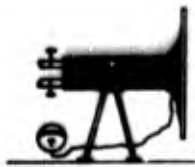
There are four different test methods covered by the FAR. These methods will be shown schematically, to indicate their significance and particulars.

2.1 Fire Proof Test

This test has to be carried out, if structural integrity with no flame penetration has to be demonstrated. The surface dimensions of the test specimen must be 250 x 250 mm regardless of the thickness, if a sheet type construction is to be considered. The flame temperature should be 1095°C nominal, having a contact area of 125 x 125 mm to the surface of the test specimen, and applied during 15 minutes. The total number of test specimens is just 1.

FRENCH TEST

F.A.R. 25 1101



SPECIMEN CONFIGURATION: 250 x 250 mm
NUMBER: 1
FLAME TEMP.: 1095 ± 25 °C
AREA CONTACTS THE FLAME: 128 x 125 mm
TIME: 15 MIN

REQUIREMENT: NO PENETRATION ON THE BACKSIDE OF THE SPECIMEN DURING APPLICATION OF THE TEST FLAME

Figure 1

2.2 Fire Resistance Test

This is the well known "45 inclined test", which has to be applied, if there is no penetration, maximum after burning time and glowing time have to be demonstrated. This method is only applicable to sheet type specimens having a surface area of 200 x 200 mm regardless of the thickness. The flame temperature should be 843°C minimum and applied during 30 seconds to the geometrical center of the specimen. The total number of test specimens is 3.

FOURTY-FIVE DEGREE TEST

FAR 25.855 - appendix F



SPECIMEN CONFIGURATION: 200 x 200 mm
NUMBER: 3
BURNER: BUNSEN BURNER WITH AIR
FLAME TEMP.: 843 °C
HEIGHT OF FLAME: 38,1 mm
IGNITION TIME: 30 SEC.

REQUIREMENTS: NO PENETRATION.
 FLAME TIME: MAX 15 SEC AFTER IGNITION
 GLOWING : MAX 10 SEC AFTER FLAME TIME

Figure 2

2.3 Vertical Test

A test specimen suspended vertically over a test flame shall not continue burning or char over either a distance of 200 mm after having been ignited during 12 seconds, or a distance of 150 mm after having been ignited during 60 seconds. When which is required depends on the place of usage in the cabin of the aircraft. This method is intended to be carried out on sheet type specimens with a surface area of 115 x 315 mm, regardless of the thickness. In some cases a maximum thickness is specified such as for foam materials. The flame temperature should be again 843°C minimum.

The total number of test specimens is set for 3 in both cases of ignition time. The code for reference to this method is V12 or V60.

VERTICAL TEST

FAR 25 1053 - appendix F



SPECIMEN CONFIGURATION: 115 x 315 mm
NUMBER: 3
BURNER: BUNSEN BURNER WITH AIR
FLAME TEMP.: 843 °C
HEIGHT OF FLAME: 38,1 mm
IGNITION TIME: 60 SEC or 12 SEC

REQUIREMENTS:
 AVERAGE CHAR LENGTH ≤ 152,4 mm (V60)
 ≤ 203,2 mm (V12)
 FLAME TIME 15 SEC (average)
 FLAME TIME OF DRIPPINGS 3 SEC (V60)
 5 SEC (V12)

Figure 3

2.4 Horizontal Test

A test specimen suspended horizontally with one of its shortest sides over a test flame shall not burn faster than 63 mm per minute or 100 mm per minute after having been ignited during 15 seconds. Again, when which requirement shall be fulfilled depends on the place of usage in the cabin of the aircraft. The dimensions, flame temperature, number of test specimens, etc. are exactly equal to those required for the earlier shown Vertical test. The reference code for the Horizontal test is H1 and H2.

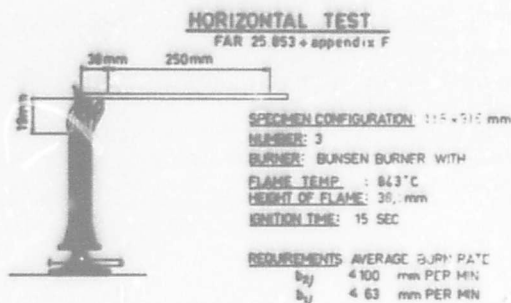


Figure 4

3. CRITICISM

What do the existing rules imply strictly? Do they have fire prevention in view, or do they prevent the use of materials which will not deteriorate nor contribute to an existing fire, or when there is by any reason a fire do they prevent a safe passage, or any reasonable survival for the occupants. As an alternative the rules may include all these suggested implications, which is hardly believable. On the contrary it is believed that these rules are specified ignoring, however, the essence of the theme. Just one example will illustrate the seriousness of the utterance:

- Panels, whether they are applied as doors, partitions, sidewalls, hat rack furnishings, etc. all around edged with a metal section, shall meet the vertical flame test requirement. Does this represent what could happen in practice; it is believed not to be so. A "45 inclination test" and/or a modification of Fire Proof Test should be more appropriate.

Now leaving this possibly headache causing subject and turning to the methods of test themselves.

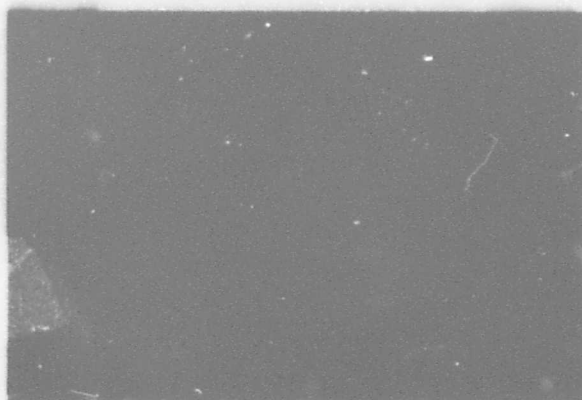


Fig.5 Partition panel all around edged with an Aluminium section; shall meet the vertical test requirement V60. A 45 test as a modified Fire Proof should be more appropriate.

3.1 Conditioning Prior to Testing

Quoting from Appendix F “. . . . until moisture equilibrium is reached or for 24 hours. Only one specimen at a time may be removed from the conditioning environment immediately before subjecting to the flame”, unquote. There are at least two impossibilities required to be fulfilled:

- Materials who never will reach moisture equilibrium in an acceptable time-span can not be tested as given in the clause, but when only conditioned for 24 hours as an alternative, differences in test results are to be faced between various batches of these materials.
- When routine testing has to be carried out, on various materials and materials batches following the 24 hours conditioning clause, quite often it will happen that the last set of test specimens to be tested will differ in conditioning time from the first set of test specimens by more than 6 hours.

The requirements given in Appendix F of FAR 25 concerning conditioning, are in various cases impossible to follow or hardly to be executed, without making mistakes. It is strongly recommended to change the existing requirements into those which are indeed feasible.

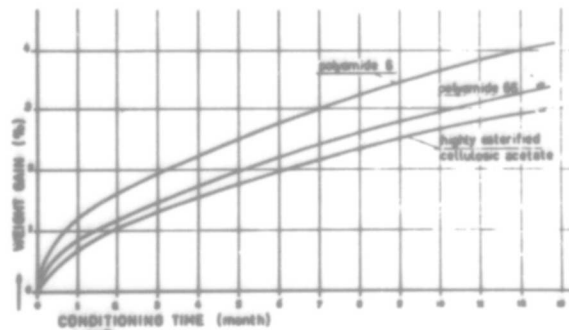


Fig.6 Conditioning time for various materials to reach moisture equilibrium.

3.2 Specimen Thickness

The conditions given in Appendix F of FAR 25 to carry out tests to show any compliance specifies the following "The specimen thickness must be no thicker than the minimum thickness to be qualified for use in the airplane", unquote. Two examples will show relativity and danger of this requirement.

- A sandwich panel of 3,25 mm thickness made from non-metallic (so-called Nomex) core faced with glass fabric phenolic resin impregnated, the core filled with a light weight filler, passes all required tests. Since in practice no thinner honeycomb core than 3 mm is used, this configuration should be considered to be the minimum thickness which will be applied in the airplane: given by the rules any other thickness more than 3 mm has been qualified as well. But the same material configuration tested with a total height of 10 mm, the previous quoted rules are put in the wrong.
- A 0.5 mm thick solid sheet material consisting of 85 percent by weight of cross plied unidirectional glass fibre/epoxy resin fulfils the 12 second and 60 second vertical test as well as both horizontal requirements. But the same material tested in a thickness of 1.5 mm does not fulfil any of these tests; again the rule is put in the wrong.

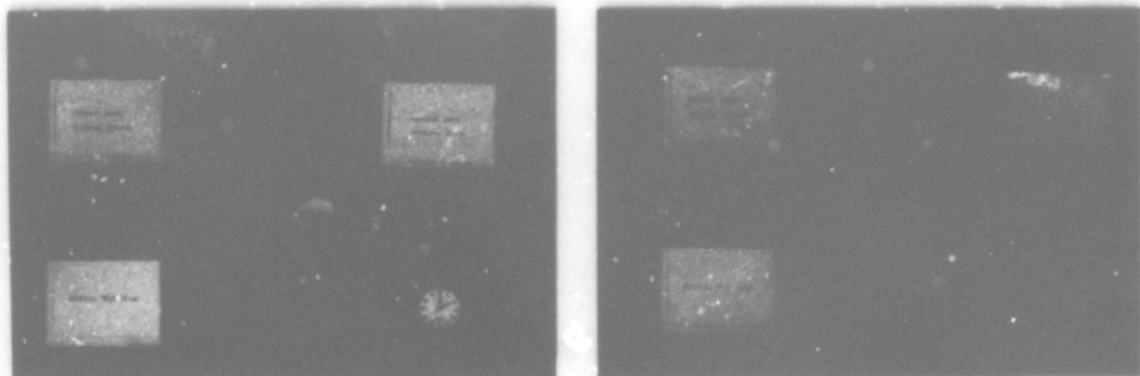


Fig.7 and 8 Panel on the left side is 3,25 mm, the other panel is 10 mm thick in cross-section. Both tested



Fig.9 and 10. Epoxy resin unidirectional glass fibre reinforced upto 85 p.b.w. of fibre. Left specimen 0,5 mm and right specimen is 1,5 mm thick in cross-section. Both tested against the vertical test requirement V60. The right side panel did not fulfill the requirements.

3.3 Place of Ignition

A glass fibre reinforced plastic sheet of 3 mm thickness completely edged with an aluminium strip, to be used as an overhead surfacing panel, must be tested in its actual cross section. It burns unacceptably in any case, i.e. vertically, horizontally as well as under 45 inclined method. After having been treated with a special coating on one side only to save weight, the panel fulfils with its protected side completely the 45 inclined test and the Fire Proof Test during 15 minutes. The product, however, may not be used since it burns on the backside, when vertically tested; which is absolutely impossible to occur in practice.

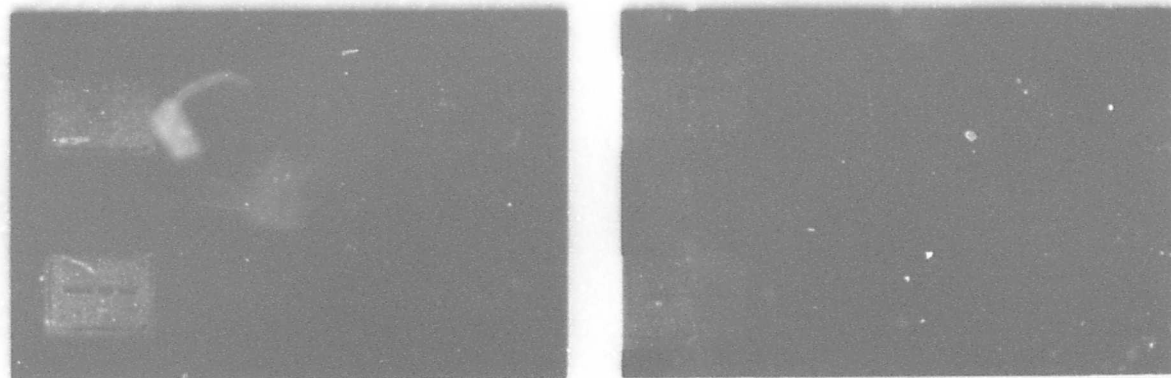
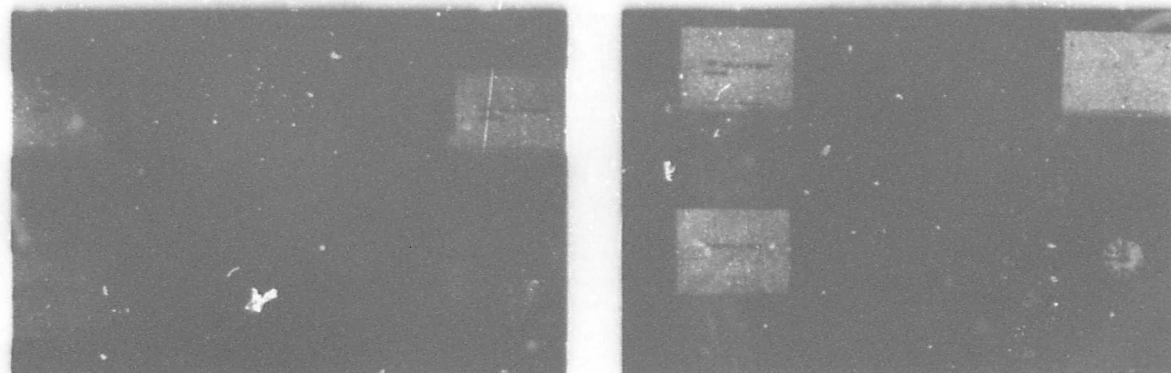


Fig.11 and 12 Vertical V12 test performed on both specimens. The left specimen without a Fire Proof Coating. The right specimen with the front side only coated with a Fire Proof Coating.



15 sec after ignition time.

14 minutes and 45 seconds.

Fig.13 and 14 The same one-side-Fire-Proof-Coated test specimen as presented in Figures 11 and 12 did pass the 45° and Fire Proof requirements, but may not be used although in practice the product is completely edged with an aluminium strip.

3.4 Flame Temperature and Time of Ignition

The test methods as given in the Appendix F of FAR 25 specify various ignition temperatures ranging from 843°C up to and including 1095°C. Also a wide variety of ignition times are specified in the various paragraphs of the FAR. These ignition times are 12 and 60 seconds (vertical tests), 15 seconds (horizontal tests), 30 seconds (45 and 60 degree tests) and finally 15 minutes (Fire Proof Test).

Various tests carried out on different ignition sources show no relation with the specified test temperature to be applied. Moreover, the plateau temperature of approximately 850°C is reached after 60 seconds, using the standard required ignition source, as specified in the FAR Appendix F. Taking into account the specified ignition times of 12 and 15 seconds just 87% is reached of the average specified ignition temperature on the end of the testing time and 95% of the temperature is reached at the end of 30 seconds ignition time period.

It is believed that more realistic evidence on material behaviour against fire will be obtained, if either the ignition times will be significantly extended at the specified testing temperature(s), or the heat-up time of the ignition source should be significantly increased.

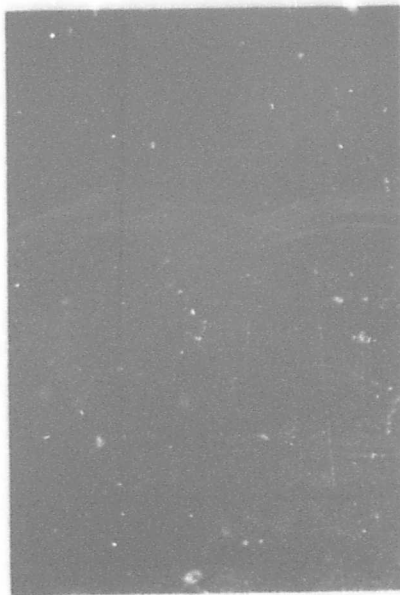


Fig.15 Averaged flame temperature reaching its plateau, for various types of ignition sources

3.5 Fire Effect in Combination of Materials

A combination of materials, which could not be foreseen and of which each fulfils the requirements of the particular FAR paragraphs, could lead to serious consequences.

An Acrylic sheet material of a thickness of 3 mm satisfies the requirement of having an average burning rate not greater than 2.5 inch per minute. This Acrylic sheet material is only intended to be used for giving information and/or instructions in the form of signs.

Polycarbonate sheet of 2 mm thickness to be used for making thermoformed parts satisfies the Vertical test requirement (V12), including an after flame time of 15 seconds and being non-dripping.

Selecting the previously discussed polycarbonate sheet for producing a relatively large cover by the thermoforming methods, and attached a warning sign made of the earlier discussed acrylic sheet on the outside surface near one of the rims visible for crew and passengers. The vertical test with an ignition time of 12 seconds now with both materials together, in which the large sheet in the test set up is polycarbonate, and the very small strip is acrylic. Ignited for 12 seconds the combination continues burning until dripping starts. These drops remain burning. This accidental material combination and its intended application could contribute significantly to the propagation of a fire.

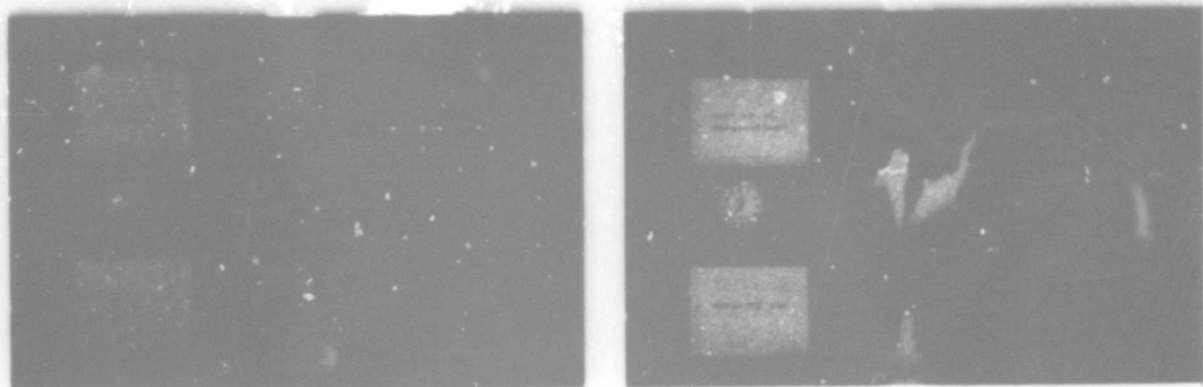


Fig.16 and 17 A vertical Test V12 performed on a combination of materials. P.C. 2 mm and PMMA 3 mm cross-sectional thickness. The combination does not pass the test.

4. CONCLUSION

The major failures of all requirements and tests is that they test one set of conditions in a particular sample size at one temperature in only one orientation with no other objects nearby. But all factors are important. To be able to predict real fire safety is a very complex problem requiring an expensive research effort.

ACKNOWLEDGEMENT

For the contribution to this paper, the assistance of Mr P.E.d'Arnaud of Fokker -VFW Dept-FPO Amsterdam is acknowledged.

DISCUSSION - PAPERS 9, 10 & 11

Mr Borsini: Mr Parker has shown the trend for new polymeric materials in the manufacture of aircraft cabin interiors. Regarding the use of flexible polyurethane foam in seat cushions, have you any comments?

Mr Parker: This is a key point; I showed you today that the cross-linked aromatic ringed systems provide inherent fire stability, limited ignition characteristics, limited smoke and toxicity. They offer a means of controlling the fire properties by planning to have a certain array of aromatic rings, but when you do this you lose flexibility. In the area of flexible materials in general, you have two options. One is inorganic materials, second is the completely chlorinated materials which are much too expensive to use as seat materials, and the inorganic materials are just becoming available. In the US we are applying the idea of halogen substitution to reduce flammability, and the neoprenes are coming into their own. In my opinion they do not do much for you in the way of smoke and toxicology and total fuel load; they are, however, very good in the early stages of ignition such as one half pound of paper on a seat. But for larger quantities of fuel, say 3 lbs of paper, you deplete the hydrogen chloride and have massive onset of ignition and then combustion.

Beyond these materials we have the hardened neoprenes, polyester cyanurates, and perfluoroethers, beyond that comes the question of construction, using the fibrous materials which are nontoxic and nonflammable such as the polycarbonates, PBI, etc.

Mr Sarkos: During your presentation you stated that if all the Tedlar used in a wide-bodied jet was consumed by fire, the concentration of HF would exceed the lethal level by a factor of 10,000. Since the LD₅₀ (5 min exposure) of HF is approximately 10,000 ppm, this would indicate that the HF concentration is 10⁸ ppm or 100 times the original volume of cabin air. Would you please explain this apparent gross impossibility?

Mr Parker: The figure was greatly simplified; Tedlar decomposes to give 18% by weight of hydrogen fluoride, but one also gets alluofluoride, vinyl fluoride, tolyofluoride of much higher toxicity. Also I based that number on the 8 hour TLV (threshold level) data.

Mr Taylor: All speakers have referenced one or two relevant accidents but there have been something like 50 to 100 relevant accidents over the last ten to fifteen years. What attempt has been made to correlate the evidence from all these others?

Mr Parker: This also must be on a cost-effective basis. Analyzing the economic impact of accidents and safety systems. In other words, is the money better spent in materials, or improved landing systems, or operating systems.

Mr Rochester:

(1) Apart from cost of materials, cost of introduction into production due to involved manufacturing procedures has to be considered. What comment has the author on the ease of manufacture of these items?

(2) Apart from flammability studies, what work has been carried out to determine their suitability for required use. In particular, life of materials in use and environmental resistance.

(3) Request the author's comment on fuselage inspection problems when using sprayed on foams for flame penetration protection.

Mr Parker:

(1) I am offering three new non-available polymers for production. NASA has used a technique of licensing for production, royalty free, with input of capital risk dollars by the US government, and with market development on the part of the company. For instance AVCO's development of both coatings and lightweight foams for fuel tank ballistic incendiary protection. This process took about 5 years and an input of about 1 million dollars from NASA from hard fullscale simulation to field use. There is some information on this and cost factors in my paper.

(2) Regarding environmental stability, weather, UV, etc. we go through standard tests and government specifications. However, it is critical with these sophisticated combinations of materials that you be very precise in manufacturing specifications; small changes in production techniques, process specifications and composition can have serious effects on the characteristics.

(3) We have had this problem in the military, in the A-4 we have used a technique of long term exposure and then peeling the foam off. More important, in the A-10 we are using a technique of installing fully packed sections which can easily be removed, and therefore provide reasonable access. That is a production item now. A new technique now used is a spray molding technique which can be used for the most complex shapes.

Mr Fuhs: What are your views on providing oxygen to the passengers during fires since you have toxic gases.

Mr Parker: I would be very hesitant to drop the oxygen for several reasons. First, these are demand systems you would get the toxic gases with the oxygen. The oxygen, of course, could contribute to the fire problem. Another important consideration is that the oxygen is provided by potassium chlorate candles in the back seats of the aircraft. Thermophysical failures of cans for these candles could be very serious. Gas masks would be a better solution if a cheap and effective one such as that under development by the Army could be used.

Mr Sarkos: One would certainly have to distinguish between in-flight fires and post-crash fires with regard to the design requirements of a gas mask system. It may be acceptable to utilize stored oxygen in the in-flight situation, but in a post-crash situation something portable, to allow freedom for safe evacuation, is what is needed. Use of any such aids must take into consideration the variable capability of a wide spectrum of passengers to cope with the emergency. Results have shown that most of the survivors in any aircraft accident are the young and alert male adults. A disproportionate number of fatalities occur among the children and older passengers. These people are incapable of positive action under the frightening situation of a crash or in-cabin fire, which has some impact on the complete usefulness of mask techniques.

Mr Hughes: From a cost-effectiveness point of view, is it better to install an onboard fire suppression system, such as one using high pressure halons or to install fire resistant materials or perhaps a combination of both. If we use both, what is the effect of halon combined with the toxic products of combustion that are normally found in the cabin environment.

Mr Parker: My personal view is, if you get a fire onboard, get it out; the first line of defense is detection, and that is dependent on the people where action can be taken. The real concern is in the unoccupied areas, lavatories, cargo holds etc., where a detection system should be combined with a suppression system. Fire hardening in these areas is an additive property. There is a program underway to assess the best intermix of expenditures from an economic viewpoint. Concerning halons, they are an intoxicant; in small concentrations it can make you drunk, in higher concentrations; it induces ventricular fibrillation; if it comes into contact with an ignition source, it will decompose to provide hydrogen bromide, hydrogen fluoride, carbonyl fluoride, etc., and provide a very toxic situation. So the idea is to use as little halon as possible and to use it as efficiently as possible, and to get a very good intelligence system to couple the dispensing system with the detector.

Mr Sarkos: The FAA has an RFP out which is a feasibility and tradeoff analysis on active extinguishing systems versus fire retardant materials, which should shed some light on Mr. Hughes' question. Regarding the toxicity of Halon 1301, a National Academy of Sciences symposium several years ago came to the conclusion that Halon 1301 can be toxic under the worst conceivable conditions; however there are 5 to 6,000 Halon 1301 installations in the US and there have been over thirty instances where a system was successfully used to extinguish a fire in areas occupied by personnel with no resulting known harmful effects on these people. There are also many people who work at Dupont with hundreds of hours of cumulative exposure without any known adverse effects on their health.

Mr Parker: The halons are considered effective in putting out fires, but from an efficiency point of view many solids such as potassium bicarbonate, and potassium sodium cryolite may be much more effective by up to two orders of magnitude; the problem, of course, is in the dispensing system, which is being worked on, and there is no toxicity problem with these agents.

Mr Madgwick: A study of in-flight incidents of fire and smoke in passenger cabins has revealed there has been an overwhelming number of incidents of smoke as distinct from fire. Not surprisingly, these were mostly caused by failure or overheat of electrical components, particularly wire-wound components, such as transformers. Bearing in mind the involvement of electrical insulating materials and potting compounds, is there any program of research being directed particularly at this aspect of aircraft and passenger safety?

Mr Parker: While the FAA and NASA play a large role in fire safety technology, we also have extremely competent aircraft companies who are doing much on their own. They are doing everything they can to reduce ignition sources;

every company has programs for reducing such hazards by controlling overloads, fuzing etc. We are also working in the area of high temperatures to 200°C which is a tough goal I admit. If we can do so, we will eliminate any smoke and toxic hazards from electrical equipment failures, using bismalyamide polymers. Hardening of electrical systems is being left to the manufacturers.

Mr Macdonald: In your laboratory tests, you quoted a requirement of two pounds of fuel to give a fire. Would this hold true for a larger compartment such as the fuselage as a whole.

Mr Parker: The scaling question is a very difficult one. I believe this type of testing must be empirical. Our programs are based on full-scale work. We have a full-scale DC-10 Cargo Bay at Sacramento for some of our testing; currently there is no confidence in scaling. It is a very difficult modelling problem in general. We had to give up using trash bags which all burned differently and go to calibrated burners.

Mr Borsini: I agree with your conclusion; present F.A.R. test methods cannot completely predict fire behaviour of materials in an aircraft cabin. Do you think a calorimetric test for heat development and limiting OX index for ease of ignition should be also taken into account for passing materials?

Mr Godfried: The answer to the question whether a material or a material combination burns or not, cannot be found by simply increasing the number and type of tests, but by establishing significances of burning.

To obtain information on the behaviour of burning of materials and material combinations, the following three subjects should be recognised;

- (1) Ignition temperature for just getting the material ignited.
- (2) Flaming properties.
- (3) Flame propagation with and without external ignition sources.

So far the F.A.R. only dealt partly with item 3. The limiting oxygen index could serve for obtaining flaming properties (2) and many tests are developed and in existence for determining the ignition temperature (1).

MESURE DES FUMÉES ET ANALYSE DES GAZ TOXIQUES PROVOQUÉS PAR LA COMBUSTION DES MATÉRIEAUX D'AMÉNAGEMENT DE CABINE D'AVION

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RESUME :

Les incidents dramatiques provoqués par les incendies de cabine dans les avions ont amené les Industriels et les Services Officiels à s'intéresser au problème d'inflammabilité dans les avions et de façon plus précise à la propagation de la flamme, à l'émission de fumée et à la toxicité des gaz dégagés par les matériaux d'aménagement de cabine.

Depuis environ 6 ans le Centre d'Essais Aéronautique de Toulouse, en relation étroite avec les Services Officiels a entrepris un vaste programme d'étude de la tenue au feu de ces matériaux. Les essais et études réalisés portent sur les trois points, inflammabilité proprement dite, émission de fumée et émission de gaz toxiques.

Après un rappel rapide sur les moyens d'essais utilisés au C.E.A.T. pour la mesure des caractéristiques d'opacité, et l'analyse des gaz, il sera fait mention de certains résultats obtenus à ce jour sur une série de matériaux élémentaires représentatifs des grandes familles utilisés dans les aménagements de cabine. Cependant ces résultats portent sur des échantillons de dimensions restreintes, aussi pour avoir une idée plus précise du phénomène, le C.E.A.T. a entrepris en relation avec les Services Officiels un programme d'essai en caisson représentatif d'un tronçon réduit de fuselage permettant ainsi de suivre en semi-grandeur et d'une manière analytique les diverses manifestations des matériaux vis à vis du feu, en respectant les proportions d'utilisation de ces matériaux à bord des avions. Dans la première phase ces matériaux sont essayés isolément dans des positions et des conditions d'environnement rencontrées dans la réalité. Les moyens mis en oeuvre pour mener à bien ce programme seront exposés dans la deuxième partie de notre exposé.

1 — PREMIERE PARTIE : RESULTATS D'ESSAIS DE FUMÉE ET ANALYSE DE GAZ TOXIQUES SUR MATÉRIEAUX ÉLÉMENTAIRES :

1.1 - Introduction :

Quand les matériaux organiques brûlent, ils tendent à donner un dégagement de CO_2 à partir du carbone contenu dans les molécules, de H_2O (à partir de l'hydrogène) de N_2 , NO , NO_2 (à partir de l'azote) HX (à partir des halogènes) et SO_2 (à partir du soufre). Pour que ces réactions se produisent, il faut que l'oxygène ou l'air soient en excès et la température suffisamment élevée. Si l'un de ces deux facteurs est déficient, il se produit une réaction incomplète de pyrolyse partielle et l'on assiste à la formation de produits intermédiaires dus à la rupture des chaînes polymères, produits qui sont très toxiques. Ainsi s'il n'y a pas assez d'oxygène dans l'environnement immédiat du feu pour oxyder complètement le carbone, il se forme alors de la fumée et de l'oxyde de carbone.

Les deux problèmes fumées et toxicité sont très liés, il n'y a pas de fumée sans dégagement toxique.

Dans ce bref exposé nous n'aborderons pas les problèmes liés aux essais d'inflammabilité proprement dit car le sujet est trop vaste pour être traité en temps restreint, il ne sera question que des résultats d'essais de fumée et d'analyse des gaz obtenus sur vingt cinq matériaux parmi les plus représentatifs de l'aménagement d'une cabine d'avion.

1.2 - Equipements mis en oeuvre :

Les mesures de densité de fumée relatées dans cette première partie ont été effectuées à l'aide d'une chambre à fumée NBS, AMINCO, très répandue aux USA et dont une dizaine d'exemplaires existe en Europe.

- Principe de la chambre à fumée NBS : (photo N° 1)

L'équipement susceptible d'être adopté par les Services Officiels est basé sur le principe de mesure de transmission d'un rayon lumineux traversant directement la couche de fumée émise par l'échantillon qui brûle en position verticale, devant une source de chaleur rayonnante de $2,5 \text{ W/cm}^2$. Les échantillons sont soumis à deux types d'exposition au four électrique (S.F) et l'exposition au four électrique en présence de flamme fournie par une source multiflamme à 6 orifices (A.F.).

Les valeurs enregistrées sont exprimées en % de transmission lumineuse T qui est liée à la densité optique D par la relation :

$$D = \log \frac{100}{T}$$



Photo N° 1 Chambre à fumée du NBS

Les prélèvements de gaz ont été effectués dans la chambre à fumée, après avoir atteint la densité optique spécifique maximale, les mesures ont été faites avec des tubes indicateurs spécifiques AUER ou DRAEGER qui donnent une précision de 10 à 20 % en règle générale. Pour les teneurs en Hcl supérieures à 50 ppm, les mesures ont été faites par potentiométrie avec électrode spécifique. Il faut signaler en ce qui concerne le gaz chlorhydrique, la difficulté du prélèvement de ce gaz, en effet, comme il a une très grande affinité pour l'eau, il se dissout rapidement dans l'eau produite par la combustion : les résultats donnés dans les tableaux 2, 3, 4, 5 et 6 sont sûrement inférieurs à la réalité pour ce gaz.

1.3 - Analyse des résultats discussion :

Les résultats sont collationnés sur les tableaux N° 2, 3, 4, 5 et 6.

D'une manière générale, tous les produits donnent naissance en brûlant, à de l'oxyde de carbone qui, comme chacun sait, est très toxique. La présence d'oxyde de carbone est décelée dès les premiers instants de la combustion comme nous avons pu le constater en faisant des dosages en continu de CO durant des essais similaires.

1.3.1 - Thermoformables transparents (tableau N° 2).

Les polyméthacrylates de méthyle (genre Altuglas, Plexiglas) sont très utilisés dans les cabines d'avion. Ils dégagent peu de fumée, et excepté l'inévitable CO, ils sont peu toxiques, mais l'intense dégagement de chaleur qui se produit pendant la combustion favorise la formation de vapeurs nitreuses avec l'azote atmosphérique.

Ces produits sont avantageusement remplacés par les polycarbonates dans les luminaires, les rampes lumineuses.

Cette valeur est convertie en densité optique spécifique D_s . Elle représente la densité optique mesurée à travers une couche de fumée d'épaisseur $L = 0,914$ m dans une chambre de volume $V = 0,503$ m³ produite par un échantillon exposant à la chaleur une surface $A = 0,423$ dm².

$$D_s = D \times \frac{V}{AL} = \frac{V}{AL} \lg \frac{100}{T}$$

$$D_s = 132 \lg \frac{100}{T}$$

Les courbes de densité de fumée sont enregistrées et l'on a coutume de relever :

- La densité optique spécifique à 90 secondes, à 4 minutes.

- La densité optique spécifique maximale.

Dans un souci de comparer les échantillons, on a jugé bon de déterminer l'indice SOI : Smoke obscuration Index qui fait intervenir la densité spécifique maximale D_m , le temps pour obtenir $D_s = 16$.

$$SOI = \frac{D_m^2}{2000 D_s = 16} \left[\frac{1}{t_{0,1}^2} + \frac{1}{t_{0,3}^2} + \frac{1}{t_{0,5}^2} + \frac{1}{t_{0,7}^2} + \frac{1}{t_{0,9}^2} \right]$$

$t_{0,1}$ $t_{0,3}$ $t_{0,5}$ $t_{0,7}$ $t_{0,9}$

temps en minute pour atteindre 10 % , 30 % , 50 % , 70 % , 90 % de D_m .

Les gaz toxiques dégagés pendant la combustion des matières plastiques n'ont pas été tous dosés et les commentaires qui suivent sont relatifs aux quatre gaz analysés CO, Hcl, HcN et NO + NO², les plus couramment trouvés lors de la combustion des matériaux.

MATERIAUX		CO ppm	HCL ppm	HCN ppm	NO+ NO ₂ ppm	D _s à 90s.	D _s à 4mn.	D _m	SOI	POIDS échantillon essaye
THERMOFORMABLES TRANSPARENTS										
POLYMETHACRYLATE de METHYLE à 3mm	SF	400	0	1,7	0	0	16,5	204	21	21,5g.
	AF	300	0	2	200	0	114	138	59	
POLYCARBONATE	SF	100	0	0	0	0	0	/	/	13,5g.
	AF	800	0	0	2,5	17	121	244	/	
THERMOFORMABLES OPAQUES										
COMPOSITE ABS + PVC	SF	600	100	30	10	18	234	581	353	19g.
	AF	3700	150	75	25	242	621	887	2631	
POLYPHENYLENE OXYDE	SF					0	2	/	/	
	AF	1000	traces	2	12	63	383	484		

1.3.2 - Thermoformables opaques : (tableau N° 2) :

Tableau N° 2

Les avions traditionnels utilisent en grande quantité les composites ABS-PVC qui sont faciles à mettre en œuvre et ont de bonnes qualités d'autoextinguibilité. Le dégagement de fumée, moins intense dans l'essai sans flamme, est rapide et abondant dans l'essai avec flamme qui est plus agressif et entraîne la formation de produits toxiques en quantité importante.

La formation d'acide cyanhydrique HCN, due à la présence d'azote dans la structure moléculaire, n'est pas négligeable : 75 ppm chiffre élevé si on songe que le M.A.C. (maximum admissible concentration pour une journée de 8 heures) est de 10 ppm.

L'effort doit porter sur le remplacement de ces matériaux trop toxiques. On pense aux polycarbonates opaques et au polyphénylène oxyde polystyrène moins dangereux, sans fumée lorsqu'il n'y a pas de flamme.

MATERIAUX		CO ppm	HCL ppm	HCN ppm	NO+ NO ₂ ppm	D _s à 90s.	D _s à 4mn.	D _m	SOI	POIDS échantillon essaye
STRATIFIES										
STRATIFIE PHENOLIQUE	SF	100	0	0	0	0	0	0	0	7,5g.
	AF	200	0	0	0	0	0	0	0	
STRATIFIE EPOXY	SF	100	1,7	7	1,5	32	161	233	113	9,5g.
	AF	700	8	20	40	425	/	426	22335	
STRATIFIE POLYIMIDE	SF	100	0	1	4	0	1	14,5	0,01	10,5g.
	AF	500	0	30	50	7,5	253	46	0,97	
STRATIFIE POLYESTER à 3mm 16 plis	SF	300	0	2	0	0	20	/	/	/
	AF	250	0	0	4	165	353	405	/	
FILM										
POLYESTER PVC à 6 microns	SF	10	9	0	/	1	2	10	/	/
	AF	50	9	0	/	12,5	16,3	22	/	

1.3.3 - Les stratifiés (tableau N° 3) :

Tableau N° 3

Ils ont les qualités et les défauts des matières plastiques qui les composent, la fibre de verre n'introduit aucun facteur de toxicité et de fumée.

Les stratifiés phénoliques sont très intéressants de même que les polyimides, un peu plus toxiques mais remarquables par leur tenue à la chaleur (thermostables).

Quant aux stratifiés époxydes, leur combustion donne lieu à un intense dégagement de fumée accompagné de dégagement toxique.

MATERIAUX		CO ppm	HCL ppm	HCN ppm	NO + NO ₂ ppm	D ₅ à 90 s.	D ₅ à 4 mn.	D _m	SOI	POIDS échantillon essayé
LAINE 100 %	SF	120	0,5	24	8	23,5	39,5	54,5	26,7	2,4 g.
	AF	500	4	40	33	64,5	109,5	113,5	102	
TISSU COTON	SF	40	traces	traces	traces	34,5	52,3	62,6	30	0,9 g.
	AF	50	3	traces	5	5,3	8	10	0,0	
TISSU NYLON POLYAMIDE	SF	10	2	0	0	0	0	0,3	0,0	0,37 g.
	AF	120	1	1	10	0,3	11,6	24,3	0,22	
TISSU POLYAMIDE IMIDE	SF	300	15	2	10	1	3	/	/	1,65 g.
	AF	1000	25	4	15	4,3	11,3	/	/	
TOILE NYLON ENDUITE de PVC	SF	700	50	15	6	169	313	395	628	4,5 g.
	AF	1000	82	30	18	428	/	533	5682	
SIMILI CUIR GRIS BLEU	SF	250	20	1	0,5	122	271	307	386	3,8 g.
	AF	500	25	2	2	309	/	406	4029	

Tableau N° 4

1.3.4 - Les tissus (voir tableau N° 4) :

Les tissus naturels et synthétiques sont également utilisés dans un avion.

— La laine donne d'excellents résultats en fumée mais, du fait de sa structure organique azotée, elle donne naissance à de l'acide cyanhydrique et des vapeurs nitreuses non négligeables.

— Le coton est de loin le moins toxique et le moins fumigène, cependant sa tenue au feu n'est pas extraordinaire tout comme le nylon encore plus sensible à la chaleur.

Les meilleurs résultats sont obtenus avec les polyamides-imides et les polyamides aromatiques non représentés sur le tableau qui allient à leur qualité de résistance à la chaleur, une faible émission de fumée et un dégagement de gaz relativement moins toxique qu'un tissu enduit de PCV ou les SOI dépassent 5 000.

MATERIAUX		CO ppm	HCL ppm	HCN ppm	NO + NO ₂ ppm	D ₅ à 90 s.	D ₅ à 4 mn.	D _m	SOI	POIDS échantillon essayé
MOQUETTE DE LAINE	SF	1500	8	80	8	66	186	503	492	11 g.
	AF	1500	20	75	150	12,5	373	561	767	
TAPIS MOUSSE GRIS VERT	SF	1500	100	10	2	107	404	810	1682	10,6 g.
	AF	1700	153	10	20	653	/	676	14600	
CHLOROPRENE	SF	600	100	2	1	10	/	573	/	17 g.
	AF	1000		2	5	684	/	897	15000	
COPOLYMERE ETHYLENE PROPYLENE	SF	1800	100	4	0	7	235	677		16,5 g.
	AF	1700		3	7	258	522	528	5000	
NITRILE	SF	50	30	30	1	272	/	480		14,6 g.
	AF	1500		75	20	570	632	632	10000	
SILICONE	SF	500	0	1	0,5	6	75	203	18,47	24 g.
	AF	1000	0,5	1	6	12,6	71	192	22,17	
FLUORÉ	SF	100	0	1	4	0	62	145	17,3	21 g.
	AF	500	0	30	50	9,3	214	281	127	

Tableau N° 5

1.3.5 - Revêtement de sol (tableau N° 5) :

Les moquettes de laine sont nettement moins génératrices de fumée que les tapis plastiques PVC bien que les vapeurs nocives dégagées par les deux matériaux soient également toxiques.

1.3.6 - Elastomères (tableau N° 5).

Les élastomères siliconés sont intéressants au point de vue fumée et toxicité, si l'on ne tient pas compte de l'oxyde de carbone. Les élastomères fluorés sont peu fumigènes mais dans l'essai avec flamme on assiste à un dégagement de HCN et NO + NO₂ qui n'est pas négligeable; d'autre part il est fort possible qu'il y ait formation d'acide fluorhydrique pendant la combustion, ce gaz FH n'a pas été recherché dans le cas présent.

Les chloroprènes, les nitriles, les éthylènes-propylènes, donnent lieu à un dégagement rapide et intense de fumée. Dans l'essai avec flamme, les SOI dépassent 15 000 pour les chloroprènes.

MATERIAUX		CO ppm	HCl ppm	HCN ppm	NO + NO ₂ ppm	D ₅ à 90 s.	D ₄ à 4 mn.	D _m	SOI	Poids échantillon essaye	
				MOUSSES SOUPLES _RIGIDES							
MOUSSE SOUPLE POLYETHER POLYURETHANNE	SF	250	20	5	4	84	143	193	281	6,5g.	
	AF	400	75	6	18	270	/	296	5335		
MOUSSE RIGIDE PHENOLIQUE	SF	800	0	1	0,5	3,3	11	23	0,08	4,5g.	
	AF	1000	0	0,5	1	3,3	96	17	0,03		
MOUSSE PVC 6,1g.	SF	600	50	15	4	115	324	463	747	6,1g.	
	AF	200	85	20	8	599	/	715	13352		

Tableau N° 6

1.3.7 - Mousses (tableau N° 6)

- Mousses souples :

Un seul type de mousse est utilisé pour les rembourrages des sièges, ce sont les mousses polyéther polyuréthane, le problème de tenue au feu des mousses est bien maîtrisé, mais celui de fumée et toxicité est critique quand on songe au volume important qu'elles occupent dans l'avion.

- Mousses rigides :

Sans hésitation possible, les mousses phénoliques sont les plus intéressantes. A leurs qualités de résistance au feu, elles joignent la propriété de dégager très peu de fumée.

Conclusions sur la première partie :

Les essais à la chambre à fumée bien que ne représentant pas parfaitement la réalité, offrent l'avantage d'une méthode d'essai relativement simple donnant des résultats reproductibles et permettant de comparer les matériaux entre eux d'une manière assez satisfaisante. Ils ne sont certainement pas suffisants pour définir des critères d'acceptation ou de rebut des matériaux.

Les différents tableaux qui viennent d'être présentés n'ont pas la prétention de couvrir l'ensemble des matériaux d'aménagement, ils permettent néanmoins de constater que dans chaque famille il existe des différences importantes de comportement au feu qui se traduisent par des émissions de fumées et de gaz toxiques souvent très différents prouvant qu'un choix judicieux est possible et nécessaire au niveau de la conception des aménagements intérieurs de cabine d'avion.

2 - DEUXIEME PARTIE : MOYENS D'ESSAI POUR L'ETUDE DES PROBLEMES D'INFLAMMABILITE DES MATERIAUX D'AMENAGEMENT DE CABINE D'AVION A L'ECHELLE SEMI-GRANDEUR.

2.1 - Introduction :

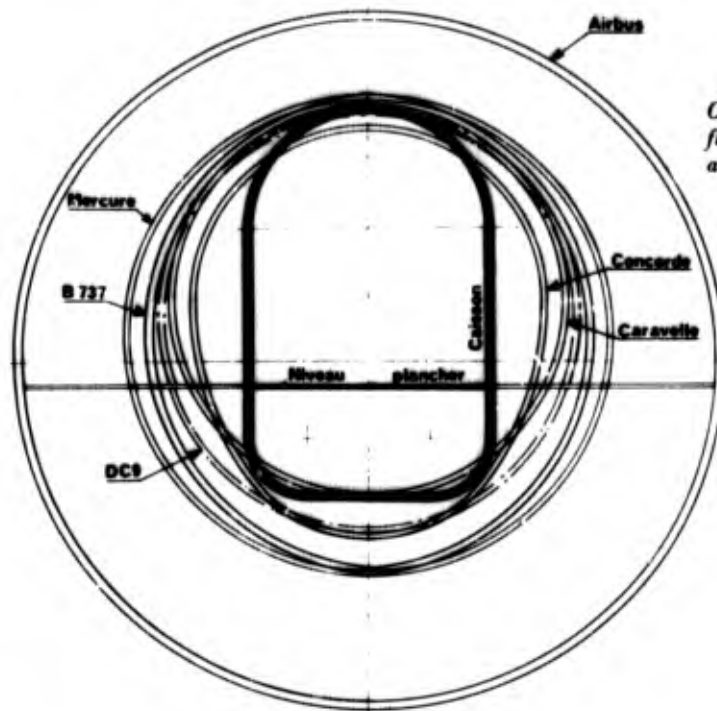
Les projets de réglementation, en matière d'inflammabilité, envisagés par les Services Officiels ont nécessité la mise en oeuvre de moyens d'essais permettant d'aborder l'étude des matériaux sur des échantillons restreints, caractérisés individuellement, indépendamment les uns des autres. Cet objectif poursuivi depuis plusieurs années a donné lieu à de nombreux essais dont la première partie de notre exposé a permis de donner une idée.

Une fois cette première étape franchie, il était normal que l'on se préoccupe de la manière dont pouvaient se comporter les matériaux les uns en présence des autres dans un incendie réel afin de recueillir des informations et préparer la réglementation future en matière de fumée et de toxicité.

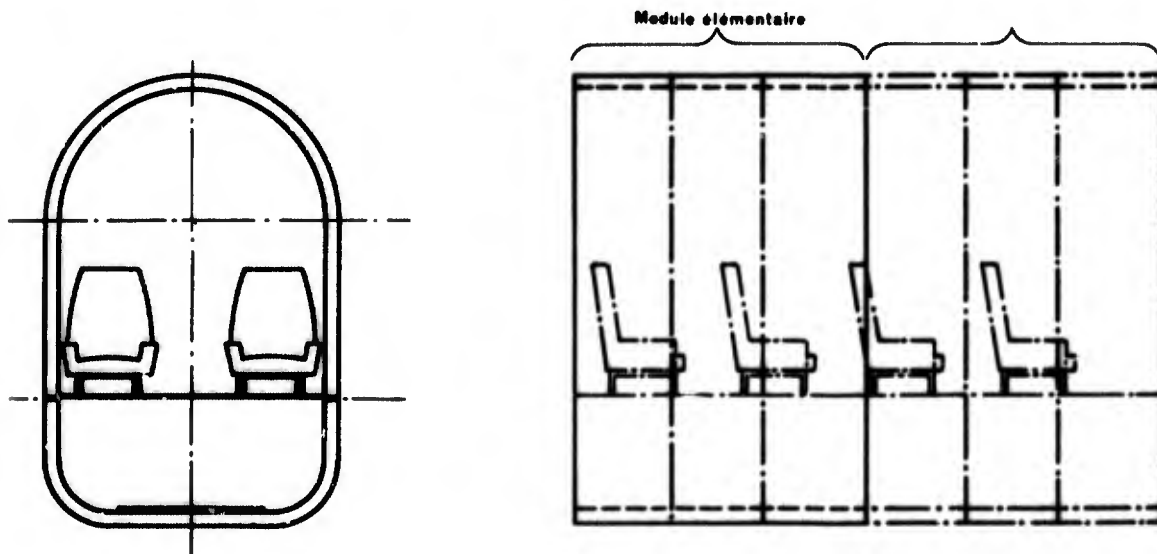
Il paraissait donc nécessaire de rechercher dans quelle mesure on pouvait établir une corrélation entre les essais en chambre NBS et les essais sur tronçon de fuselage réel avec son aménagement.

De l'avis même des spécialistes l'essai vraie grandeur avec aménagement complet spécifique d'un type d'avion donné est coûteux pour les résultats que l'on peut en retirer si l'on n'a pas fait au préalable une approche serrée du problème.

Ainsi a-t-il été décidé après accord avec les services officiels d'envisager les essais dans un caisson ayant un diamètre voisin de celui d'un avion commercial actuel (voir croquis N°7) avec possibilité d'extension longitudinale (croquis N°8).



Dans ce caisson il est possible d'effectuer différents cas d'essais en présence de la totalité ou d'une partie des matériaux d'aménagement de cabine d'avion.



Croquis N° 8

Dans ce bref exposé, on examinera successivement les critères pris en compte pour l'étude d'un caisson d'essai d'inflammabilité avant d'en présenter la réalisation, puis les moyens de mesure et d'observation seront passés en revue et on définira sommairement les bases du programme d'essais.

2.2 - Critères retenus pour l'étude d'un caisson d'essai d'inflammabilité :

Les causes essentielles qui, au bout d'un temps plus ou moins long peuvent entraîner la mort des passagers sont :

- Asphyxie par manque d'oxygène et augmentation de la teneur en CO_2
- Intoxication ou paralysie causée par les gaz dangereux (CO , Cyanogène etc...)
- Température excessive
- Panique provoquée par la fumée : diminution de la visibilité, irritation suffocation

On peut donc définir les objectifs d'étude ci-après :

- Propagation du feu et observation du comportement des matériaux.
- Evolution de la teneur en oxygène et en gaz toxiques en fonction du temps.
- Evolution des températures en divers endroits de la cabine en fonction du temps.
- Evolution des fumées (opacité) en fonction du temps.

Ces objectifs dépendant des paramètres suivants :

- Nature des matériaux
- Quantité par rapport au volume total
- Position occupée dans la cabine par rapport à la source d'initiation
- Ventilation de la cabine
- Nature et intensité de la source d'initiation
- Assemblage ou combinaison des matériaux d'aménagement (éléments réels par exemple).

Il faut donc :

— Un caisson d'essai permettant de séparer ou de combiner les paramètres à prendre en compte dans les différents cas d'essais.

— Des moyens de mesure et d'observations correspondant aux objectifs visés.

2.3 - Description du caisson d'essai :

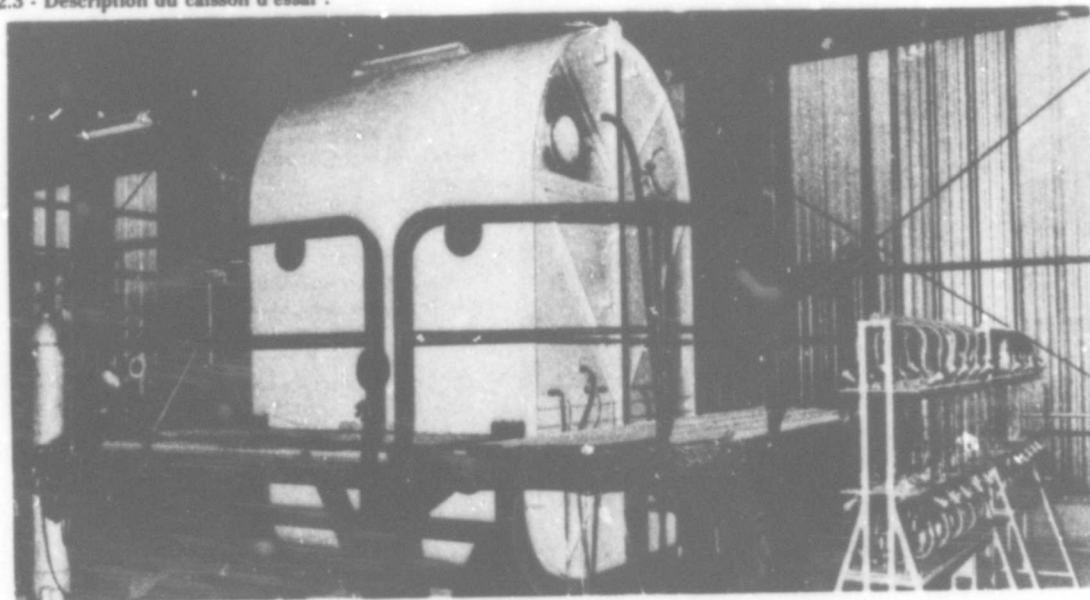


Photo N° 9 : Vue générale du caisson d'essais.

2.3.1 - Caractéristiques générales : (photo N°9).

- Le module de base a les caractéristiques générales suivantes :
- Volume total : 11 m³ environ
- Dimensions hors tout :
 - Longueur : 2 m
 - Largeur : 2 m
 - Hauteur : 3,15 m

Nombre de hublots : 13

Il est divisé par un plancher en deux compartiments distincts, la soute et la cabine, les deux extrémités sont obturées par deux panneaux démontables qui autorisent une extension modulaire de la formule (voir croquis N°8). Deux portes sont disposées sur le panneau avant. Elles donnent accès l'une au compartiment cabine, l'autre au compartiment soute.

L'ensemble est réalisé en A-G3 selon la technologie classique cadre-lisses revêtement riveté. Sa forme et ses dimensions, comparées à celles de quelques avions de transport modernes sont illustrées par le croquis N°7.

Il repose sur un berceau mobile entouré de passerelles destinées à faciliter l'évolution des opérateurs et à recevoir des matériels de mesure, d'observation et de sécurité.

2.3.2 — Caractéristiques de la partie cabine pour un module élémentaire (voir photo N°10) :

Volume total : 8 m³ environ Surface au plancher : 4 m² (2 x 2) Hauteur plancher - plafond : 2,25 m.

Elle est équipée de 9 hublots (3 sur parties latérales, 2 sur fond arrière et 1 sur avant) qui autorisent une observation à différents niveaux par rapport au plancher soit 0,27, 1,08 m, 1,25 m et 1,62 m.

2.3.3 - La soute : - Volume total 3m³ environ - Hauteur : 0,9m -

Elle est équipée de quatre hublots (2 sur chaque partie latérale) disposés à 40 cm du plancher.

Dans cette partie inférieure, une trappe de 1/2 m² environ a été aménagée en vue de réserver des possibilités de conditions d'essais (feu d'origine extérieure appel d'air etc...).

2.3.4 - Le plancher :

Il est constitué de plaques carrées montées en treillis. Cette solution permet l'adaptation :

- D'un faux plancher
- D'un assemblage mixte plancher réel - faux plancher
- D'un plancher réel.

Il assure si nécessaire la séparation étanche de la cabine par rapport à la soute et inversement.

Vue intérieure du caisson (partie cabine) avec dossier de siège en mousse prêt pour un essai.

On distingue :

- En haut les bouches de prélèvement des gaz.
- Au fond une mire d'opticien pour évaluation de la visibilité.
- Un arbre à thermo-couple.
- En bas à droite, un des opacimètres.
- Les caméras sont extérieures et filment au travers des hublots.



Photo N° 10

2.3.5 - Ventilation (voir croquis N° 11) :

Des rampes de trémies de ventilation permettent d'assurer soit un écoulement d'air frais en cours d'essai (simulation contrôlable de la ventilation) soit une évacuation efficace des gaz de combustion à la fin de l'essai (sécurité des opérateurs).

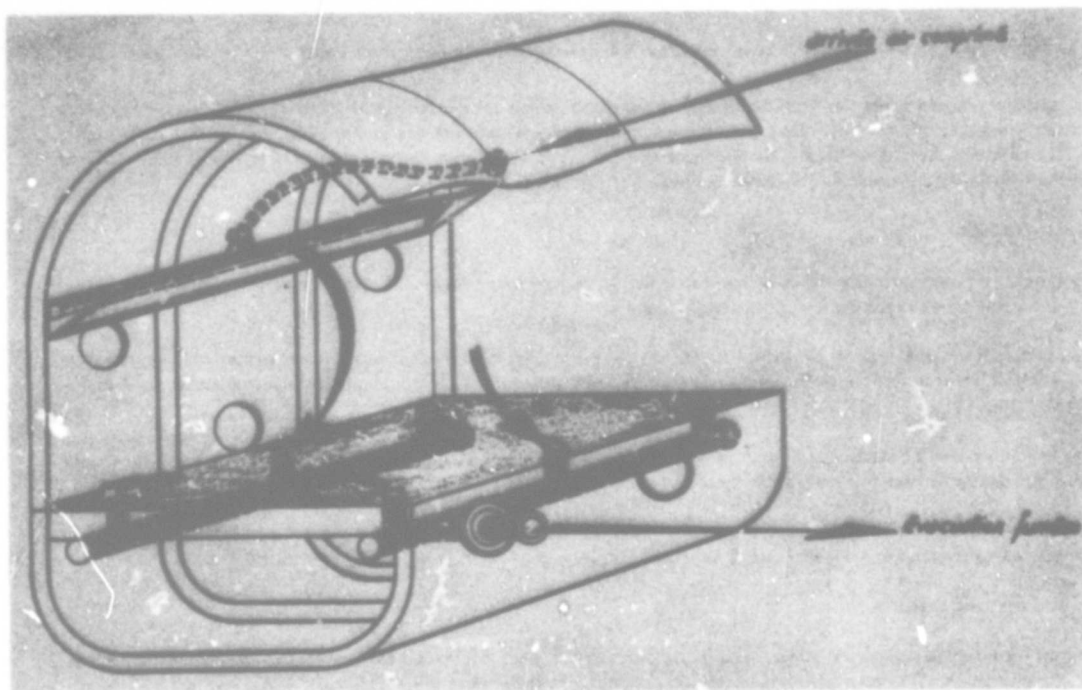


Photo N° 11 : Schéma du circuit de ventilation.

2.4 - Dispositifs de sécurité :

Outre le système de ventilation mentionné dans le paragraphe précédent, concernant la sécurité des personnels, le caisson est équipé de dispositifs de sécurité destinés à le préserver contre l'incendie généralisé de l'aménagement réalisé, une élévation intempestive et excessive de la température, une augmentation brutale de la pression, l'agression corrosive des gaz de combustion.

2.4.1 - Système d'extinction :

Pour maîtriser un éventuel incendie généralisé de l'aménagement de cabine risquant de détruire la structure métallique du caisson on a retenu un système d'extinction par CO_2 capable de saturer simultanément la cabine et la soute à raison de 3 kg de CO_2 par m^3 d'air en 19 secondes environ. Des moyens classiques extérieurs de lutte contre l'incendie complètent cette installation.

2.4.2 - Protection thermique :

Conçue à partir de matelas d'isolation capables de supporter des températures de 1250°C, ils maintiennent la structure en principe à moins de 100°C.

De faibles dimensions et d'un prix réduit, ils permettent une maintenance aisée, une protection partielle contre la corrosion et un nettoyage facile.

2.4.3 - Clapets de surpression :

5 soupapes de surtête à faible débit maintiennent une pression constante dans la cabine (3) et dans la soute (2). Des clapets de sécurité ajustables, à gros débit et à faible inertie protègent le caisson en cas de surpression brutale qui pourrait se produire dans une cas de flash point.

2.4.4 - Protection contre la corrosion :

En plus de la protection assurée par les matelas d'isolation thermique, une peinture polyuréthane aviation protège la structure intérieurement et extérieurement des gaz corrosifs dégagés par la combustion des matériaux essayés.

2.5 - Eclairage :

La cabine est dotée d'un éclairage et de consignes de secours conformes aux exigences mentionnées par la réglementation F.A.R. Parts 25 et 121.

2.6 - Moyens de mesures et d'observation :

2.6.1 - Mesure des densités de fumées émises :

L'enregistrement en continu de la densité des fumées émises est réalisé en continu à l'aide d'opacimètres mis au point au C.E.A.T.

Des caméras placées devant les hublots filment en continu l'intérieur de la cabine pour suivre l'obscurcissement de la cabine ainsi que la propagation du feu ; des mires ou consignes, placées dans le champs de prises de vues permettent d'apprécier l'opacité de l'atmosphère. Une caméra de télévision disposée près d'un hublot permet de suivre en temps réel, depuis la salle de commande le déroulement de l'incendie à l'intérieur du caisson.

2.6.2 - Analyse des gaz :

Les teneurs en oxygène et en oxyde de carbone sont enregistrées en continu à l'aide d'un détecteur paramagnétique pour O₂ et à absorption de rayonnement infra-rouge pour CO.

Une installation de dosage en continu des vapeurs nitreuses, des hydrocarbures, de l'anhydride carbonique est en cours d'installation. Dans un proche avenir, il est envisagé de s'équiper en analyseur en continu d'acide cyanhydrique et d'acide chlorhydrique.

De plus on procède à quelques prélèvements échelonnés dans le temps à l'aide d'un système de pompage et d'un groupe de bouteilles préalablement mises sous vide.

Le contenu de ces bouteilles est ensuite analysé par le laboratoire de Clamie. On détermine ainsi la variation en fonction du temps des concentrations en HCl, HCN vapeurs nitreuses, phosgène, ammoniac...

2.6.3 - Mesure des températures :

Durant l'essai on enregistre en continu les températures de l'air et de différentes parties du caisson. Ces mesures nécessitent une quarantaine de thermo-couples disposés sur des supports facilement escamotables.

2.7 - Programme d'essais :

Un programme en trois phases a été établi. L'expérience acquise au cours du développement des essais peut occasionner les modifications susceptibles d'en améliorer la représentativité.

2.7.1 - Phase - Mise au point de l'essai :

Indépendamment des essais de mise au point de l'installation d'essai et des moyens de mesure et d'observation, cette première étape concerne également l'initiation du feu. L'étude des facteurs positions et temps de maintien de source et ventilation a été explorée sur deux matériaux de base (mousses et stratifiés) à partir des modes d'initiation ci-après :

- Coupelle d'alcool
- Bougie électrique (résistance surchargée)
- Gaz.

2.7.2 — Phase II — Matériaux élémentaires essayés isolément :

Il s'agit d'étudier en une vingtaine d'essais le comportement des principaux matériaux d'aménagement de cabine pris isolément et de comparer le résultat avec ceux obtenus dans la chambre à fumée du NBS.

Tous les matériaux retenus pour cette étude doivent satisfaire aux exigences de la FAR 25-32 relative aux essais d'incendie.

- Élément de décoration etc...
- Mousses avec et sans tissu de recouvrement
- Stratifiés :
 - époxydique
 - phénoliques et panneaux sandwichs
 - polyester
- Isolation thermique et phonique
- Carpettes
- Luminaires
- Entourage de hublots

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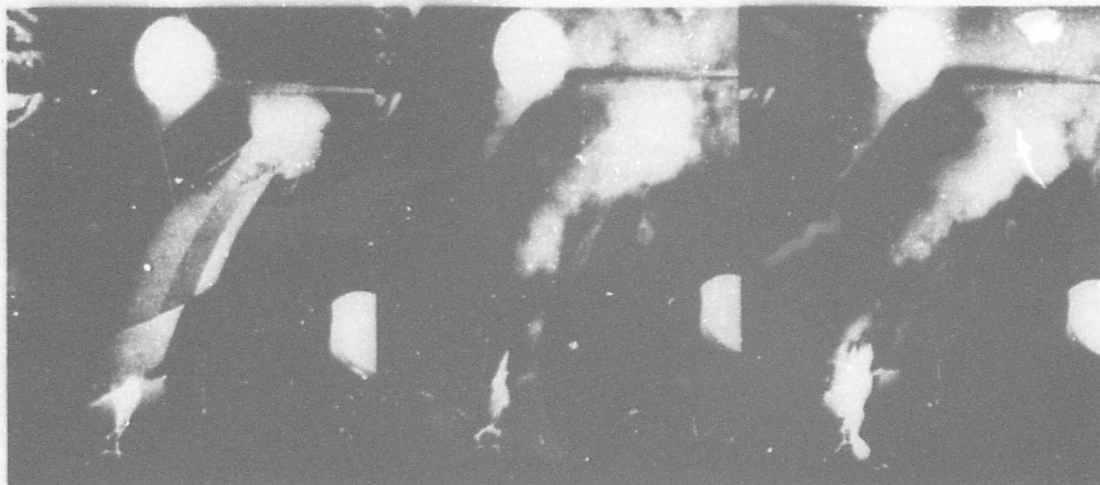


Photo N° 12 : Exemple d'essai en caisson.

Résultats d'essais sur le dossier de siège présenté à la photo N° 10. Les trois photos correspondent aux temps $E = D$: mise à feu par coupelle d'alcool, $t = 20$ secondes et $t = 40$ secondes. L'émission importante de fumée rend inexploitable les photos prises après 40 secondes.

2.7.3 - Phase III - Essai avec aménagement simplifié de cabine :

L'essai de plusieurs types d'aménagements simplifiés de cabine compose cette phase.

Par aménagement simplifié de cabine on entend des habillages comprenant plusieurs éléments par exemple :

- Élément de plancher
- Paroi latérale
- Élément de plafond
- Fauteuil
- Luminaire

La définition et la réalisation de ces aménagements sont conduits en étroite relation avec les constructeurs.

3 — CONCLUSION :

Les recherches concernant l'élaboration des matériaux résistant au feu et présentant le maximum de sécurité au point de vue fumée et toxicité se poursuivent dans les différents laboratoires concernés. L'opinion publique a été sensibilisée par les accidents souvent dramatiques survenus au cours de dernières années soit dans les établissements publics soit dans les avions. Il paraît nécessaire d'arriver rapidement à dégager des critères d'acceptation pour tous ces matériaux afin d'arrêter des règlements garantissant un niveau de sécurité toujours plus élevé. Mais, nous venons de le voir le choix de ces critères n'est pas simple, il doit tenir compte de nombreuses considérations exiger un nombre d'essai important et une analyse critique de tous les résultats en relation étroite avec les Services Officiels, les producteurs, les avionneurs, le corps médical et les grands laboratoires. C'est dans ce but que nos travaux dont l'orientation générale vient de vous être présentée se poursuivent actuellement.

En attendant une réglementation en matière de fumée et de toxicité on conseillera, même si cela paraît évident, chaque fois que le choix est possible de retenir pour un aménagement donné le matériau qui fume le moins et dégage le moins de résidus toxiques dans la mesure où il satisfait la norme en vigueur sur l'inflammabilité proprement dite, conscient que de cette façon on ira progressivement vers un niveau de sécurité toujours plus élevé.

DISCUSSION - PAPER 12

Mr Einhorn: I agree on the second part of the paper, that this is a useful approach. However, if we are to use the criteria mentioned here with the MBS chamber and are talking about safe or toxic and non-toxic then we will still be discussing results four years from now, with no progress toward hardening the aircraft. One must use various fluxes; consider the rate at which a material produces toxic gases; and you must use animals to predict this. An example is Douglas Fir exposed in the MBS chamber at a 2.5 watt flux; you will find the animals are incapacitated at a carboxyl-haemoglobin level of 7%. The nature of the products is aldehydes, ketones, acids, etc. At 5 watts per square centimeter flux, the animals are incapacitated and they have 70% carbon monoxide saturation. All the major products at the low flux level have been destroyed. If you take a material like urethane or some experimental materials such as benzyl midacol, which we have looked at, at 2.5 watts there are no smoke or toxic products after 90 minutes, but at 7.5 watts, though it meets all the criteria of the proposed new FAA standard, that is, it does not smoke or burn, all the animals die. They die from a high release of HCN and cyanogen. We cannot make guesses on three or four materials; we must test in a real fire scenario which your tank test approaches. Computer techniques are useful as well as the mass optical density principles; we can predict within 2 or 3% the amount of smoke as well as the nature of the products with these techniques. This is the proper use of an MBS chamber.

Mr Auvinet: Je pense que la majorité des gens dans cette salle connaissent les travaux extrêmement intéressants qu'a poursuivi le Dr. Einhorn à l'Université de l'Utah sur ces questions.

Je voudrais dire que des études sur la toxicité en présence d'animaux ont été évidemment envisagés et si nous n'avons pas commencé dès le départ de cette manière, c'est parce que nous avons pensé qu'il était nécessaire, tout d'abord de dégrossir le problème qui était extrêmement complexe. Je suis tout à fait d'accord qu'actuellement on a coutume de juger un nombre de gaz comme étant très toxiques, alors qu'on laisse de côté des tas de produits qui le sont tout autant, sinon plus, et que seule une étude en présence d'animaux pourra nous permettre de juger de l'importance de la nocivité. Nous avons bien l'intention de continuer nos études sur ces essais en relation étroite avec le corps médical en présence d'animaux.

SOME ASPECTS OF SMOKE AND FUME EVOLUTION FROM OVERHEATED NON-METALLIC MATERIALS*

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SUMMARY

The development to date of a dynamic system for assessing the smoke and fume emission characteristics of non-metallic materials is described. A sample of the material under examination is heated from ambient to 500°C in a stream of air. In this way, the behaviour of the material under in-flight electrical overheating conditions is simulated more closely than in the NBS smoke chamber test. Sample temperature, smoke density and electrode response in a water bubbler are monitored. Results obtained for various materials are presented and discussed.

INTRODUCTION

Since an accident to a Boeing 727 aircraft at Salt Lake City in 1965, considerable effort has been applied to establishing test methods for screening flammability and smoke-emission properties of aircraft interior materials. The Boeing crash landed short of the runway and caught fire. Of the 91 persons on board, 50 escaped but the remaining 41 were killed by heat, smoke or fumes, or a combination of these factors, although the report¹ concluded that this was a survivable accident.

Work initiated by the Federal Aviation Administration led to the introduction of more stringent regulations regarding flammability of aircraft interior materials, and further regulations regarding smoke emission are imminent. It is thought that smoke-emission properties will be specified in terms of performance in the Aminco-National Bureau of Standards smoke chamber test², originally designed for assessing building materials. In this test, intense radiant heat, with or without a pilot flame, is applied to a specimen of prescribed area in a chamber of volume 18 ft³. The optical density of the smoke is measured with a light beam and photometer arranged vertically to overcome the effects of smoke stratification. Smoke emission of a material is given in terms of 'specific optical density', ie optical density over unit path length in a chamber of unit volume and produced by a specimen of unit surface area. Various factors can be measured, eg maximum smoke density, rate of smoke accumulation, time to reach maximum smoke density, time to reach a prescribed smoke density. The Aminco-NBS smoke chamber test is suitable for assessing the behaviour of materials in a crash fire, since conditions of intense radiant heat in a static enclosed environment are simulated.

At the Royal Aircraft Establishment, we have been concerned with a less dramatic but more insidious form of aircraft fire hazard, the in-flight electrical fault. Whilst the smoke chamber test may give some idea of a material's smoke-emission characteristics in a fully-established in-flight fire, we considered it inappropriate for studying the equally important earlier stages of the fire, ie during heating of the insulant material but before flaming occurs. Our concern was particularly with electrical faults in the cockpit with their attendant possible incapacitating effects, by smoke and fume emissions, on the aircrew. The requirements of a test to simulate the behaviour of insulant materials in this situation were considered to be:

- 1 Temperature of specimen to be raised from ambient to that at which decomposition is complete, preferably with the option of several heating rates.
- 2 Heating to be carried out in a controlled gas flow.
- 3 Facility for recording smoke density during heating.
- 4 Facility for monitoring toxic or irritant gases.

As no existing test method met all these requirements, a prototype apparatus^{3,4} was built at RAE in which samples of materials used in aircraft electrical systems were heated up to 360°C over a period of about 20 min in a stream of air (100 ml min⁻¹). The rate of heating was not constant because the 'furnace' was simply a drilled aluminium block on an electric hot plate which was allowed to reach its maximum temperature from cold without control. The effluent was passed through a cuvette in a selenium cell photometer fitted with a blue filter, transmission being measured with a galvanometer. Provision was also made for smelling the effluent and testing it for carbon monoxide (indicator tube) and with damp litmus paper. The results of these preliminary tests indicated that reasonably consistent smoke/temperature patterns could be obtained and that the effluent often had a noticeable smell some time before the instrument detected any smoke. No carbon monoxide was detected in any of the tests.

The apparatus was next modified to a form in which the effects of variables could be examined.^{3,4} The rate of temperature rise was controlled by means of a temperature programmer connected to an electric furnace operating to 500°C. Ten different temperature rise rates, from 1 to 20°C min⁻¹, could be used. For measuring smoke intensity, a spectrophotometer was used instead of the selenium cell photometer, so that the wavelength of light to be absorbed by the smoke could be varied between 200 nm and 800 nm. It

was also possible to stop the air flow and hold the furnace temperature at any point in an experiment in order to scan the ultraviolet spectrum of the smoke. Since acids and alkalies are the most readily monitored broad class of irritants, a glass combination electrode in a water bubbler was included in the train. Chloride- or fluoride-sensing electrodes were used in some experiments with PVC or PTFE, respectively. With a heating rate of $20^{\circ}\text{C min}^{-1}$, decreasing the air flow rate resulted, as would be expected, in increased smoke intensity. Decreasing the wavelength of light resulted in apparently increased smoke intensity; this would be expected, as light of shorter wavelengths is scattered more than longer wavelengths and, in the ultraviolet region, light is absorbed by certain chemical groups.

The modified apparatus suffered from the following disadvantages:

- 1 The smoke traces were not quantitatively comparable in peak height, or area when absorbance was monitored, and the temperatures at which events were first detected were reproducible only to $\pm 10\text{-}20^{\circ}\text{C}$.
- 2 The sample size was limited both by the size of the combustion tube and by the necessity to keep smoke intensities within the meaningful range of the spectrophotometer.
- 3 Condensation usually occurred in the spectrophotometer cell; the onset of condensation could not be seen inside the cell compartment.
- 4 The sample could not be seen during an experiment.
- 5 The temperature of the sample itself was not known and endothermic or exothermic reactions could not be detected.

Despite these drawbacks, the apparatus was used to examine the smoke and fume emission properties of a range of materials. In many cases it was found that a material emitted irritant fumes at temperatures significantly below those at which visible smoke was detected. It was also demonstrated by simple subjective tests that small steps in the acidic or alkaline fume traces usually represented sufficient amounts of irritants to affect the nose or throat.

APPARATUS

The apparatus was modified to try to overcome the disadvantages mentioned above and particularly to make the smoke results more reproducible and quantitative. The current system is shown diagrammatically in Fig 1. Air is drawn through the combustion train via a rotameter and control valve. A thermocouple D is embedded in the sample C and its response monitored by a potentiometric recorder E. The furnace B is constructed of glass so that the sample is visible throughout the run. The furnace temperature is controlled via a platinum resistance thermometer F by a temperature programmer G (usually set to give a temperature rise of $20^{\circ}\text{C min}^{-1}$). Smoke and gases emitted by the heated sample are drawn between flat, parallel windows I, in the light path of a selenium cell photometer H, which is connected to a logarithmic potentiometric recorder J and, from there, through a retransmitting potentiometer to a digital integrator K. Finally the smoke and gases pass through a bubbler L containing water. Changes in pH of the water are monitored by a combination glass electrode M connected to a pH meter (valve millivoltmeter) N, whose output is fed to a potentiometric recorder O.

This system, although basically similar, incorporates several improvements over the apparatus previously described, viz:

- 1 The combustion tube is larger, allowing samples of about 400 mg to be examined; the previous sample weight was 50-100 mg. Although the test is still very much a small-scale one, the increased capacity allows the use of a more representative sample than before.
- 2 The furnace is constructed of glass so that the behaviour of the sample can be observed throughout the run. Swelling, melting, colour changes, bubbling, incandescence, etc can be related to events on the recorder traces.
- 3 The temperature of the actual sample is monitored by a thermocouple embedded in it. Exothermic and endothermic reactions can be detected and related to events on the other traces.
- 4 The spectrophotometer is replaced by a simple filter photometer, the spectral response of which is close to that of the human eye. In the preliminary experiments, little additional information was gained from the ability to vary wavelength by use of the spectrophotometer.
- 5 Instead of transmittance, absorbance of the smoke is monitored by means of a logarithmic recorder. Absorbance is, by Beer's Law, proportional to concentration of the absorbing medium, hence the area under a plot of absorbance against time (ie the trace from recorder J) is proportional to the total amount of smoke passing the windows in that time. From this area, a smoke number, representing the amount of smoke evolved by a standard weight of a material, can be calculated. To facilitate the area measurement a digital integrator is used, but the measurement can also be made by tracing, cutting out and weighing the peaks on the recorder chart.

RESULTS

In each experiment performed with the apparatus described, three recorder traces are produced (eg Fig 2), all of which are related to the same time scale. The first trace records the rise in temperature of the sample; temperatures at which events occur on the other traces can be found by reading across to this. Any deviation from the smooth temperature rise observed in an inert specimen represents an endothermic or exothermic reaction. The second trace is that of pH (or other chemical-sensing electrode response) in the bubbler, and the third that of absorbance of the smoke passing between the windows.

From these traces and the integrator reading representing the area under the smoke trace, the following information can be extracted:

- 1 Temperatures of initiation of endothermic and exothermic reactions.
- 2 Temperatures at which acidic or alkaline fumes are emitted.
- 3 Semi-quantitative estimate of such emissions (bubbler efficiency is only about 80-90% for hydrochloric acid gas).
- 4 Temperatures of smoke emissions; temperature of initiation of smoke is considered to be more useful than temperature of maximum smoke intensity for a peak.
- 5 Rate of smoke evolution.
- 6 Maximum smoke intensity.
- 7 Smoke number, ie amount of smoke emitted per gram of material per 1 cm light path. The amount of smoke is calculated in absorbance minutes from the area under the smoke trace, so the units of the smoke number are absorbance min $g^{-1} cm^{-1}$. The smoke number can be used to compare the total smoke emitted by standard weights of different materials under the dynamic conditions of the test.

To illustrate the kind of information provided by the apparatus, Fig 2 shows the traces given by rigid PVC and rigid PVC containing a smoke suppressant. The suppressant has the effect of reducing the smoke number from about 3.4 to 0.5. The traces also show that, whilst the dehydrochlorination of PVC is an endothermic process, the effect of the suppressant is to make emission of smoke and acid fumes at this stage more abrupt due to some exothermic process. In addition the final exothermic decomposition process, which produces a visible glow and hence the possibility of ignition of nearby materials, occurs much sooner in time (yet at a similar temperature) when the suppressant is present.

A number of materials have been tested in the apparatus and the results are summarized in Table 1. The materials can be ranked in various ways, as shown in Table 2. The positions of some materials in the list, eg nylon 6 and fire-retardant polyurethane foam, are changed when the temperatures of smoke initiation are taken into account. In the situation of overheating electrical components in aircraft these temperatures are important. It is also interesting to note that NBS smoke chamber tests on equal thicknesses of polymethylmethacrylate (PMMA) and wool under non-flaming conditions⁵ showed that PMMA gave over three times the maximum smoke density observed for wool; the total smoke emitted in our experiments was over three times as great for wool as for PMMA.

The traces produced by tests on wool and nylon 6 are shown in Fig 3. In each case, both acidic and alkaline fumes were emitted alternately and some of the emissions occurred before any visible smoke was produced. These two materials and rigid PVC were subjected to thermogravimetric analysis (TGA), a technique which has been advocated for studying flammability and smoke emission properties⁶. The TGA curves were differentiated and plotted alongside our smoke traces (Fig 4). A broad correlation can be seen but the TGA peak does not necessarily give a reliable estimate of the smoke intensity. Neither, of course, is any information given about the nature of the emissions.

The effects of added plasticiser on the traces for PVC are shown in Fig 5. The most obvious effect is the increase in intensity of the first smoke peak in relation to the second. The exotherm marking the final stages of decomposition appeared earlier for plasticised PVC; altogether the presence of this plasticiser (a phthalate) worsened the performance of the PVC in the test.

Fig 6 compares the behaviour of two flexible polyurethane foams, one of them made fire retardant by its low drip temperature. The fire-retardant foam produced less smoke, and no exotherm corresponding with the smoke intensity maximum. Although alkaline fumes appeared at a slightly lower temperature in the case of the fire-retardant foam, its performance was definitely better on the whole.

Traces for expanded polystyrene (EPS) and PMMA are shown in Fig 7. In both cases acidic fumes were detected before visible smoke. These are not the only irritant fumes emitted: it is well known that both polymers can break down largely to their monomers, both of which are irritants but would not be detected by the electrode system used in these experiments.

Fig 8 shows traces for wood (British Columbian pine) and polytetrafluoroethylene (PTFE). The wood gave some alkaline fumes before visible smoke, the smoke being accompanied by acidic fumes. A large exotherm corresponded to the final glowing decomposition and to an abrupt decrease in the smoke intensity (cf Fig 2, PVC + smoke suppressant). Finally, the traces for PTFE show once again that a material exhibiting low smoke-emission may still evolve undesirable fumes when heated, often at surprisingly low temperatures.

DISCUSSION

Despite the replacement of the spectrophotometer, the latest apparatus retains much of the versatility of the previous system. The gas flowing through the combustion train can itself be varied, eg nitrogen can be used to simulate non-oxidative, sub-surface pyrolysis, or an oxygen-enriched atmosphere can be simulated. The flow rate of the gas is also easily varied, as is the rate of temperature rise; preliminary investigations of the effects of these two variables are discussed below. Although the bubbler has contained water and a glass (pH-sensing) electrode in most experiments done so far, other chemical-sensing electrode systems could obviously be substituted. Chloride- and fluoride-sensing electrodes were successfully used with the previous apparatus, and electrodes responding to cyanide, ammonia, sulphur dioxide, etc could be useful in the examination of particular classes of polymers. Preliminary experiments have shown that sensitive monitoring of aldehydes (a class of irritant evolved in the oxidative pyrolysis of

wood and many synthetic polymers) should be possible by an electrode method.

The effects of temperature-rise and air-flow rates on the smoke produced by rigid PVC have been investigated. Tables 3 and 4 show the effects found; as would be expected faster air flow gives lower smoke numbers, because of dilution and increased throughput of air. The rate of temperature rise has little effect over the range examined. The higher heating rates are beyond the capacity of the temperature programmer and were reached by direct heating of the combustion tube with a gas burner flame. The lack of effect of varying the rate of temperature rise is encouraging because a common criticism of dynamic test methods is that the results cannot be extrapolated to the rapid heating rates found in real fires.⁷ The rate of electrical overheating being considered in the present work can occur over a wide range and these preliminary results indicate that heating at a standard rate might be satisfactory for test purposes. Both of these effects will have to be checked on different materials before firm conclusions can be drawn. It is suspected that a sample weight effect may exist and until this is explored more fully, samples weighing between 350 mg and 450 mg are being used regardless of the smoke intensity produced. Clearly it would be advantageous to eliminate any such effect as the sample weight could then be adjusted to give absorbance values in the most suitable range.

Further modifications contemplated include development of methods for monitoring specific classes of irritants and the addition of a combustible gas detector as an indication of potential flammability of evolved gases. A facility for the introduction of a sample into the furnace preheated to a temperature of interest (ie flash pyrolysis) would be useful, particularly for temperatures at which smoke or fume emission is just starting: it is suspected that some materials emit large amounts of smoke if held at such a temperature. In cases where it is desirable to monitor several irritants simultaneously, a multiplex system could be used for taking the readings of several electrodes in rotation on a single recorder. As high-temperature-resistant materials will be obvious candidates for aircraft electrical insulants, a furnace and programmer working to higher temperatures might be considered; at these temperatures, carbon monoxide emission would be expected to become significant and should be monitored.

The apparatus described, whilst relatively simple and inexpensive, provides a considerable amount of information directly relevant to the behaviour of a material under electrical overheating conditions in flight. Whilst more sophisticated (and more expensive) systems involving gas chromatography linked with mass spectrometry give more information on the chemical composition of the degradation products, the RAE apparatus could probably be modified to monitor broad classes of toxic and irritant emissions. The method could more readily be adapted as a standard test for assessing potential materials for use in aircraft electrical systems and would give useful information not provided by the NBS smoke chamber.

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TABLE 1
SUMMARY OF RESULTS

Sample	Temperatures of:				Smoke Number of peak	Total Smoke Number	Total smoke No x 100 1st Smoke Temp
	Endo- Therm	Exo- Therm	pH Change	Smoke Initiation			
Rigid PVC	280	500	250	230	0.6	3.3	1.4
" "	280	500	260	420	2.7		
				260	0.5	3.5	1.4
				420	3.0		
Rigid PVC + smoke supp		270	270	230	0.2	0.5	0.2
				480	0.3		
" "		270	270	250	0.1	0.3	0.1
				470	0.2		
Plasticized PVC wire sheath			200	160	3.0	4.6	2.9
			265	445	1.6		
" "			185	165	3.0	4.1	2.5
			260	440	1.1		
Flexible PU foam		310	90	120	6.0	6.0	5.0
			190				
" "		310	85	140	5.8	5.8	4.1
			190				
Flexible PU (FR)			80	180	3.1	3.1	1.7
			145				
" "			85	170	2.9	2.9	1.7
			145				
PTFE	320				0.0	0.0	0.0
"	320				0.0	0.0	0.0
Nylon 6	220		355	375	6.7	6.7	1.8
"	230		345	370	5.8	5.8	1.6
Wood	70	290	80	160	2.7	2.7	1.7
			170				
"	70	290	100	170	2.3	2.3	1.4
Wool	230		80	270	5.4	5.4	2.0
	310		245	400			
"	230		70	260	4.4	4.4	1.7
	300		230	400			
EPS			120	250	3.5	3.5	1.4
			220				
"			120	250	3.8	3.8	1.5
			210				
PMMA			140	275	1.6	1.6	0.6
"			95	255	1.6	1.6	0.6

TABLE 2
RANKING OF MATERIALS TESTED

By smoke no	By first smoke temp	By $\frac{\text{Total smoke No} \times 100}{\text{First smoke temp}}$
Nylon 6	PU foam	PU foam
PU foam	Plast PVC	Plast PVC
Wool	Wood	Wool
Plast PVC	PU foam(FR)	PU foam(FR), nylon 6
EPS	PVC + Supp	
Rigid PVC	Rigid PVC, EPS	Wood
PU foam(FR)		EPS
Wood	Wool, PMMA	Rigid PVC
PMMA		PMMA
PVC + Supp	Nylon 6	PVC + supp
PTFE	PTFE	PTFE

TABLE 3
EFFECT OF AIR FLOW RATE ON SMOKE NUMBER
FOR RIGID PVC (Temp rise $20^{\circ}\text{C min}^{-1}$)

Flow rate (ml min^{-1})	Smoke number	
300	4.2,	5.0
600	3.6,	3.3
1200	1.8,	2.0

TABLE 4
EFFECT OF TEMPERATURE RISE RATE ON SMOKE NUMBER
FOR RIGID PVC (Air flow 600 ml min^{-1})

Temp rise rate ($^{\circ}\text{C min}^{-1}$)	Smoke number	
10	3.5,	3.7
20	3.6,	3.3
ca 50	3.9,	3.6
ca 100	3.8,	4.1

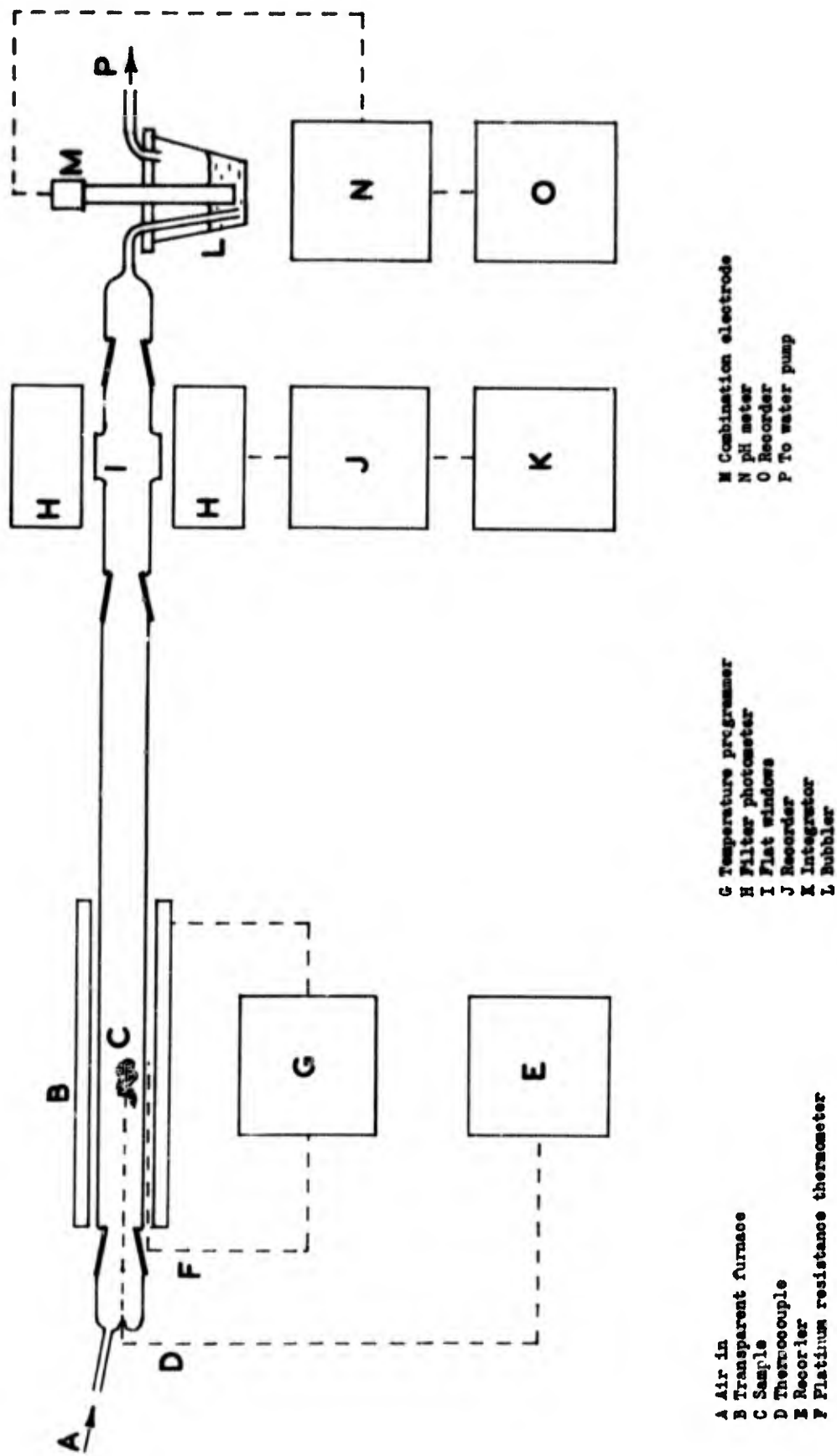


FIG.1 SMOKE AND FUME APPARATUS

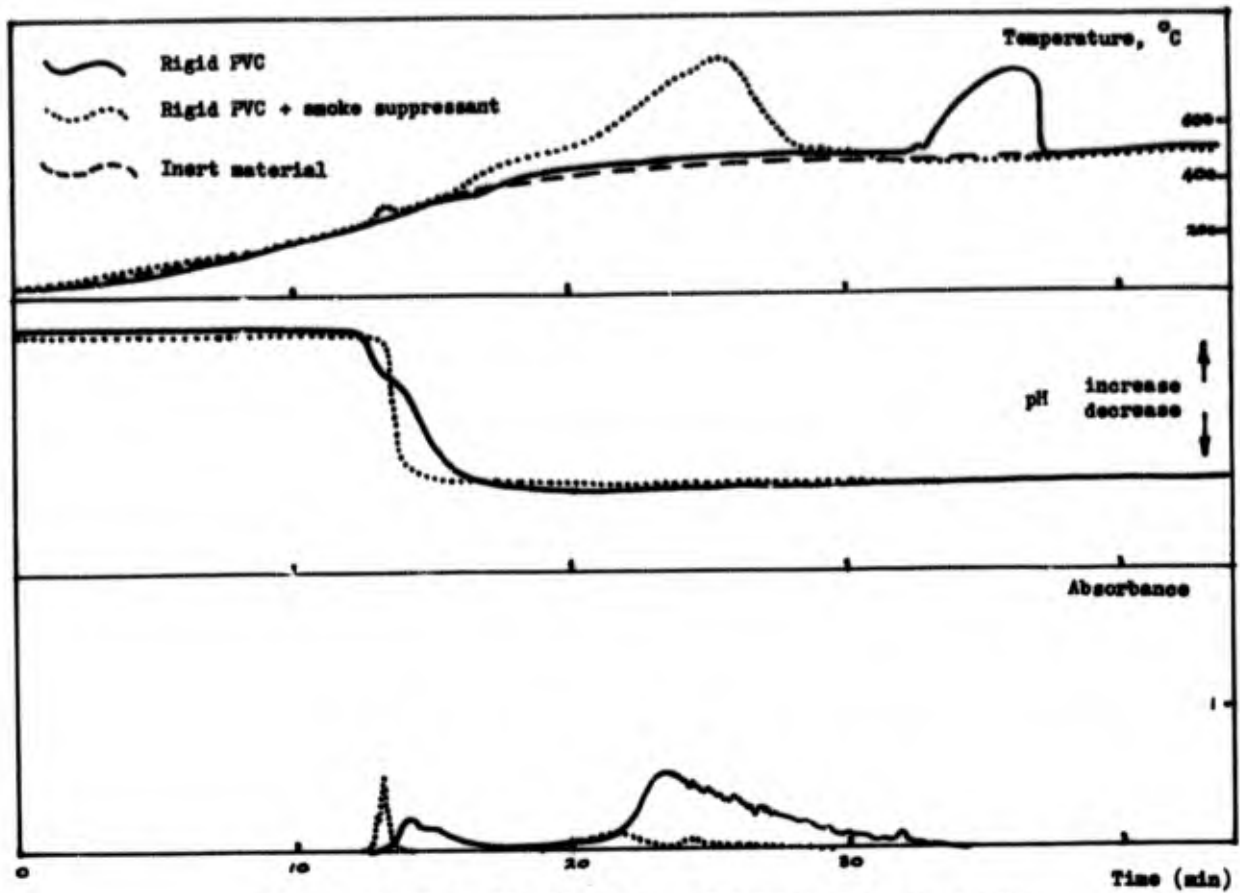


FIG. 2 RECORDER TRACES FOR PVC, WITH AND WITHOUT SMOKE SUPPRESSANT

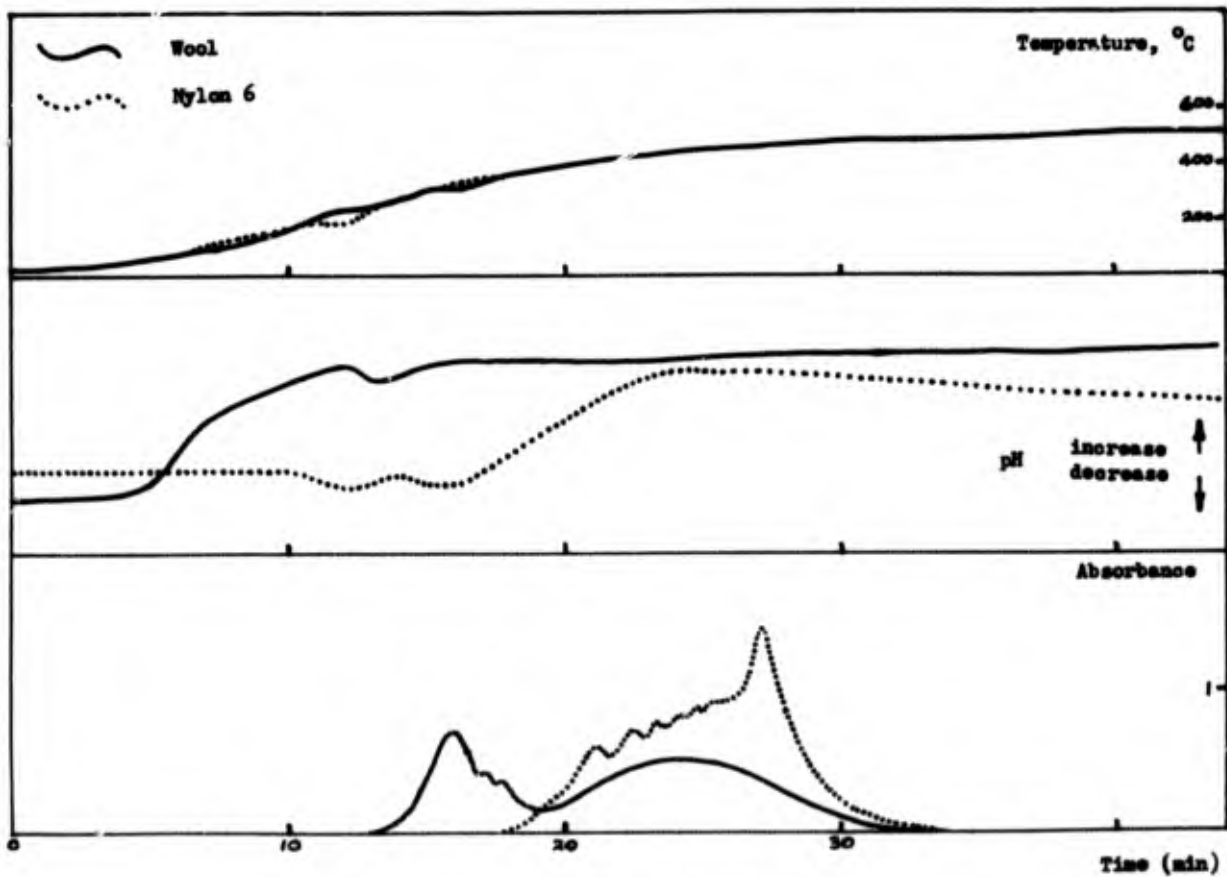


FIG. 3 RECORDER TRACES FOR WOOL AND NYLON 6

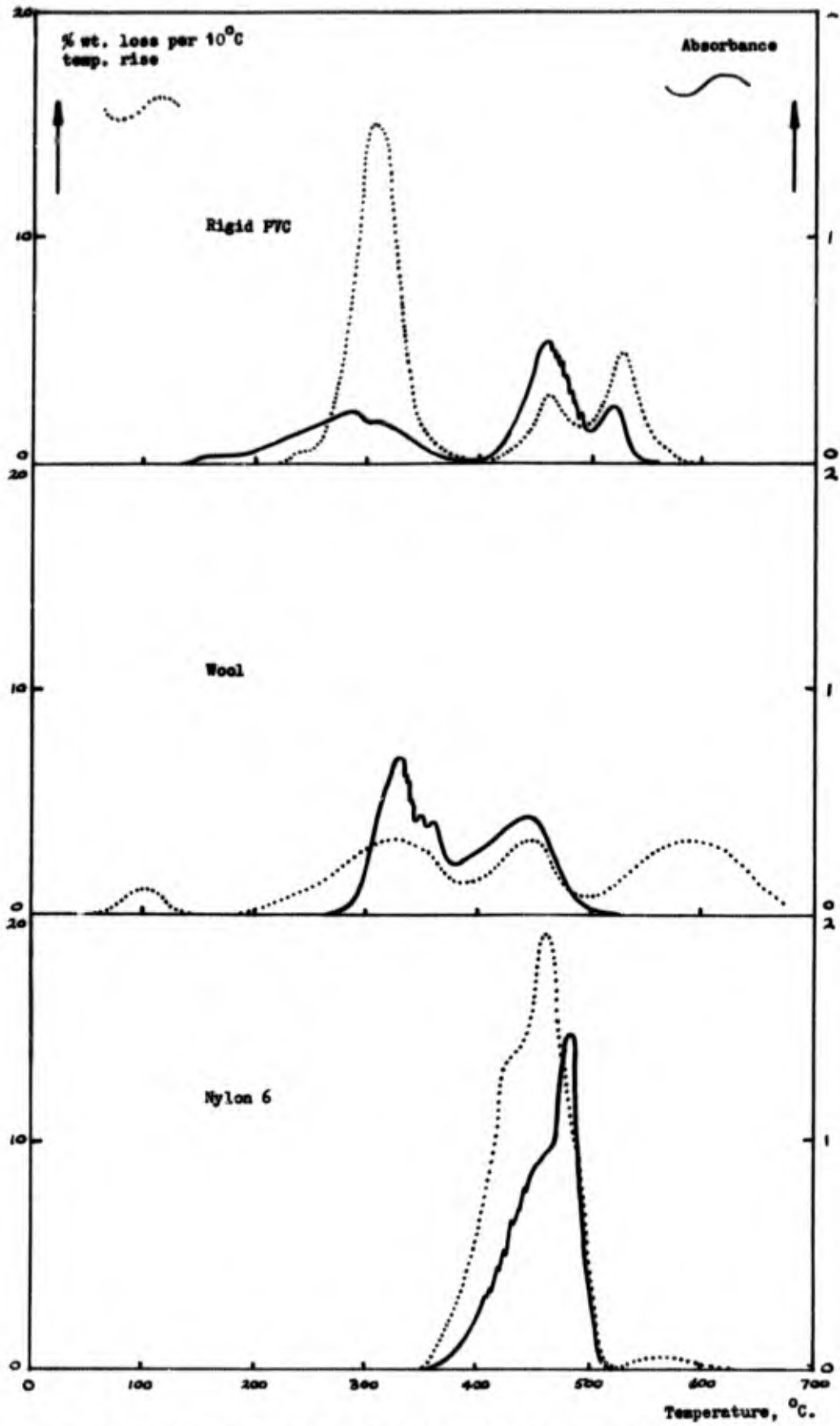


FIG.4. COMPARISON OF TGA AND SMOKE TRACES FOR THREE MATERIALS

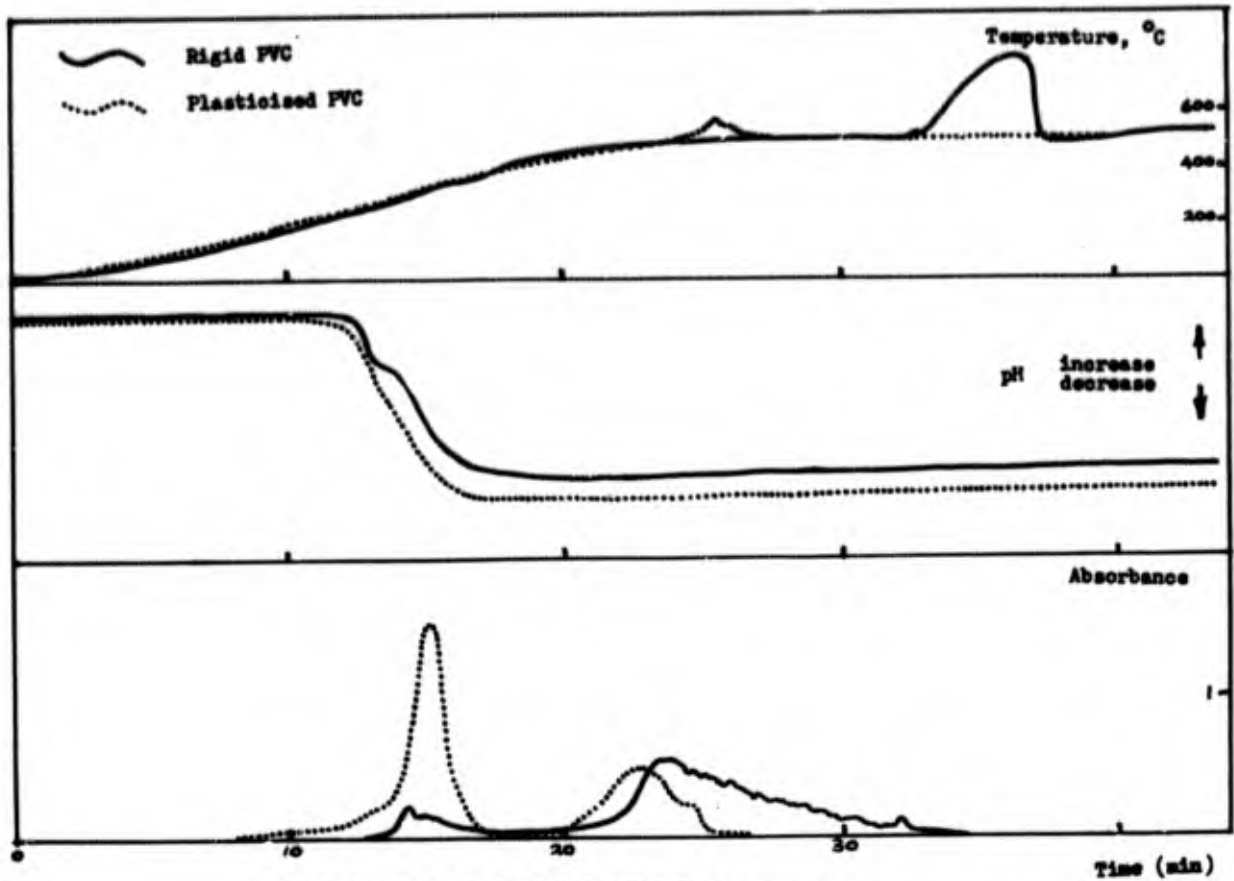


FIG.5 RECORDER TRACES FOR RIGID AND PLASTICISED PVC

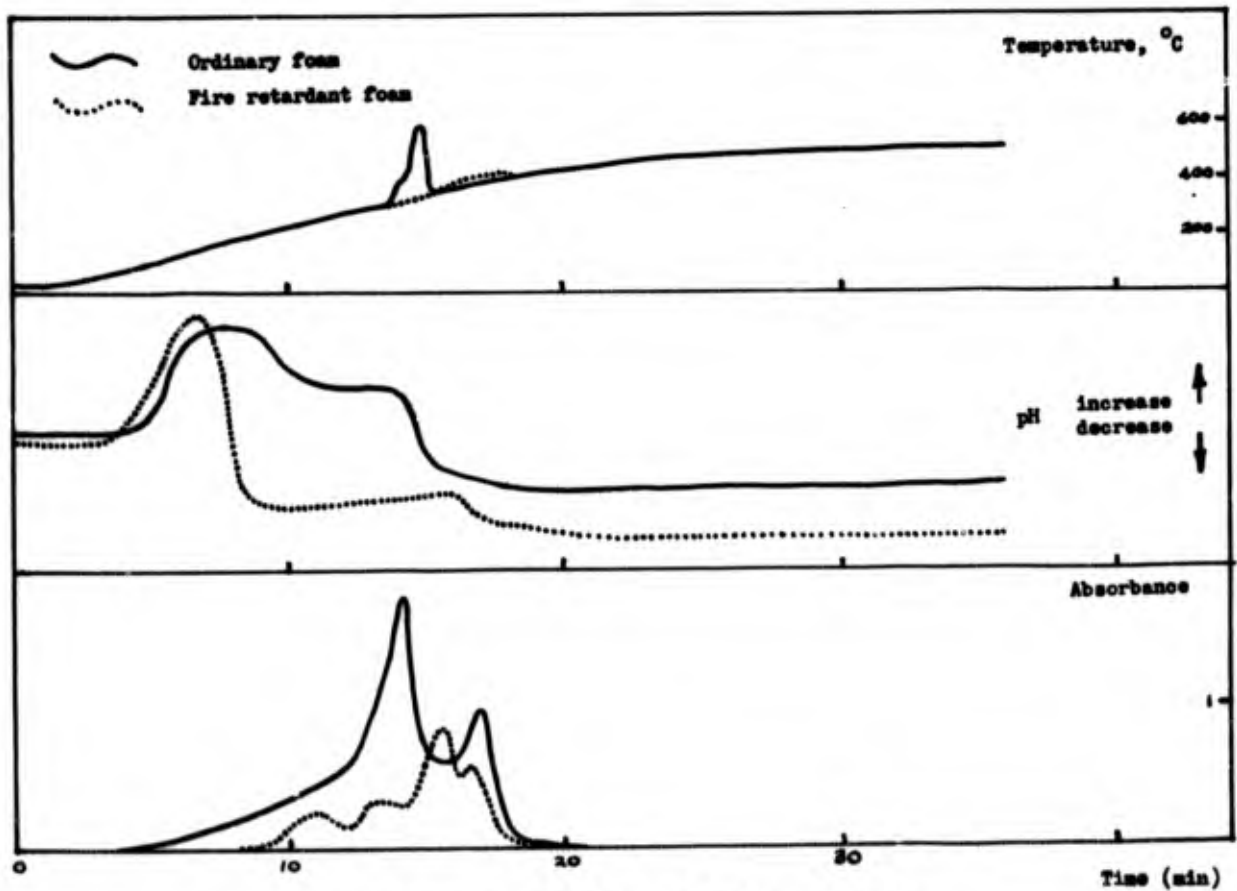


FIG.6 RECORDER TRACES FOR FLEXIBLE POLYURETHANE FOAMS

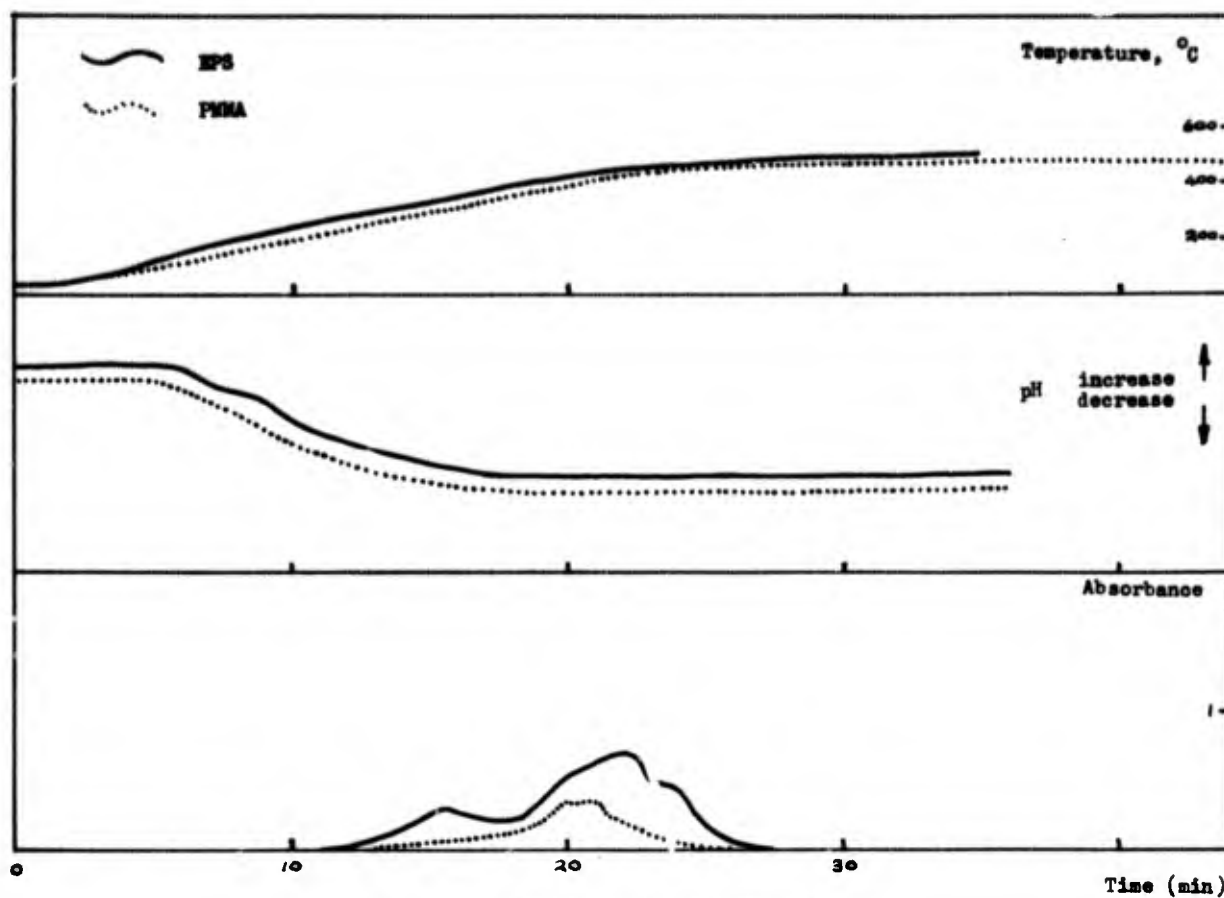


FIG.7 RECORDER TRACES FOR EPS AND PMMA

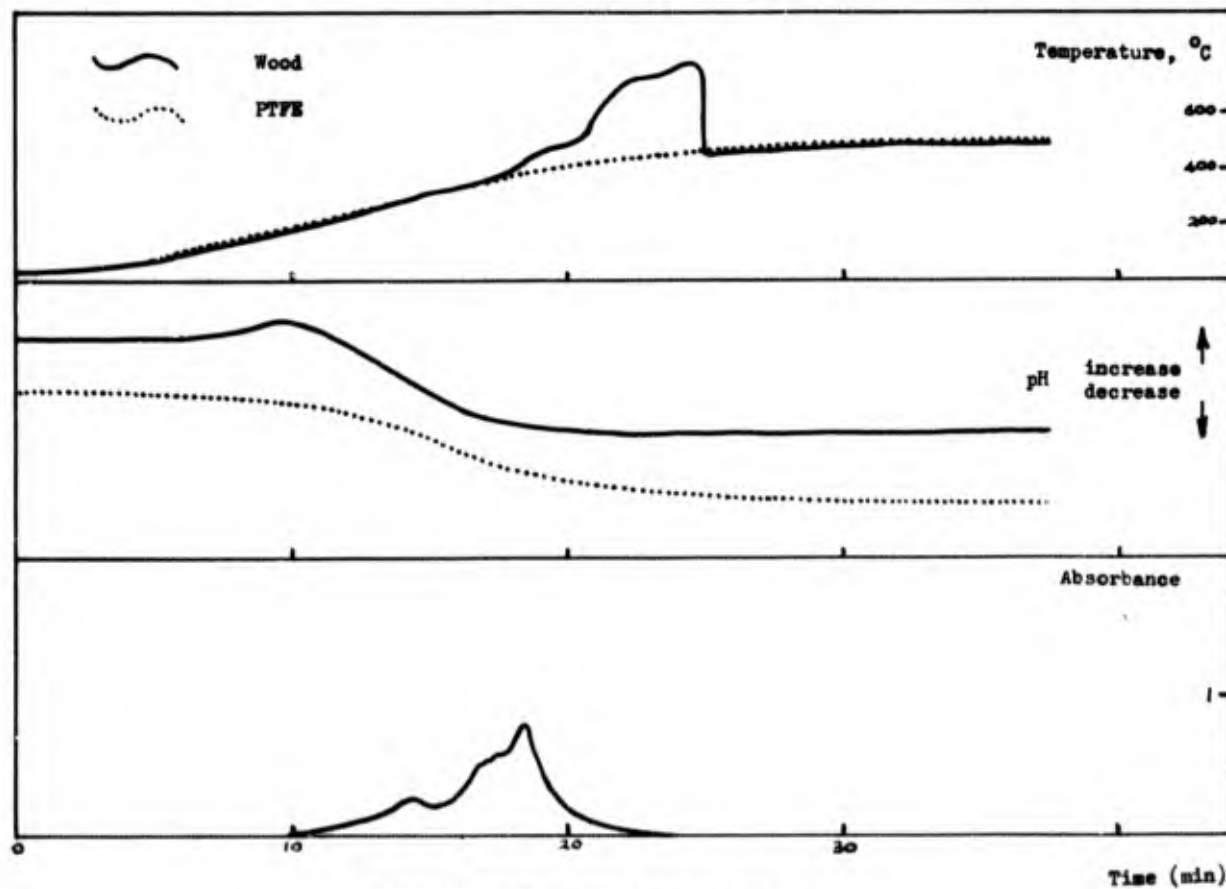


FIG.8 RECORDER TRACES FOR WOOD AND PTFE

DISCUSSION - PAPER 13

Mr Sarkos: I noticed there was a substantial length of glass tubing between the locations of pyrolysis and gas sampling. Have you ever measured the level of condensed gas losses on the surface of this tubing?

Mr Christopher: This cool length of tubing is included to simulate cool surfaces which smoke and gases from overheated electrical equipment would almost certainly meet before entering the cockpit or cabin atmosphere and also to prevent obscuration of the optical windows of our apparatus. We make visual observations of the condensed products but have not so far examined their composition or attempted to find out what degree of obscuration they would have produced before condensing.

Mr Jackson: When will suitable insulation for electrical cables which are smoke and acid free be known to the aircraft industry.

Mr Christopher: A short answer would, of course, be "never", but considerable improvements can certainly be made. We propose to examine a range of new electrical insulation materials shortly and the results of this survey may give some indication of the best materials to consider from the smoke and gas point of view. Polyimides are probably the most promising materials available at present.

Mr Macdonald: Is there a scale effect? If the surface area varies, would you expect a different result?

Mr Christopher: There are indications of a sample weight effect. Until we are certain we are keeping the sample weight close to 400 milligrams.

Mr Parker: I would not be surprised that there is a sample weight effect. The ability to get heat to the sample depends on radiant transfer processes; when the sample smokes you do not get the incident radiant energy to the sample. My argument is that the amount of energy deposited that should be defined is not necessarily the amount of energy radiated by the source. When you don't have smoke you shift your exotherm to what appears to be a much lower temperature, that is a higher heat flux at the wall. I would predict that as you went to smaller and smaller samples you would tend to drive the two peaks for PVC toward concurrence. The big gap in our understanding seems to be that no one measures the driving force for the production of smoke and toxic gases, namely the heat deposited at the wall.

**ANALYSIS OF THE PRODUCTS OF THERMAL DECOMPOSITION OF AN AROMATIC POLYAMIDE
FABRIC USED AS AN AIRCRAFT INTERIOR MATERIAL**

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SUMMARY

In this study, the thermochemistry of an aromatic polyamide fabric used in the interior of wide-bodied commercial jet aircraft was explored using several analytical techniques. The principal emphasis of this investigation was to identify the products resulting from pyrolysis, oxidative degradation, and flaming combustion. The pyrolysis data has been used to obtain a material balance between the elemental composition of the original polymer and the degradation products.

In the three environments studied, a thermally-resistant char was formed only in the inert environment. The oxidation of the sample was complete by 1000°C in both air and in oxygen. The rate at which the material was consumed was greater in oxygen than in air. In the pyrolysis and the oxidative degradation experiments, a noticeable fraction of the sample weight loss was in the form of a condensable brown material. In the pyrolysis experiments, the residue was found to be a mixture of para-dicyanobenzene and para-cyanobenzoic acid in a 10:1 ratio, but in an air environment this ratio was 1:1. There were also considerable differences in the quantities of water, carbon monoxide, and carbon dioxide formed in these two modes of degradation. Some significant changes were observed between the product distributions in non-flaming studies and the flaming combustion experiments.

The details of the analytical methodology were sufficient to obtain a complete material balance between the original polymer and the sum of the products formed in the pyrolysis experiments at 550°C. From these balances, 100.3 percent of the carbon, 92.1 percent of the hydrogen, 99.5 percent of the nitrogen, and 98.8 percent of the oxygen of the original polymeric material was accountable in the volatile products and the residues formed.

INTRODUCTION

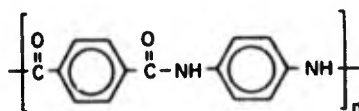
Considerable effort has been directed toward the development of space-age materials used in the fabrication of aircraft interiors which are resistant to fire. To date the major concern of those engaged in the development of fire-retardant materials has been the reduction of the ignition tendency and flame propagation. Thus, it has been possible to meet code and regulatory requirements regarding flame spread, but in the opinion of the authors, the total physiological and toxicological hazard resulting from thermal degradation processes has not been defined. An aromatic polyamide used in the interior of wide-bodied commercial jet aircraft was selected for study. A program was designed to characterize this polymer and to identify the products of degradation resulting from pyrolysis, oxidative degradation, and flaming combustion.

Special emphasis was directed toward obtaining a complete material balance so as to serve as the basis for further mechanistic studies pertaining to modes of polymer thermal decomposition. The qualitative and quantitative analysis of the products resulting from the material degradation is serving as the basis of animal bioassay experiments designed to predict potential physiological and toxicological hazards to humans during fire exposure.

The methodology reported in this paper is also being utilized to provide input for computerized modeling studies directed toward prediction of smoke obscuration and product distribution which may result during aircraft fires. This research is thus directed toward providing the engineering design criteria which will serve as the basis for promulgation of realistic standards to assess the hazard to humans during fire exposure.

MATERIAL

The aromatic polyamide was supplied for this study by the Chemical Research Projects Division, NASA-Ames Research Center, Moffett Field, California. The assumed structure of the polymer is an AABB configuration



with a molecular weight of 238 grams per mole of repeating unit.

The elemental composition of the polymer is shown in Table I. These values show that there is considerable disagreement between the theoretical calculations, based on the assumed structure of the aromatic polyamide fabric, and the experimental analytical results. Although the source of this discrepancy has not been completely resolved, it should be pointed out that the inclusion of one water molecule per

repeat unit would account for the difference between the calculated and measured elemental analysis. Since the polyamide linkage is formed in a condensation reaction between the corresponding diacid and diamine, the results obtained in the elemental analysis are not surprising. Additional evidence supporting the presence of water is provided by the thermoanalytical studies.

The infrared spectrum was obtained by grinding the fiber sample and by pressing it into a potassium bromide pellet. The spectrum exhibits a broad N-H stretch at 3430 cm^{-1} and an aromatic C-H stretch at approximately 3050 cm^{-1} . The carbonyl stretching frequency for an amide, which was found at $1650\text{--}1660\text{ cm}^{-1}$, and the R_2NH bending mode of a secondary amine at $1520\text{--}1540\text{ cm}^{-1}$, are very characteristic for this type of polymer. Wells and Crawford¹ have examined a series of aromatic polyamide polymers using internal reflectance spectroscopy. The infrared spectrum of this aromatic polyamide, supplied by NASA, is a peak-for-peak match with the spectrum for Nomex II provided by these authors. As Wells and Crawford pointed out, the infrared spectrum contains less bands than would be expected from an ortho- or a meta-substituted isomer.

EXPERIMENTAL PROCEDURES

Analytical Methodology

The general analytical scheme that was used in the analysis of this polymer is shown in Figure 1. As indicated in Figure 1, the three aspects covered in this study were (1) polymer characterization, (2) thermal characteristics as a function of heating rate and environment, and (3) thermal degradation in an inert and an oxidative environment.

Polymer characterization has been limited to the determination of the elemental analysis and the infrared spectrum of the polymer. The carbon, hydrogen, and nitrogen content of the polymer was determined utilizing an F & M Model 185 Carbon, Hydrogen, Nitrogen Analyzer. Infrared spectra were obtained using the KBr pellet technique on a Perkin-Elmer Model 237 Grating Infrared Spectrometer. All thermoanalytical studies were performed using a Mettler Thermoanalyzer 1 equipped with a corrosive gas inlet.

Prior to analysis, all samples for the studies using the Mettler Thermoanalyzer were dried at 60°C at 10^{-6} torr for several days. All gases used were checked for purity using a gas chromatograph (GC); the helium was ultra high purity grade from Matheson Gas Products and the oxygen was C.P. grade. Studies conducted in an air environment employed laboratory air that was dried by passing it through a calcium sulfate trap. The studies to determine the effect of heating rate or environment used a 10 ± 0.1 mg sample size and a carrier gas flow rate of 160 ± 10 ml/min. In order to obtain sufficient quantities of the gaseous species resulting from either pyrolysis or oxidative degradation, larger sample sizes were used in the studies conducted on the Mettler Thermoanalyzer employing trapping techniques. Samples were subjected to temperature-programming from ambient to 1000°C at dynamic heating rates of 10, 25, or $100^\circ\text{C}/\text{min}$. All experiments were performed in triplicate using aluminum oxide as the reference material.

The sub-classification of Thermal Degradation Studies (Figure 1) includes pyrolysis, thermal oxidative degradation, and flaming combustion. The schematic representation of the analytical methodology used to identify the products of degradation that eluted from the polymeric material is illustrated in Figure 2.

The chamber used to generate the products of degradation resulting from flaming combustion consisted of a 3-neck, 2-liter Pyrex flask that was similar in design to that used by Sumi and Tsuchiya.² A nichrome heating element was used as the ignition source and as a means of sustaining the combustion process until the samples ceased to flame. The sample size (0.2 gm) was determined by the availability of oxygen content in the bulb and by using the stoichiometric balance between carbon, hydrogen, nitrogen, and oxygen required to ensure complete combustion. The walls of the combustion chamber were maintained at 150°C with a heating mantle to reduce the condensation of high molecular weight species.

An arbitrary division of decomposition products into "volatiles" and "residues" has been made on the basis of compound volatility (see Figure 2). The former category includes compounds that have a significant vapor pressure under the conditions imposed by the apparatus used to trap components. Compounds classified as "residues" had low volatility and condensed on the walls of the reaction vessel or in the connecting gas transfer lines.

In the pyrolysis and oxidative degradation experiments, the volatile components were trapped for subsequent analysis using porous polymer traps at -110°C . The utility of porous polymers for trapping has been described by several investigators.^{3,4,5} At -110°C , the light gases (hydrogen, methane, and carbon monoxide) were not retained. Within the scope of the present investigation, hydrogen gas evolution was not quantitated. An estimate of the quantity of methane generated was obtained utilizing gas chromatographic techniques. The CO evolution was measured using a Miran I Infrared Spectrometer, which has a cell path-length of 20 meters, by monitoring the absorption at 2160 cm^{-1} . The trapping system used in the flaming combustion studies consisted of one porous polymer trap at room temperature in series with a similar trap maintained at -110°C . The use of the dual traps was required because of the excess water and carbon dioxide generated during the combustion process.

The identification of the degradation products produced in these studies made use of infrared spectroscopy (IR), and a computerized gas chromatograph/mass spectrometer (GC/MS) system. A Hewlett-Packard Model 7620A Research Gas Chromatograph interfaced to a Hewlett-Packard Model 5930A Mass Spectrometer utilizing a silicone membrane separator, was employed to separate and identify the complex mixtures of degradation products. A thermal conductivity detector (TC) and a flame ionization detector (FID) were used simultaneously by splitting the effluents. A splitting ratio (TC to FID) of 10:1 was employed.

An automatic electronic integrator with printout capability was used to record chromatographic peak areas and retention times for quantitative analysis. Internal standards were injected into the gas

chromatograph in known quantities to produce a plot of standard weight vs peak area. A table of response factors for gas chromatographic analysis was used to calculate the quantitative amounts of products obtained from the thermal degradation of the polymer being studied.⁶

The identification of materials separated by the gas chromatograph was obtained using a Hewlett-Packard dodecapole mass spectrometer. This system completely scans a mass range of 1 to 650 amu in two seconds. This is sufficiently fast to furnish spectral identification of separate GC peaks in real time. In the periodic scan computer-controlled mode, the mass spectrometer repetitively scans a complete GC run and stores all of the data on disc. To facilitate rapid handling of the enormous quantity of data that is gathered during a GC run, the mass spectra of the unknown compounds are compared to the enriched Alder-maston file, which contains over 18,000 mass spectra in digital form. The extensive use of a search routine employing compound molecular weight, mass fragment, and Kováts' Retention Indices, developed by Flammability Research Center personnel, greatly facilitates unknown compound identification.^{7,8}

To facilitate positive identification of compounds, three different GC column packings were used in this study: Chromosorb 101 and Chromosorb 103 (Johns-Manville Company, Denver, Colorado) and Dexsil 400 GC (Anlabs, Inc., North Haven, Connecticut). The mass spectral information that is gathered on each component that elutes from the GC column, coupled with the use of the Kováts' Retention Indices from two or more of these GC supports is usually more than ample information to identify unknown compounds.^{7,8}

The residue mixtures were analyzed using both electron impact (EI) and chemical ionization (CI) techniques.⁹ The residue mixtures were introduced via a direct insertion probe into an extensively-modified MS-30 mass spectrometer.¹⁰ The utility of CI-MS techniques to identify complex mixtures is a great asset in the identification of the compounds present in the residues.

Thermoanalytical Studies

The aromatic polyamide polymer was studied to determine what effects were evident in the polymer degradation process as the dynamic heating rate and oxygen content of the environment were changed.

Effect of Heating Rate

Samples of the polymer were heated in the Mettler Thermoanalyzer as described previously. The thermograms, as illustrated in Figure 3, indicate the changes in sample weight as a function of heating rate. There was a noticeable weight loss in the polymer at temperatures as low as 100°C, which was suggestive of a loss of water that was absorbed by the sample during handling. The loss of a water molecule from the repeat unit can account for the initial sample weight loss below 200°C of approximately two percent. A distinct increase in the rate of sample weight loss occurred between 400°C and 500°C. It was only above 500°C that the effects of the different heating rates became evident. By 600°C the sample weights of the original polymer remaining at 10, 25, and 100°C/min heating rates, were 13, 42, and 68 percent, respectively. In all three cases, oxidation of the polymers was complete by 1000°C with essentially no char remaining.

Effect of Environment

To aid in elucidating the overall mechanism of polymer degradation, the effect of oxygen concentration was investigated. The thermograms obtained for the polymer in helium, air, and oxygen environments are summarized in Figure 4. From this figure, it is apparent that the availability of oxygen plays an important role in the rate of polymer degradation at temperatures greater than 475°C.

The differential thermal analysis (DTA) thermograms for the polymer obtained in helium, air, and oxygen environments are displayed in Figure 5. As expected, the temperature for onset of the exothermic reactions decreased with an increasing concentration of oxygen. In the oxygen atmosphere the polymer ignited spontaneously, while a black char was formed without flaming combustion occurring in the air atmosphere.

Pyrolysis Studies

Analysis of Volatiles. Using the Mettler Thermoanalyzer and the procedures outlined previously, samples of the polymer were pyrolyzed in a nitrogen atmosphere at 550°C. In this series of experiments, the polymer specimens were temperature-programmed from ambient to 550°C at a heating rate of 100°C/min. The effluents from the thermoanalyzer were trapped for a subsequent analysis beginning at 300°C. This is the temperature which is just prior to the onset of the second major weight loss. The initial sampling of effluents continued for a period of three minutes after a temperature of 550°C was attained. The carbon monoxide evolution from the polymer was measured under conditions of pyrolysis in the nitrogen environment utilizing non-dispersive infrared analysis techniques. The total weight loss from the polymer attributed to carbon monoxide during pyrolysis was 3.19 percent. The details of the analytical procedure employed in the quantitation of carbon monoxide will be covered later.

The volatile products resulting from the pyrolysis were collected using the trapping system, desorbed from the porous polymer trap, and analyzed using the computerized GC/MS system. A system of 14 pyrolysis runs were conducted for identification and quantitation of the volatile products described herein.

The volatile products resulting from the pyrolysis of the aromatic polyamide at 550°C (TC and FID detection traces) are presented in Figure 6. These results were obtained using a 10-foot by 1/8-inch O.D. stainless steel column containing Chromosorb 101 stationary phase that was temperature-programmed from -20 to 240°C at a rate of 10°C/min. The compounds that have been identified from these experiments, together with the corresponding peak number for reference purposes to Figure 6, and the trapping efficiencies, and response factors used in calculating the quantity of each compound, are presented in Table II. The average weight, in mg, of the identified compounds are recorded in Table II per gram of

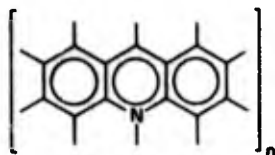
original sample. Thus, 170.55 mg/gm of original sample (including carbon monoxide) were accounted for as volatile materials resulting from the pyrolysis of the aromatic polyamide during the isothermal phase of the pyrolysis conducted at 550°C. Since virtually all (>95 percent) of the peak area in the chromatogram in Figure 6 has been identified and the quantity of each component determined, it is assumed that the remaining polymer weight loss may be attributed to hydrogen or ammonia (not quantitatively determined) plus the material which condensed in the furnace or did not elute from the chromatograph. The origin of the chlorine content in chlorobenzene is believed to be from the process employed in the fiber manufacture.

Residue Analysis. The brown residue that was deposited on the quartz walls of the furnace after heating the aromatic polyamide polymer to 550°C in a nitrogen environment was analyzed by infrared spectroscopy and CI/MS techniques. The results of these experiments are discussed below.

Infrared Analysis of Residue. The infrared spectrum of the residue was obtained by applying a thin film of this residue to a sodium chloride plate. Two very strong and sharp bands appeared at 850 and 2230 cm^{-1} which closely resemble the major absorptions from para-dicyanobenzene and not the meta isomer of the aromatic compound.¹¹ Unless there are significant chemical rearrangements involved in the pyrolysis process, these data support the conclusion that the diacid used in the manufacture of this aromatic polyamide polymer is also in a para configuration. Ehlers *et al.*¹² have published the infrared spectra of several pyrolyzates from aromatic imides and aromatic polyamide polymers. They studied an aromatic polyamide similar to the sample under investigation in this study with the exception that the diacid and diamine precursors both contained the meta configuration. The pyrolyzate obtained from this polymer when heated to 550°C in vacuum was substantially different from that observed in our present study.

Mass Spectrometric Analysis of the Residue. The residue from the pyrolysis of the aromatic polyamide was also investigated using EI and CI modes of operation on the MS-30 mass spectrometer. The temperature of the sample was programmed from 50 to 200°C over a period of five minutes while the mass spectrum was continually scanned. Only two compounds were identified from the residue: para-dicyanobenzene and cyanobenzoic acid. The former compound comprised greater than 90 percent of the total ion current produced by the sample of residue. There was no evidence to confirm the presence of free acid or base in the mass spectrum. Higher molecular weight compounds were present in lower concentrations, but these were not identified. The mass-to-charge ratio of the ions not identified were 194, 210, 212, 214, 246, and 247.

Residue and Char Analysis. The residue that remained after exposure to 550°C in the nitrogen atmosphere was 34.68 mg of the original 56.00 mg sample. The char that remained after a 1000°C exposure was 23.00 mg. This residue and char were analyzed for carbon, hydrogen, nitrogen, and oxygen content, and the averaged results from four such analyses are shown in Table III. These results indicated that almost all of the hydrogen and oxygen content and approximately one-half of the nitrogen was lost from the original polymer at 1000°C. The high carbon, but low hydrogen, content is consistent with a graphite-like structure, and the nitrogen content may suggest the presence of a nitrogen heterocyclic-type structure for the monomeric unit. This elemental analysis is consistent with a compound containing the stoichiometry C_{13}NH (C = 91.3%, H = 0.6%, and N = 8.2%). Although many chemical isomers can be drawn from this stoichiometry, one can envision a graphite-like structure of the form



Based upon the initial polymeric composition and the products that were observed to be lost in the degradation process, an argument can be made that the above structure is a likely formula for the char. The hydrogen content of the char can be thought to be a discontinuity in the aromatic structure where a hydrogen atom is present on one of the aromatic rings. A report by Mickelson *et al.*¹³ covers the in-depth study of char formation and char erosion processes.

MATERIALS BALANCE - PYROLYSIS PROCESS

Since quantitative data were presented in earlier sections of this paper on the volatile products, the condensed residues, and the char that remained from the pyrolysis of the aromatic polyamide in an inert environment, one can estimate the reliability of those data through a simple calculation of the material balance. These calculations are based upon the knowledge that 61.9 percent of the original polymer remains as a solid residue at 550°C. The composition of the aerosol residue was assumed to be a 10:1 mixture of para-dicyanobenzene and para-cyanobenzoic acid.

Table IV contains a summary of the material balance that one obtains from this experimental study of the aromatic polyamide during pyrolysis in the nitrogen environment. The TGA thermogram obtained during the pyrolysis experiments indicated that only 0.6 mole of water is associated with each repeat unit. This results in a revised average molecular weight of 248.75. Support of this hypothesis may be seen by the excellent agreement indicated in Table IV (100.3% C; 92.1% H; 99.5% N; 98.8% O), when compared to the analysis of the initial polymer.

Oxidative Degradation Studies

Samples of the aromatic polyamide were degraded in the presence of air isothermally at 550°C following a dynamic heating phase at 100°C/min from ambient to 550°C. Detailed analysis of the volatiles, aerosol residues, and char was conducted using the methodology described in the previous pyrolysis

studies. More than 20 trapping experiments were performed for identification and quantitation of the volatile products resulting from the oxidative degradation of the polymer. Seven of the experiments utilized 25 to 80 mg sample sizes; the remaining experiments were conducted with sample sizes varying from 50 to 250 mg to aid in structural identification.

Studies were also conducted to determine the nature of products formed at temperatures lower than the temperature at which the maximum rate of weight loss was observed (T_{max}); these results were also quantitated. These investigations are discussed in the following sections.

Analysis of Volatiles. The volatile products resulting from the oxidative degradation of the aromatic polyamide at 550°C (TC and FID detection traces) are presented in Figure 7. A 10-foot by 1/8-inch O.D. stainless-steel column containing Chromosorb 101 support was temperature-programmed from -20 to 220°C at a rate of 10°C/min to obtain this degree of resolution. More than 30 compounds have been observed as products from these experiments and Table V lists those compounds that have been identified. The peak numbers correspond to peaks in Figure 7; trapping efficiencies (T.E.) and response factors (R.F.) that were used in the calculations are also included in Table V.

It should be noted from consideration of the data presented in Table V that a discrepancy exists between the weight loss as measured by the TGA in the Mettler Thermoanalyzer and that determined as a result of quantitation of the volatiles by analytical procedures. It is evident that a large fraction of the oxygen content found in carbon monoxide, carbon dioxide, and water that is liberated from the sample must have resulted from an interaction between the sample and its environment.

Residue Analysis. The residue that was formed on the quartz walls of the furnace during the oxidative degradation of the aromatic polyamide was collected and analyzed using the same procedures that were discussed previously under the section pertaining to pyrolysis studies. The infrared spectrum was essentially the same as that observed in the pyrolysis studies. However, CI/MS analysis indicated that the residue contained approximately 50 percent para-cyanobenzoic acid. The ratio of the major products is considerably different than that obtained when the polymer sample was decomposed in an inert environment. This observation is not surprising since it is very likely that free oxygen in the air does interact with the polymer in the degradation process.

Char Analysis. Unlike the polymer degradation studies conducted in the inert environment wherein a char residue of 50 percent was observed at 1000°C, no visible char remained at 1000°C in the oxidative environment. A non-volatile residue was present at 550°C, but the composition of this material was not pursued at this time.

Analysis of Volatile Products at a 20 Percent Weight Loss. To obtain a better understanding of the oxidative degradation process, the volatile gases that were produced from the aromatic polyamide were studied in a temperature range below that where the maximum rate of degradation occurred. Using the TGA trace in Figure 4 as a guideline, products from the oxidative degradation experiments were trapped up to a maximum temperature of 425°C, which roughly corresponds to the point at which 10 percent of the sample weight was lost. A majority of the products that were trapped should be those compounds that are associated with the maximum in the sample weight loss at 380°C.

In this experiment, a 260 mg sample of the aromatic polyamide was temperature-programmed at 100°C/min from ambient to 425°C. The products from the oxidative degradation process were trapped beginning at 300°C and the sampling period was extended for three minutes after the final temperature of 425°C was attained. The polymer sample lost an average of 51.4 mg of weight, or 19 percent of the total polymer weight, during the sampling period. Table VI summarizes the compounds identified and the quantity of each that was found during this sampling period. Of the 51.4 mg of sample weight lost, only 7.0 mg was found as volatile products. The remaining weight loss, it must be assumed, is in the form of aerosol residues.

Carbon Monoxide Analysis

The evolution of CO from the aromatic polyamide was evaluated in both nitrogen and air environments from ambient to 800°C. The temperature of the samples was increased at 100°C/min with the exception of an isothermal hold of the programming rate at 550°C for 30 seconds to establish an accurate reading of CO concentration at T_{max} . Figure 8 shows the change in the carbon monoxide concentration as the polymer was heated in both nitrogen and air environments. As this figure shows, the CO evolution from the sample begins at approximately 350°C and maximizes at values of 9.5 and 3.2 percent of the original polymer weight at 550°C. Above T_{max} , there is a slight increase in the CO produced when the sample is heated in air, but this increase is not present in the data taken in the inert environment.

Flaming Combustion Studies

The products from the degradation of the aromatic polyamide, under conditions of flaming combustion, were studied using the apparatus that was described previously. A 0.2 ± 0.05 g sample of the polymer was ignited and the flaming mode was sustained by using the nichrome wire heat source. A total of four samples were ignited and the products were trapped and then desorbed from the porous polymer trapping system for subsequent GC/MS analysis. Figure 9 contains the FID and the TC detector traces from the effluents produced in these flaming combustion studies that condensed in the low temperature (-110°C) trap. The products that were collected in the room temperature trap were only the less volatile products that are shown in Figure 9.

Table VII is a summary of the volatile products that have been identified from these flaming combustion studies. The peak numbers corresponding to the GC traces in Figure 9 and the quantity of each compound in milligrams per gram of polymer is included in this table. The quantities of each compound that were measured must be considered as only an approximate lower limit to the actual amount because of the uncertainties imposed by the trapping arrangement used during these experiments. It

should be noted that the amount of hydrogen and carbon monoxide produced in the flaming combustion mode was not determined.

The sum of the products in Table VII account for 429-mg per gram of original polymer weight. A major portion of the organic fraction in the products is acetone, benzonitrile and a compound with the composition of $C_{10}H_{12}$. Nitric oxide, carbon dioxide, ethanal, nitromethane, and styrene are other compounds that are present in significant quantities. Further work is presently under way to quantitate these results.

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TABLE I
ELEMENTAL ANALYSIS FOR THE AROMATIC POLYAMIDE POLYMER

Element	Percent Composition			
	Sample As Received		Theoretical ^a	Theoretical ^b
	FRC Analysis	Commercial ^c Laboratory Analysis		
Carbon	65.2	64.4	70.6	65.5
Hydrogen	4.8	4.9	4.2	4.8
Nitrogen	12.6	10.8	11.8	10.9
Oxygen	17.4	19.3	13.4	18.8

^aBased upon the assumed structure of the repeat unit.

^bBased upon the assumed structure of the repeat unit if one molecule of water per repeat unit is present.

^cResults from Schwartzkopf Microanalytical Laboratories.

TABLE II
SUMMARY OF THE VOLATILE PRODUCTS FROM THE PYROLYSIS OF THE
AROMATIC POLYAMIDE FIBRIC IN NITROGEN AT 550°C²

Compound	Peak No. ^a	T.E.C. ^c	R.F.d	Quantity ^e
Carbon monoxide	1	0.00	0.670 ^f	32.
Methane	2	0.05	1.031 ^f	2.9
Carbon dioxide	3	0.97	0.915 ^f	56.
Nitrous oxide	4	1.00 ^g	0.820 ^f	0.01
Ethylene	5	0.96	0.980	0.027
Acetylene	6	0.96 ^g	0.930	0.003
Ethane	7	0.98	1.031	0.014
Cyanogen	8	0.44 ^g	1.5 ^g	0.001
Propene	9	0.98 ^g	0.652 ^f	0.014
Hydrogen cyanide	11	0.44	1.5 ^g	0.44
Water	10	0.82	0.550 ^f	53.
Acetonitrile	14	0.95 ^g	2.564	0.27
Acetone	14	0.95 ^g	2.041	0.020
Propenenitrile	15	0.95 ^g	1.679	0.029
Acetic acid	17	0.80 ^g	4.167 ^f	0.43
3-Butenenitrile	18	0.95 ^g	0.727 ^f	0.17
Benzene	19	0.90	0.893 ^f	7.1
Butanenitrile	20	0.95	0.727 ^f	0.020
Dioxane	21	0.95	1.25 ^g	0.037
Toluene	22	0.95	0.935	1.9
Chlorobenzene	23	0.95 ^g	1.10 ^g	0.033
Xylene	23	0.95	0.971	0.13
Phenol	24	0.88	1.380	0.1
Benzonitrile	25	0.90 ^g	1.136	13.6
Tolunitrile	26	0.90 ^g	1.10 ^g	1.2
Dicyanobenzene	27	0.80 ^g	1.37 ^g	1.1
Total				170.55

^aEstimated.

^bThe pyrolysis of four samples with an average weight of 56 mg of sample and a 19 mg sample weight loss during the sampling period (as measured by the TGA on the Mettler Thermoanalyzer).

^cCorresponds to peak numbers in Figure 6.

^dRelative trapping efficiencies.

^eRelative response factors for flame ionization detector.

^fMilligrams of compound produced per gram of polymer as measured by analytical techniques.

^gRelative response factors for the thermal conductivity detector.

^hElution time greater than 45 minutes, thus this peak does not appear on the chromatogram.

TABLE III
ELEMENTAL ANALYSIS OF THE AROMATIC POLYAMIDE
RESIDUES AT 550°C AND 1000°C²

Element	% of Composition	
	At 550°C	At 1000°C
Carbon	80.5	91.9
Hydrogen	3.6	0.3
Nitrogen	11.7	8.0
Oxygen	4.2	0.0

^aChar remaining after pyrolysis in nitrogen atmosphere to the specified temperature.

TABLE IV
SUMMARY OF THE MATERIAL BALANCE FOR THE AROMATIC POLYAMIDE
FABRIC IN NITROGEN AT 550°C

	Weight (mg)				
	Total	Carbon	Hydrogen	Nitrogen	Oxygen
Original polymer	56.00	37.83	2.52	6.30	9.35
Material recovered	56.00	37.95	2.32	6.27	9.46
Volatiles	9.41	2.93	0.5	0.23	5.75
Amrosol residues	9.59	7.11	0.3	1.99	0.19
Residue after pyrolysis	34.68	27.91	1.26	4.05	1.46
Initial loss of water ^a	2.32	---	0.26	---	2.06
Percent of polymer accountable in products	100.0	100.3	92.1	99.5	98.8

^aWater lost by the sample as measured by the TGA on the Mettler Thermoanalyzer prior to the trapping of the volatiles.

TABLE V
SUMMARY OF THE PRODUCTS RESULTING FROM THE OXIDATIVE DEGRADATION OF THE
AROMATIC POLYAMIDE FABRIC IN AIR AT 550°C^a

Compound	Peak No. ^b	T.E. ^c	R.F. ^d	Quantity ^e
Carbon monoxide	1	---	---	95.2
Methane	3	0.05	1.031 _f	0.085
Carbon dioxide	4	0.97	0.951 _f	322.000
Nitrous oxide	5	1.00	0.890 _f	2.600
Ethylene	6	0.96	0.990 _f	0.066
Acetylene	7	0.96 ^g	0.930 _f	0.130
Cyanogen	8	0.44 ^g	1.500 _f	0.230
Propene	9	0.98 ^g	0.652 _f	0.002
Hydrogen cyanide	11	0.44	1.500 _f	0.790
Water	10	0.82	0.550 _f	103.000
Acetonitrile	16	0.95 ^g	2.564 _f	0.160
Acetone	16	0.95 ^g	2.041 _f	0.062
Propenenitrile	17	0.95 ^g	1.679 _f	0.240
Nitromethane	18	0.95 ^g	2.000 _f	0.036
Acetic acid	g	0.80 ^g	4.167 _f	0.092
3-Butenenitrile	19	0.95 ^g	0.727 _f	0.017
Benzene	20	0.90	0.893 _f	0.430
Butenenitrile	21	0.95 ^g	0.727 _f	0.009
Dioxane	g	0.95 ^g	1.250 _f	0.016
Toluene	22	0.95	0.935 _f	0.022
Chlorobenzene	23	0.95 ^g	1.500 _f	0.039
Xylene	23	0.95	0.971 _f	0.062
Phenol	24	0.88 ^g	1.388 _f	0.140
Benzonitrile	25	0.90 ^g	1.136 _f	2.700
Tolunitrile	26	0.90	1.343 _f	0.011
Benzoic acid	27	0.90	1.590 _f	0.980
Dicyanobenzene	28	0.80	1.400 _f	1.100
Total				531.000

^aEstimated.

^bThe oxidative degradation of five samples with an average weight of 64 mg and a 21 mg sample weight loss during the sampling period (as measured in the Mettler Thermoanalyzer by TGA).

^cCorresponds to peak numbers in Figure 7.

^dRelative trapping efficiencies.

^eRelative response factors for the flame ionization detector.

^fMilligrams of compound produced per gram of polymer as measured by analytical techniques.

^gRelative response factors for the thermal conductivity detector.

^hObserved on a Chromosorb 103 column only.

TABLE VI
A SUMMARY OF THE VOLATILE PRODUCTS FROM THE OXIDATIVE
DEGRADATION OF THE AROMATIC POLYAMIDE POLYMER
AT 300 TO 425°C IN AIR^a

Compound	T.E. ^b	R.F. ^c	Quantity ^d
Carbon monoxide	0.0	0.915 ^e	9.4
Carbon dioxide	0.97	0.915 ^e	0.04
Water	0.82	0.550 ^e	25.
Acetonitrile	0.95 ^g	2.564	0.06
Benzene	0.90	0.893	0.04
Toluene	0.95	0.935	0.02
Chlorobenzene	0.95 ^g	1.5 ^g	0.002
Xylene	0.95	0.971	0.004
Benzonitrile	0.90 ^g	1.136	1.4
Tolunitrile	0.90 ^g	1.343	0.08
Total			35.05

^aEstimated.

^bThe oxidative degradation of a 263 mg sample with a weight loss (as measured by the TGA on the Mettler Thermoanalyzer) of 51.4 mg during the sampling period.

^cRelative trapping efficiencies.

^dRelative response factors for the flame ionization detector.

^eMilligrams of compound produced per gram of polymer as determined by analytical techniques.

^fRelative response factors for the thermal conductivity detector.

TABLE VII
A SUMMARY OF THE VOLATILE PRODUCTS FROM THE FLAMING COMBUSTION
OF THE AROMATIC POLYAMIDE POLYMER^d

Compound	Peak No. ^b	Quantity ^c
Nitric oxide	2	9.0
Carbon dioxide	3	74.
Ethylene	4	2.6
Cyanogen	5	1.3
Water	6	157.
Propene	7	0.6
Hydrogen cyanide	8	12.
Methanol	9	0.6
Ethanol	10	6.7 ^d
Ethanol	11	0.6 ^d
Acetone	12	42.
Nitromethane	13	7.0
Acrylic acid	14	1.6
Benzene	15	0.2
Toluene	16	0.7
Xylene	17	3.3
Styrene	18	6.1
Methyl styrene	20	0.2
C ₉ H ₁₀	21	10.
C ₁₀ H ₁₄	22	3.5
C ₁₀ H ₁₂	23	71.
Benzonitrile	e	19.
Total		429.

^aThe flaming combustion of 0.25 gr samples.

^bCorresponds to peak numbers in Figure 9.

^cMilligrams of compound produced per gram of sample as measured by analytical techniques. The absolute quantity of each compound is not certain due to experimental difficulties. These values should be considered to be lower limits to the actual quantity of volatiles produced in the combustion process.

^dFrom the coolant bath and on the porous polymer trap.

^eElutes at a time greater than 30 minutes, thus it does not appear in this chromatogram.

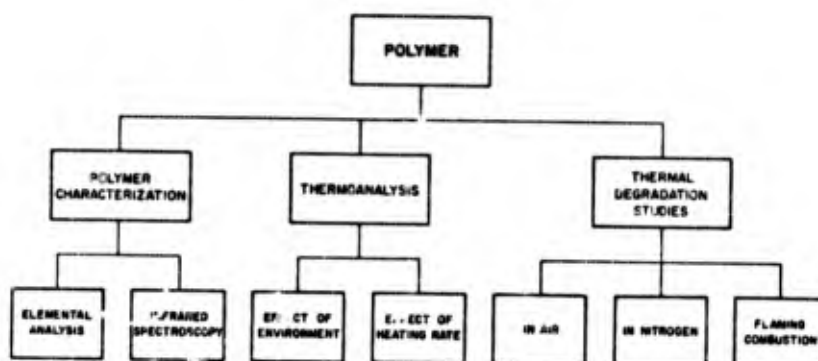


Figure 1. The analytical scheme for the study of the aromatic amide polymer.

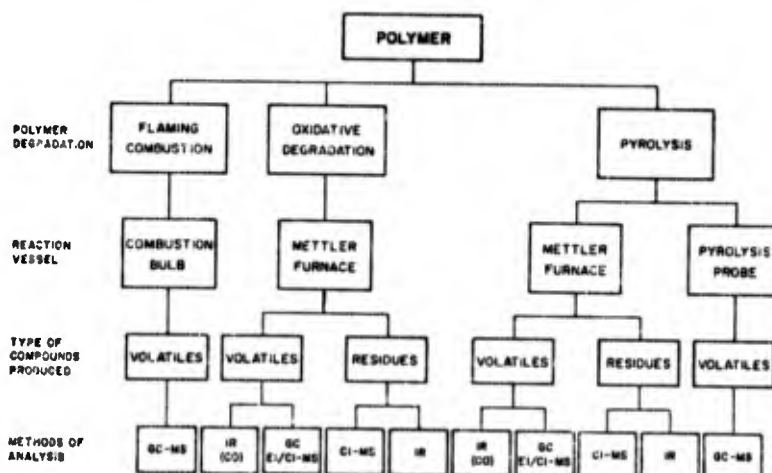


Figure 2. Analytical scheme for the analysis of the products from polymer degradation.

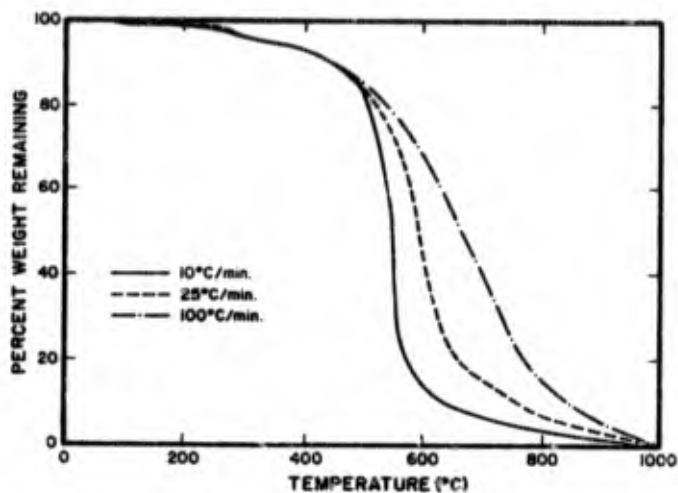


Figure 3. Effect of heating rate on sample weight loss for the aromatic amide polymer in air.

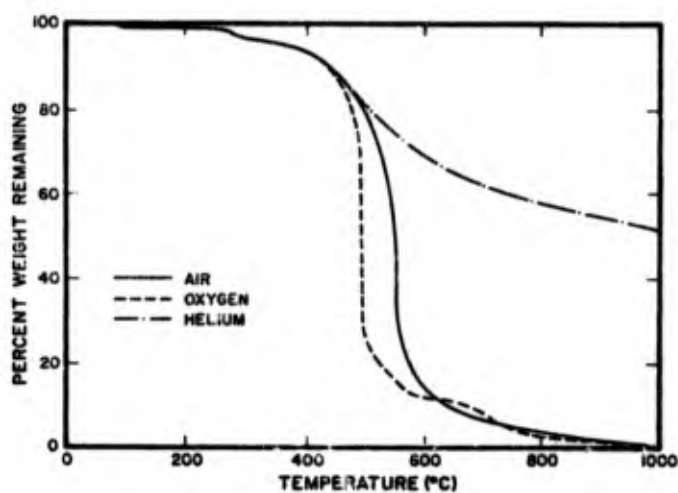


Figure 4. The effect of environment upon the weight loss of the aromatic amide polymer at a heating rate of 10°C/min.

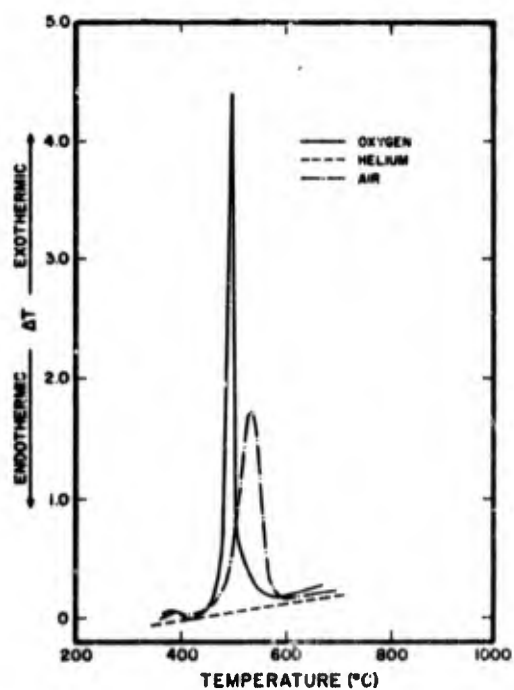


Figure 5. The DTA traces for the aromatic polyamide in helium, air and oxygen environments.

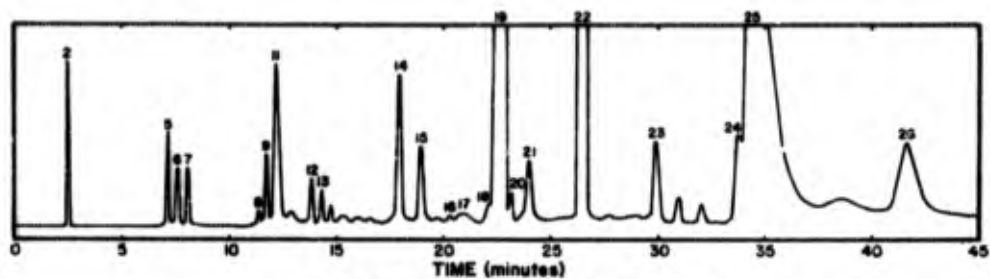


Figure 6a. Flame ionization detector response.

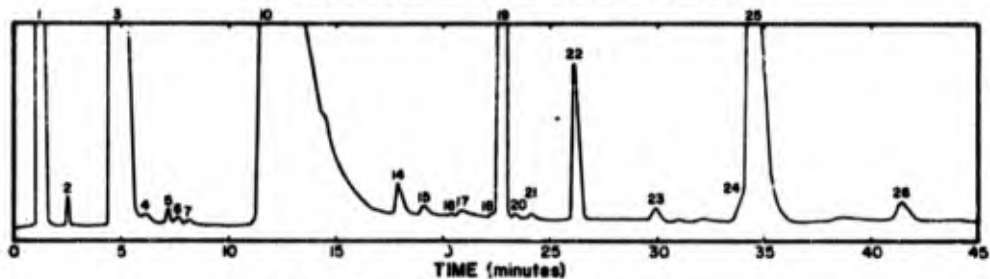


Figure 6b. Thermal conductivity detector response.

Figure 6. Volatile products from the pyrolysis of the aromatic amide polymer in nitrogen at 550°C.

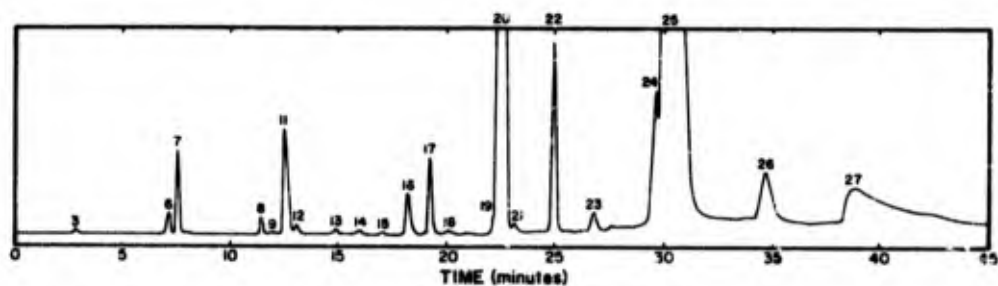


Figure 7a. Flame ionization detector response

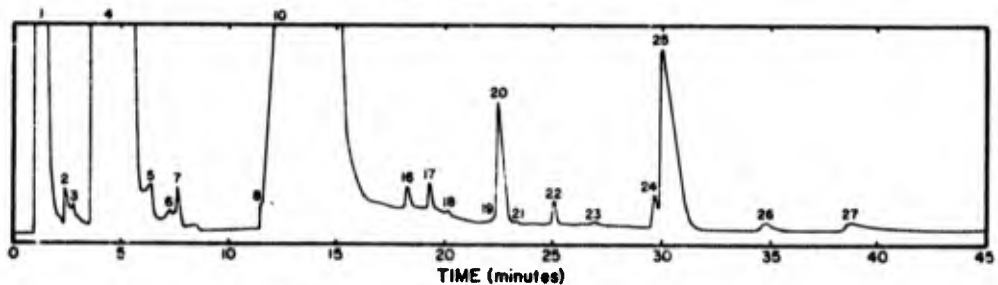


Figure 7b. Thermal conductivity detector response.

Figure 7. Volatile products from the oxidative degradation of the aromatic amide polymer in air at 550°C.

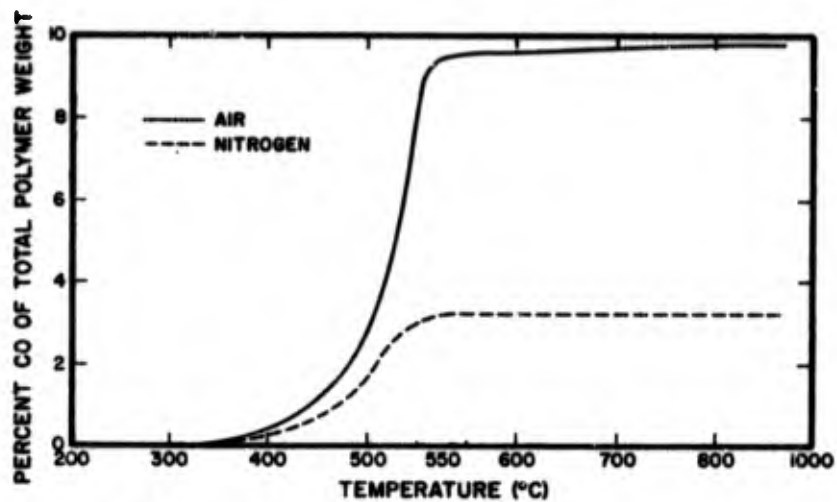


Figure 8. Carbon monoxide evolution from the aromatic amide polymer as a function of temperature in nitrogen and air environments. A heating of 100°C/min., held isothermally at 550°C for 0.5 minute.

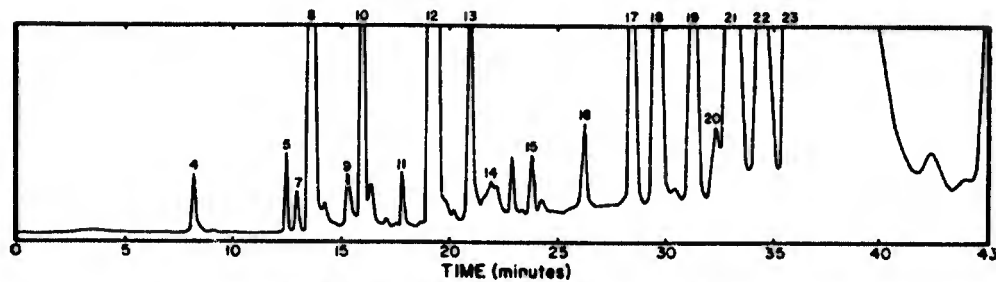


Figure 9a. Flame ionization detector response.

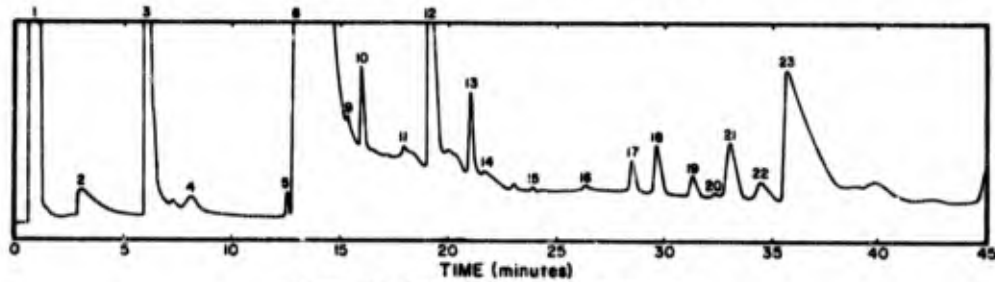


Figure 9b. Thermal conductivity detector response.

Figure 9. Volatile products from the flaming combustion of the aromatic amide polymer.

DISCUSSION - PAPER 14

Mr Glassman: I am surprised that you have an increase of HCN with the presence of air as compared to nitrogen, because in the work that we do in the environmental problem areas we know that the cyanogens react very rapidly with the oxygen compounds. I would have expected just the opposite.

Mr Einhorn: Studies pertaining to thermal degradation of polymeric materials via pyrolysis, oxidative degradation, and flaming combustion have been carried out for a number of generically different systems. The concentration of HCN increased as the concentration of oxygen was raised in the test environment. The presence of oxygen leads to a more exothermic reaction which may provide the energy necessary for conversion of such products (nitrites, amides, imides, etc., normally produced during pyrolysis) to HCN.

FLAME SPREADING ACROSS MATERIALS: A REVIEW OF FUNDAMENTAL PROCESSES

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SUMMARY

A critical review of the existing researches on flame spread above solid combustible materials is given; both theory and experiment are considered. Special attention is given to the determination of the rate-controlling mechanism for energy transfer ahead of the flame and therefore to the determination of the flame spreading rate. The mechanism could be either gas-phase conduction, radiation, gas-phase convection or some combination of these. Important factors which are discussed are: natural convective flows, orientation of the direction of flame spread with respect to gravity, thickness of the burning material, and the values of the conductivity, diffusivities, heats of reaction and pyrolysis, chemical kinetic constants, and ambient oxygen concentration. It is indicated how changes in these factors can produce changes in the rate-controlling mechanism.

LIST OF SYMBOLS

$$a = \frac{\bar{\lambda} \rho_s C_s V_F}{\lambda_s \rho_m C_p V}$$

A pre-exponential constant in soldering kinetics

$$B = \frac{\rho_s V_F \tau C_p}{\pi \lambda_m}$$

C_s specific heat capacity (solid)

C_p constant pressure specific heat capacity (gas)

E activation energy

$$L = \frac{\bar{\lambda}}{\rho_m C_p V}$$

Q energy release per unit mass of solid fuel

R universal gas constant

$$s = \frac{\pi}{L} = \left(\frac{C_p}{\bar{\lambda}} \right)^2 V \xi$$

T temperature

u = $-\frac{\partial \theta(s, 0)}{\partial y_s}$, heat flux into the solid

V_F flame spreading velocity

V convective flow velocity

y distance from gas solid interface

$$y_s = -y/L$$

Y mass fraction

$$z = y \int \frac{1}{\theta} \frac{dy}{L}$$

τ fuel-bed nondimensional thickness

ρ density

v stoichiometric fuel-air ratio

$$\Lambda = \frac{A}{\pi V}$$

λ conductivity

$$\theta = \frac{T}{T_{\infty}}$$

$$\theta_c = \frac{E}{RT_{\infty}}$$

Superscript

- average value

Subscript

O oxidizer

g gas

s solid

∞ evaluated far away from the combustion zone

0 reference quantity

INTRODUCTION

The purpose of this paper is to review the existing major theories of flame spread above solid with emphasis on the fundamental processes. This paper will cover, for the purpose of some degree of completeness, some of the material discussed in a previous review by Sirignano (1972). However, for the most part, more recent theoretical and experimental developments are discussed. Nevertheless, it is suggested that the interested reader examine that previous reference as well as this paper to see this author's total effort to critically review the subject.

The main goal of any flame spread theory is to predict the rate of flame spread as a function of certain parameters which describe the solid fuel and its environment (typically air). There is secondary interest in predicting profiles of temperature, species concentration, and velocity in the gas phase and of temperature in the solid phase. Obviously, the flame spreads because energy released in the flame is transported ahead of the flame to heat and gasify the fuel; then the fuel vapors can mix with the oxygen in the air and react. The interesting problem is to determine which mechanism(s) of heat transfer (gas phase conduction, gas phase convection, solid phase conduction, or radiation) dominates in which regime of the parameters. The pertinent parameters are the thermal conductivities, specific heats, and mass diffusivities of the solid and gas environment, kinetic constants for the gas phase reactions and surface pyrolysis, the material thickness, flame emissivity, and the ambient pressure, temperature, and oxygen concentration.

The spreading rate is not known a priori but appears as a parameter in the system of equations. See, for example, de Ris (1968) or Sirignano (1972, 1974) where the spreading rate is regarded as an eigenvalue in the mathematical problem.

DISCUSSION OF EXISTING THEORIES OF FLAME SPREAD ABOVE SOLID FUELS

De Ris (1968) presented the first interesting theory of flame spread above a solid fuel. He considered a laminar diffusion flame spreading over a solid fuel against an incoming air stream. Two models are considered: a thick-bed model and a thin-bed model. Radiation is considered only in the thick-bed model. Chemical kinetics are sufficiently fast and the fuel is sufficiently volatile that the flame stands away from the surface but within the gas diffusion layer.

In the de Ris model, the details of the gasification process and the mixing and reaction of the fuel vapor and oxidizer have not been specified. It is asserted that temperature of the unburned solid must reach a certain critical value T_{vap} before the flame could spread above it. There is serious question about the utility of such a parameter since it is a function of many other parameters and is not a property of the fuel alone but rather a property of the system.

In the thin-bed case, the spreading rate is found to be inversely proportional to the fuel-bed thickness and independent of the incoming air velocity. In the case when the bed thickness becomes large compared to the thermal layer thickness, the spreading rate is independent of the bed thickness and directly proportional to the air velocity. The spreading rate is independent of pressure in the thin-bed case and directly proportional to pressure in the thick bed case. The eigenvalue spreading rate is found to be independent of the solid phase conductivity in the direction of flame propagation.

Ohki and Tsuge (1974) treated a problem with smoldering combustion at the surface followed by a diffusion flame sheet. The gas phase kinetics are assumed to be very fast so that the diffusion flame is very thin. The kinetics of the smoldering combustion are not so fast; so they are a controlling factor. The mathematical problem is linearized by an ad hoc representation of the smoldering kinetics. That is, an exponential representation of the gasification rate in front of the flame followed by a slowly varying gasification rate behind the flame front is assumed.

There is some qualitative agreement between the Ohki and Tsuge theoretical results and the experimental results of McAlvey, et al. (1969, 1971). There are some important quantitative differences, however. Furthermore, it is possible that a gas-phase kinetic controlled model would predict results which compare just as well with the experimental data. The authors do not proceed to discern whether gas-phase conduction or solid-phase conduction dominates with regard to the transfer of energy ahead of the flame.

A recent theoretical development by Fernandez-Pello, Kindelan, and Williams (1973) is based upon the assumption that the energy is transferred ahead of the flame solely through solid-phase heat conduction. The spreading rate is not predicted by this theory but rather is taken as an empirical input. The surface temperature is predicted to be an average of an error function and exponential function with distance ahead of the flame. The error function dominates in a thick fuel bed case while the exponential function dominates in a thin fuel bed case. By adjustment of the weighting factor in the averaging process good agreement with experimental results for surface temperature is obtained.

The authors claim that their study involved a critical test for determining the mode of heat transfer ahead of the flame. However, their argument is not convincing since spread rates were not calculated but rather provided empirically and some arbitrary adjustment of a parameter in the theory was involved.

It is not clear a priori that gas phase conduction is less significant than solid phase conduction. It seems to this author that, among other factors, the comparison between characteristic thermal lengths in the gas and solid are important. The phase with the larger thermal length would tend to be the phase with the dominant forward conduction of heat; that is, the greater the thermal length of a given phase, the greater the temperature rise at a given point ahead of the flame due to conduction through that phase.

The characteristic thermal length is the ratio of a thermal diffusivity to the flow velocity. The fact that the gas phase density (at atmospheric pressure) is several orders of magnitude less than the solid phase density tends to make the gas phase thermal length large compared to the solid phase thermal length. However, due to natural convection, the gas phase velocity tends to be several orders of magnitude larger than the solid phase velocity (which equals the spreading rate). This velocity effect would tend to make the solid phase thermal length larger than the gas phase length.

It can only be concluded that a theoretical model should include both solid phase and gas phase conduction and the determination of which mode dominates should come as a conclusion and not an assumption of the theory.

There is a theory developed in a series of papers by Sirignano (1972), Sirignano (1974), and Feng and Sirignano (1974) which does allow for both solid and gas heat conduction in the model. As a result of calculations based upon this theory, conclusions can be drawn concerning the dominant mode of heat transfer. The major shortcoming of the theory is that, at present, it is limited to a consideration of surface or smoldering combustion only.

In this theory, steady flame propagation across a solid and against an incoming air stream is considered but all reaction occurs at the surface. The eigenvalue spreading rate is determined as a function of fuel bed thickness, gas phase velocity (due to natural or forced convection), thermo-chemical properties, and ambient temperature and oxygen concentration.

A system of partial differential equations were established. Based upon an Oseen-type approximation whereby the free-stream velocity is substituted for the coefficient in the convective term, a linear differential operator is obtained for the energy and species equations. A Green's function is developed and employed to reduce the system of two-dimensional partial differential equations to a system of one-dimensional integral equations (applicable along the gas-solid interface). The statement of continuity for the solid fuel leads to an integral representation for the eigenvalue. The only nonlinearities in the system appear in the integrands which result from the reaction rate dependence upon temperature. A method of successive substitutions is used to solve these integral equations for surface temperature and surface oxygen concentration. From these results, the oxygen concentration throughout the gas phase, the temperature throughout the gas and solid phases, and the eigenvalue spreading rate may be immediately calculated.

ROLE OF FUNDAMENTAL PROCESSES

In this section, we shall use the results of Sirignano and Feng to determine the role of the fundamental processes in the spreading phenomenon.

Figure 1 shows the influence of convective flow velocity on the flame spreading rate for fixed fuel-bed thickness. The spreading rate increases with increasing convective velocity. It peaks and then decreases with further increases in flow velocity. The data of Lastrina and co-workers exhibited increasing flame spreading velocity with increasing convective flow velocity until a "critical" flow velocity is reached. Beyond the "critical" flow velocity, the flame spreading velocity decreases with increasing flow velocity. Two of their experimental cases are included in Figure 1. The theoretical and experimental results are in good agreement despite a difference in the oxidation processes: i.e., gas phase versus surface reactions. The convective flow condition near the solid surface is also different. For the experimental case, a boundary layer always exists with the resulting retarded flow velocity near the surface; while in the theoretical model, the convective velocity profile is assumed to be uniform throughout the gas phase region. As the gas velocity increases, the conduction from the surface into the gas phase increases, but it always becomes more difficult to conduct upstream in order to propagate the flame. The results suggest a "crossover" in these two effects.

Notice that for the theoretical reference quantities, one set of the solutions subscripted with 0 are taken. For experimental reference quantities, a set of experimental results and parameters subscripted with 0 is taken which is different from the former. All symbols are defined in the nomenclature.

Below the critical flow velocity, V_F and V may be correlated by the power-law relationship.

$$V_F \propto V^{0.33} \quad \text{and} \quad V_F \propto V^{0.43}$$

for $\tau/\tau_{O_2} = 2.11$ and $\tau/\tau_{O_2} = 1.08$, respectively. These compare favorably with Lastrina and co-workers finding of

$$V_F \propto V^{0.34}$$

for all of the data from their experiments, while de Ris (1969), on the other hand, predicted

$$V_F = V$$

Figure 2 shows the corresponding temperatures and oxygen concentration profiles for $\tau/\tau_{O_2} = 2.11$. It is seen that as the flame spreading rate increases, the dimensionless length of the portion of the solid fuel under active oxidation, Δs , increases with an accompanying increase in temperature and with a slight increase in the minimum surface oxygen concentration. However, since

$$s = \frac{x}{L}, \quad L = \frac{\bar{\lambda}}{\rho_{\infty} C_p V}, \quad \text{and} \quad \Lambda = \frac{A}{\pi V}$$

we then have

$$\Delta x = \frac{\bar{\lambda} \pi}{\rho_{\infty} C_p A} (\Delta s) \Lambda$$

where Δx is the dimensional counterpart of Δs . With the available values for Δs and Λ , it can be shown that as the flame spreading velocity increases, the actual length of the portion of the solid fuel under active oxidation decreases.

The calculated values of the flame spreading velocity for various values of a , B , and Λ are shown in the following table:

TABLE I

$\frac{V_F}{V_{F0}}$	B	a	Λ
0.44	0.07	10.8	419.0
0.69	0.11	5.0	122.6
1.07	0.18	2.0	31.83
1.49	0.24	1.0	11.37

Figure 3 shows the influence of fuel-bed thickness of the flame spreading velocity for fixed convective velocities. When the fuel-bed is very thick, the flame spreading velocity tends to approach an asymptotic value. As the fuel-bed thickness decreases, the spreading velocity increases until τ/τ_0 reaches a minimum value for each fixed V/V_0 . Then the spreading velocity further increases as τ/τ_0 increases resulting in a left upper branch of the curve. This is in agreement with the phenomenon shown in Figure 1. There the curves peak at some "critical" convective velocities and the flame spreading velocity increases with an increase in convective velocity between the "critical" velocity and decreases with further increase in convective velocity. In Figure 3, on the left upper branches of the curves, as the convective velocity increases from 0.543 to 1.50, for a fixed fuel bed thickness, say $\tau/\tau_0 = 1.5$, the flame spreading velocity also increases from 0.98 to 1.16. On the right portion of the curves, say at $\tau/\tau_0 = 4.0$, an increase in convective velocity from 0.036 to 0.144 results in a decrease in flame spreading velocity from 0.085 to 0.072.

Notice that the end points at the left upper branches represent the limits beyond which convergent solutions are not obtained. It is not clear yet whether these represent numerical limits or actual flammability limits.

To understand the effect of the change of $\frac{\lambda}{\lambda_{\infty}}$ on the flame spreading rate, one may calculate the results which are shown in Table II. These are the points corresponding to those which appear in Figure 1 with $\tau/\tau_{O_2} = 2.11$. The points in Table II from the bottom value to the top value correspond to those in Figure 1 from the left to the right on the curve with $\tau/\tau_{O_2} = 2.11$.

TABLE II

a	B	Λ	$\frac{\Delta(v_F/v_{F0})}{\Delta(\lambda_s/\lambda_\infty)} \lambda_\infty$	$\frac{\Delta(v_F/v_{F0})}{\Delta(\lambda_s/\lambda_\infty)} \lambda_s$	$\frac{v_F}{v_{F0}}$	$\frac{v}{v_0}$
0.25	0.20	3.376	-0.00414	-1.265	1.26	5.03
0.50	0.2585	5.777	-0.1726	-0.2759	1.47	2.94
1.00	0.053	28.56	-0.0113	-0.2565	0.5944	0.5944
2.0	0.18	31.84	-0.0928	-0.1126	1.07	0.533
5.00	0.10	118.3	-0.0853	-0.122	0.718	0.144
10.8	0.08	386.4	-0.1813	0.637	0.475	0.044

It is noted that, in general, the effect of the change of $(\lambda_s/\lambda_\infty)$ on the flame spreading rate is slight and that an increase in solid phase conductivity will result in a decrease in the flame spreading rate while an increase in gas phase conductivity results in an increase in the flame spreading rate.

Figure 4 shows the temperature profiles inside the solid and gas phase regions for one case. As expected, the temperature decreases with increase in the distance from the gas-solid fuel interface. The temperature decreases more in the solid than in the gas with the same distance from the interface since the heat diffusivity for the solid is much less than that for the gas. The corresponding heat flux into the solid or gas phase is shown in Figure 5.

Figure 6 shows the influence of the fuel-air ratio v . As v increases, the amount of oxygen needed decreases. The maximum temperature increases with accompanying increase of heat transfer into the solid fuel bed below. Due to temperature increase, the length of fuel bed under active oxidation decreases. Λ decreases from 2 to 0.9745 implying an increase in gas velocity V .

The increase of t_{max} maximum temperature could be due to an increase in the fuel consumption. This situation is possible since in the case that $V = v_F$, a decrease of Λ implies an increase of v_F .

Figure 7 shows in comparison with Figure 6 the influence of conductivity ratio, $\frac{\lambda_s}{\lambda_\infty}$. As $\frac{\lambda_s}{\lambda_\infty}$ increases from 0.1 to 4.51, the maximum temperature decreases while the minimum Y_0 also decreases. Since "a" is held constant $\frac{v_F}{v}$ is increased by the same amount as $\frac{\lambda_s}{\lambda_\infty}$. With a faster rate of fuel consumption, the minimum Y_0 increases in spite of the fact that maximum temperature decreases due to an increase in λ_s .

When the activation energy, θ increases from 6 to 10, the minimum Y_0 decreases and the maximum temperature increases with an accompanying decrease in the length of the fuel-bed under active oxidation. This is shown in Figure 8.

To see the effect of varying oxygen concentration, Y_0 was changed from 1.0 to finally 0.35 in several steps as shown in Figure 9. It is seen that the maximum temperature decreases slightly as Y_0 decreases and the length of the fuel bed under active oxidation also extends slightly. The heat transfer into the fuel bed, however, decreases quite appreciably.

When the bed is insulated at its bottom, Figure 10 shows that the temperature and the minimum oxygen concentration are generally slightly lower for infinite bed thickness than for finite bed thickness. This is expected since for finite fuel-bed thickness, the heat flux does not go beyond the bottom of the fuel bed. Figure 11 shows the corresponding surface heat flux profile. It is interesting to note that for the case of finite bed thickness, heat is transferred from the solid to the gas phase ahead of and behind the flame. Underneath the flame, heat released is partially transferred into the bed.

In conclusion, the influences of convective flow velocity and fuel-bed thickness on the flame spreading velocity are delineated for the case of exothermic surface reaction. The trend is in good agreement with the findings from experiments using thermoplastic materials. For direct comparison, experiments with surface reaction materials, though less common than those with gas phase reaction, are needed. It is clearly indicated that chemical reaction rates are important in determining the spreading rate; faster chemical rates imply faster propagation. Note that the existence of a limiting bounded value for the propagation rate as chemical rates become infinite is not indicated; diffusion alone is never controlling. Furthermore, in the range of parameters considered, gas phase conduction is a dominant mechanism for heat transfer ahead of the flame while solid phase conduction is a dominant mechanism for heat loss from the flame. That is, an increase in gas phase conductivity causes an increase in the propagation rate while an increase in solid phase conductivity causes a decrease in the propagation rate.

NEED FOR FUTURE RESEARCH

There still exists the need for a theoretical model which considers finite gas phase kinetics. Note that we should really not expect the existence of a diffusion controlled limit where kinetics are unimportant. This spreading problem will have similarity with the problem of a propagation of a laminar flame through a premixed combustible gas. There the propagation rate increases without bound as either the chemical reaction rate or the transport properties increase. In this problem of flame spreading above solid fuels, the propagation rate should also continually increase with the chemical reaction rate.

If the gas phase thermal length remains very large compared to the solid phase thermal length, we would expect that the spreading rate increases as gas phase conductivity increases and decreases as solid phase conductivity increases.

An interesting set of papers by Hirano, et al (1974) indicates that gas phase convection may become important in some cases. Their experimental observation with flames spreading across thin fuel sheets indicated that recirculating flows can occur on the underside of the sheets. (They were never observed on the top side.) These reversed flows seemed to increase the rate of energy transport ahead of the flame; in particular, increased propagation rates are measured when the recirculation occurs.

A plausible explanation for the cause of the recirculation is a buoyancy effect. Whenever a non-uniform heat flux is applied to a fluid from above a recirculating convection pattern occurs. This would not occur if the fluid were heated from below. The energy released in combustion would provide the heat flux which results in the increase of temperature, the related decrease in density, and the subsequent convective pattern.

When this reversed flow occurs, the Oseen-type of differential equations can no longer be employed. The full nonlinear equations must be encountered and solved by numerical means. None of the existing theories would therefore apply in this situation. Some of the techniques utilized by Torrance (1971) and Herring and Sirignano (1974) for flame spread above liquid fuels can become useful here.

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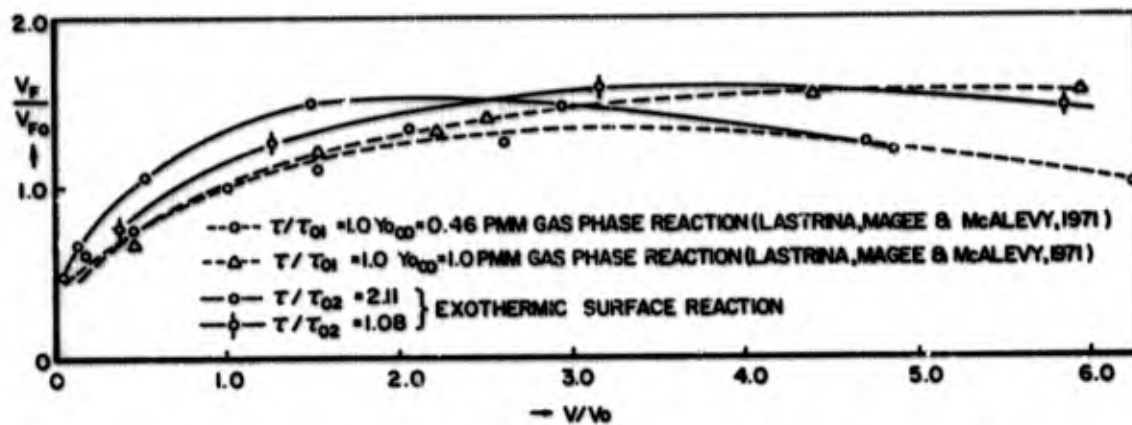


FIG.1 DIMENSIONLESS FLAME SPREADING VELOCITY vs GAS VELOCITY

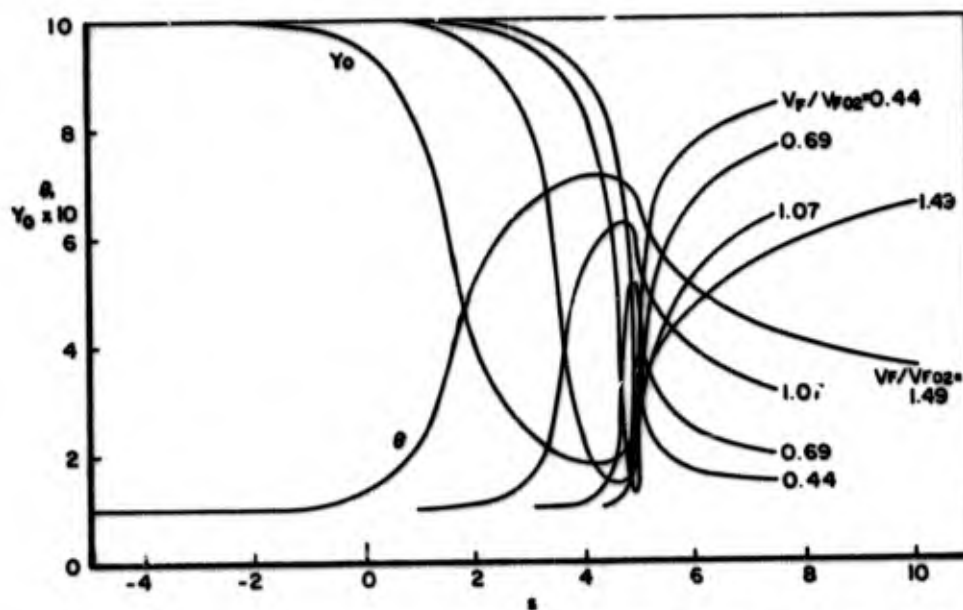


FIG.2 SURFACE OXYGEN CONCENTRATION AND TEMPERATURE vs POSITION

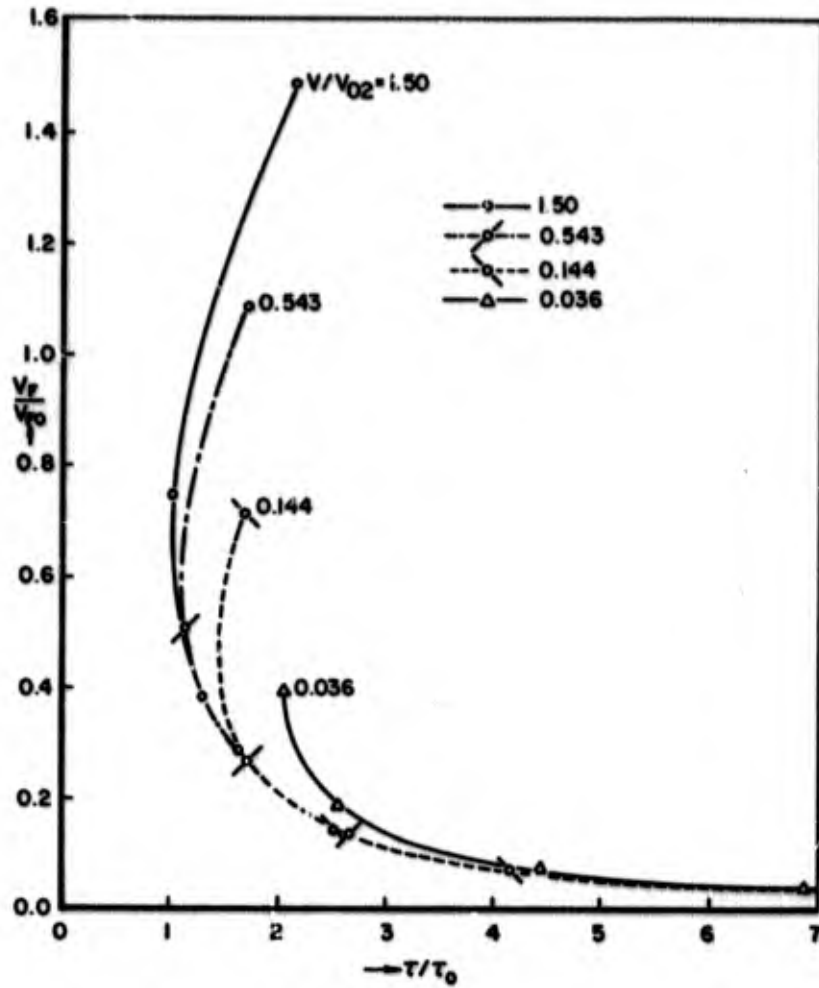


FIG. 3 DIMENSIONLESS FLAME SPREADING VELOCITY vs FUEL BED THICKNESS

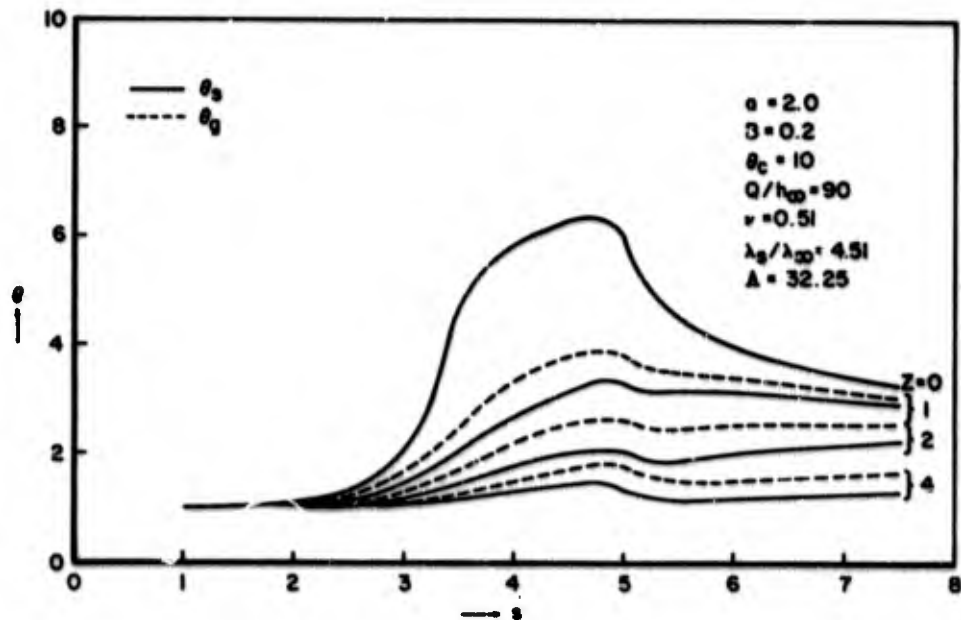


FIG. 4 TEMPERATURE PROFILE INSIDE SOLID AND GAS REGIONS

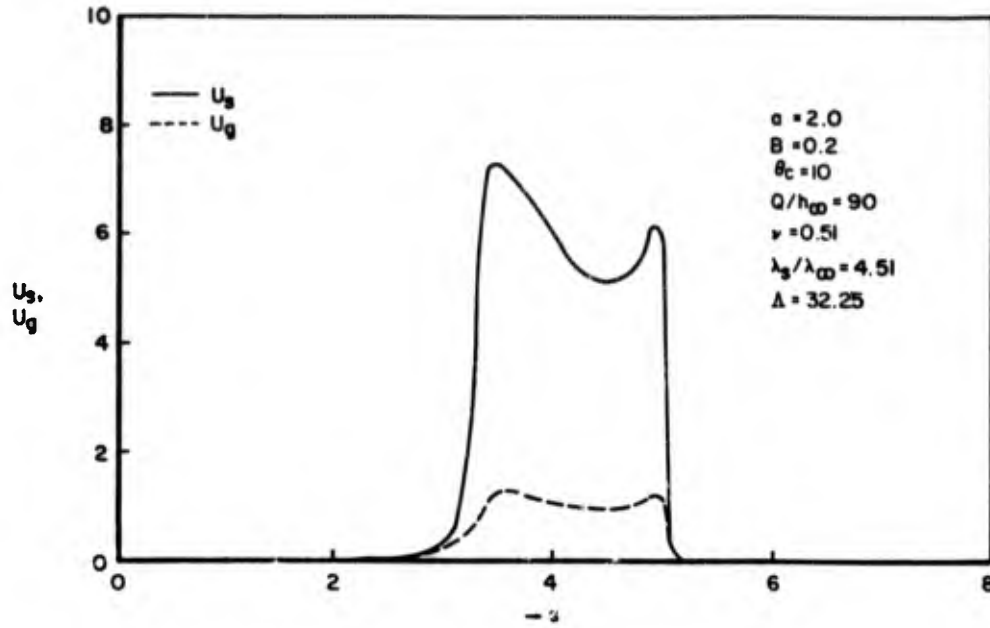


FIG. 5 HEAT FLUX TO THE SOLID AND GAS REGIONS

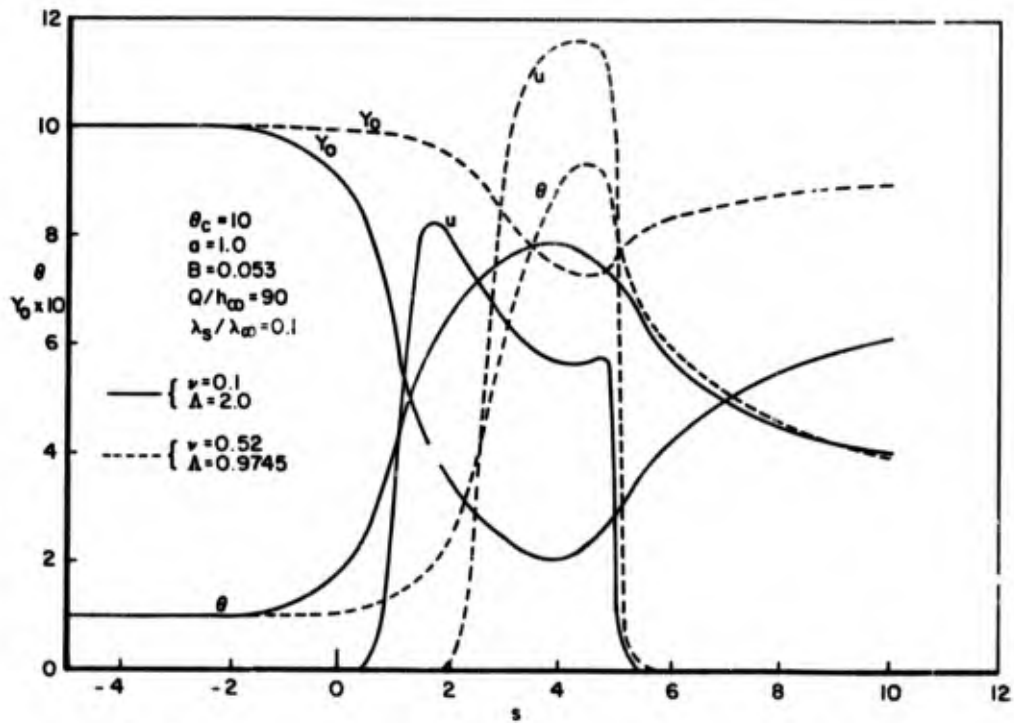


FIG. 6 SURFACE OXYGEN CONCENTRATION TEMPERATURE AND HEAT FLUX vs POSITION

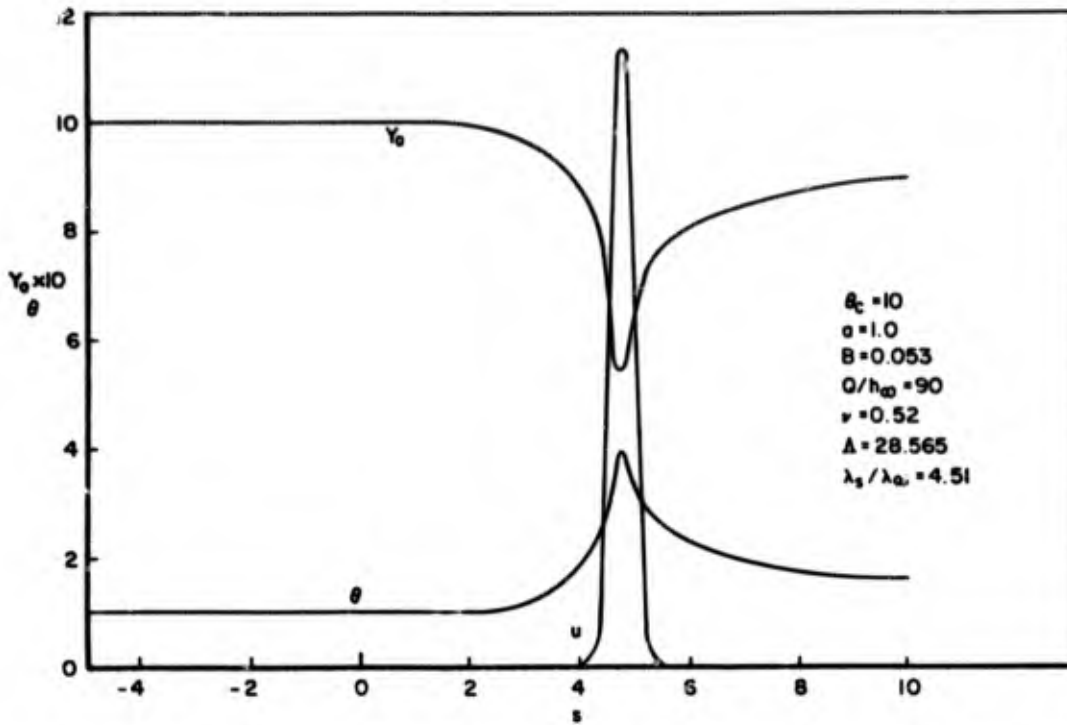


FIG.7 SURFACE OXYGEN CONCENTRATION, TEMPERATURE AND HEAT FLUX vs POSITION

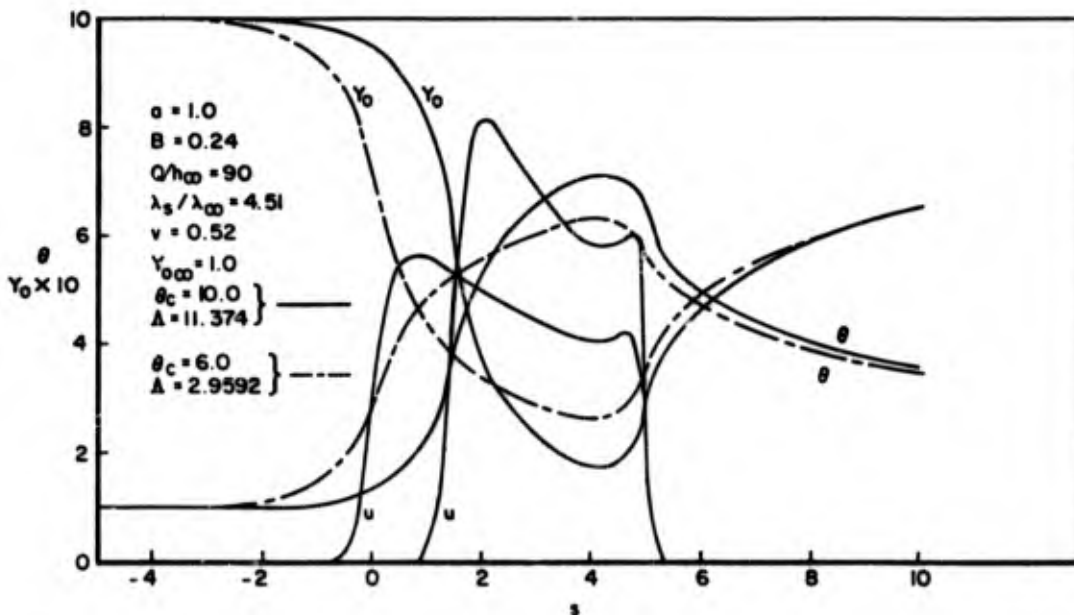


FIG.8 SURFACE OXYGEN CONCENTRATION, TEMPERATURE AND HEAT FLUX vs POSITION

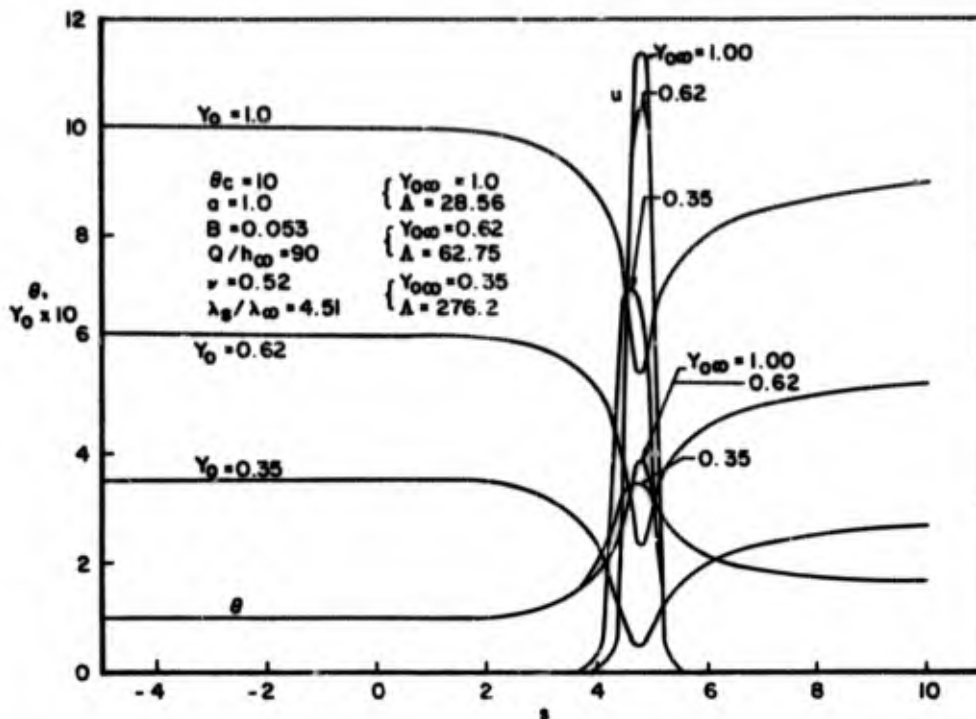


FIG. 9 SURFACE OXYGEN CONCENTRATION, TEMPERATURE AND HEAT FLUX vs POSITION

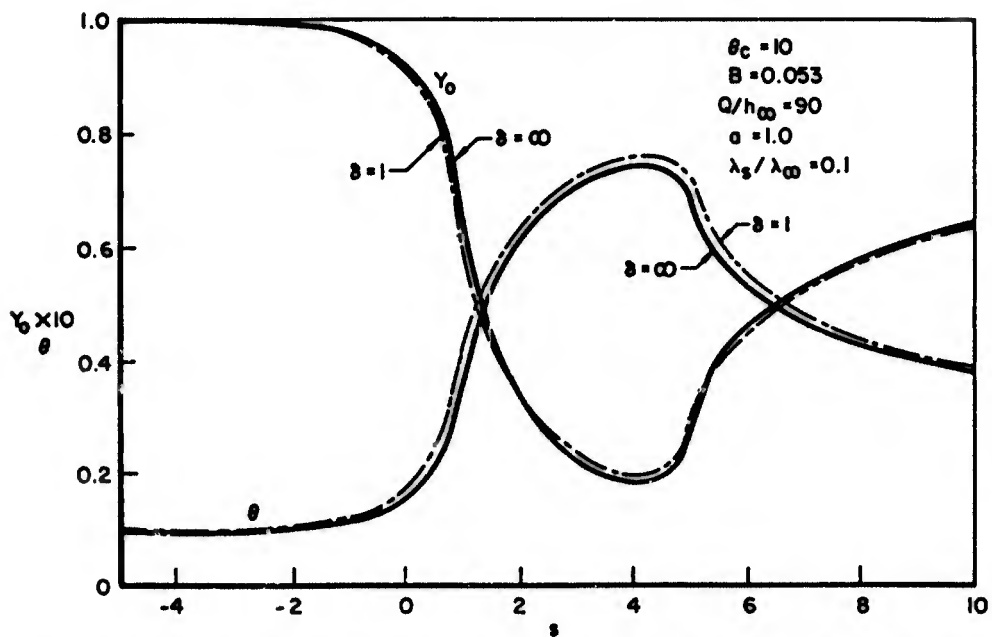


FIG. 10 SURFACE OXYGEN CONCENTRATION AND SURFACE TEMPERATURE vs POSITION

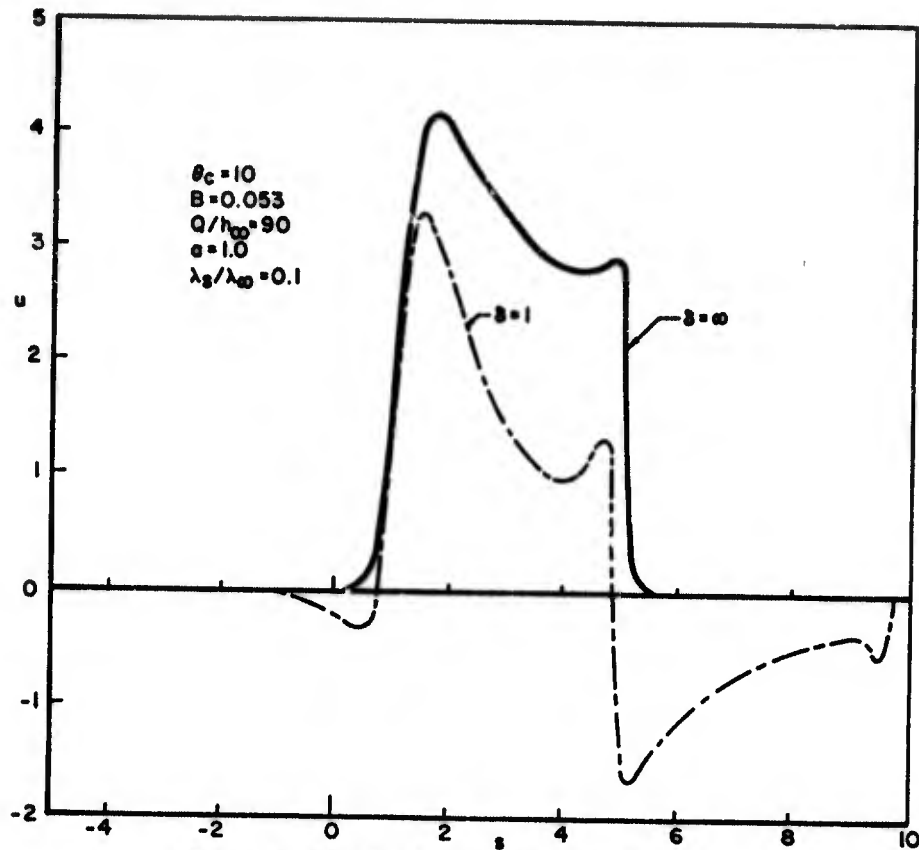


FIG.11 SURFACE HEAT FLUX vs POSITION

DISCUSSION - PAPER 15

Mr Hennecke: I wonder about the equations you solved: are they boundary layer equations or the full Navier-Stokes equations? If they are the former, I don't think that you will be able to see, in your results, the whole effect of the gaseous heat conductivity on the flame spreading rate.

Mr Sirignano: The diffusion of heat and mass in both directions is considered; that is, the elliptic rather than the parabolic (or boundary layer) forms of the equations for energy and species conservation are considered. The Oseen approximation is made for the convective term so that the momentum equation is uncoupled.

ON THE APPLICABILITY OF RETICULATED FOAMS FOR THE SUPPRESSION OF FUEL TANK EXPLOSIONS

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SUMMARY

It is known, that reticulated foams can inhibit flames, which develop inside fuel tanks. The application of such foams in aircraft tanks necessitates a compromise to be made between best flame suppression properties and lowest additional weight of the foam structure. Also technological questions, like mechanical behaviour during refuelling, have to be considered.

Investigations have been carried out at DFVLR, Porz-Wahn, in which the flame suppression properties of polyurethane foams with varying cell size have been studied by means of a flame tube and an explosion vessel. Results on the thickness of the foam layer necessary for flame quenching will be given, depending on pore size, fuel-air ratio and on pressure. The behaviour of reticulated foam during explosion in a closed vessel will be discussed, as well as its mechanical behaviour. Conclusions with respect to the application of foam structures in tanks will be drawn.

INTRODUCTION

FOR MILITARY AIRCRAFT it is highly desirable to have technical systems which can prevent the explosion of aircraft fuel tanks when subjected to enemy actions. There are several systems which can fulfill this duty, for example nitrogen inerting systems, fast-response fire-fighting systems or the application of reticulated plastic foams, which are fitted to the interior of fuel tanks. Whereas the physical working-principles of the first two mentioned systems are rather well understood, only little information is available on the fire-suppressing properties of reticulated foams. Therefore an investigation concerning these and some other interesting mechanical properties has been started under a contract of the Min. of Def., F.R.G.

There are several important points which have to be clarified before optimum use of reticulated foam in aircraft fuel tanks can be made. Tests carried out under the guidance of military authorities of several NATO-countries have shown that it is possible to avoid explosions of fuel tanks after being hit by projectiles, if the tank volume is filled with reticulated foam. However, the volume of the solid structure of the foam, on one hand detracts from the usable storage capacity of the tank; on the other hand it withholds, by means of adhesive forces, a certain amount of fuel. This means that the fuel stored in the tank cannot be fully used for propulsion purposes. Hence, a reduction of the range of the aircraft is inevitable. A further penalty results from the additional weight of the foam structure which decreases the payload. Therefore, a need for optimization of the foam structure with respect to the mentioned losses exists.

There are several ways to achieve this. One is to decrease the specific mass of the foam structure by increasing the cell size and reducing the dimensions of the cross-pieces, without changing the flame suppression qualities. Another possibility is to divide the available tank space into small volumes by using layers of reticulated foams of a certain thickness and a cell-size which is sufficient to prevent a flame from spreading from a cavity to the neighbouring ones. For this case it is also of interest to know how large the size of the cavities left free from foam can be.

From these objectives a number of questions can be deduced which have to be answered before an optimum design of flame-suppressing foam structures can be made. The first part concerns the foam layer thickness necessary for flame suppression as a function of cell size, mixture ratio, fuel quality, pressure and temperature. The second part concerns the tolerable cavity sizes formed by the crosswise foam layers inside the tank, and a third area is given by mechanical and chemical problems, like flow resistance, fuel retention by the foam structure, suppression of fuel sloshing, aging of the foam, and so on. The experiments reported in the following were intended to get better informations on some of these areas. They are by no means complete and have to be carried on.

EXPERIMENTS ON THE FLAME SUPPRESSION PROPERTIES OF RETICULATED FOAMS

In general, an explosion inside a fuel tank is ignited within a limited area, e.g. the surface or the wake of a hot projectile [1]. The flame which develops will then spread with increasing speed throughout the whole tank volume. This flame spreading is to be suppressed by the action of the reticulated foam structure. A suitable means for the simulation of this process is resembled by a flame tube. However the spreading of a flame in such a flame tube is a quasi-one-dimensional process, whereas the flame spreading through a combustible mixture from a projectile or its wake is at least quasi-two-dimensional. This difference however, is no disadvantage, because if a flame tube is used, the studies are carried out under more severe conditions. Generally, one can assume that the

flame speeds in the tube are larger than those of flames developping from projectiles in tanks. Therefore a flame-tube was chosen for most of the experiments. The experimental set-up is shown in Fig.1. The flame tube has a diameter of 60 mm, and a length of 2 m. At some distance from the ignition end of the tube, a cylindrical foam specimen was placed between two flanges. This distance was chosen so that certain fixed values of the flame speed were obtained in the region immediately upstream of the foam specimen.

The measurement of the flame travelling speed was performed optically, by using foto-transistors, which observed the passing-by of the luminous flame front. Three of these detectors were installed upstream of the specimen with a distance of 100 mm between two of them.

Ignition of the combustible mixture was achieved by a spark or by a hot wire. The combustible mixture was formed from fuel and air flows measured by rotameters. In order to vary the mixture temperature, the two gas flows were heated or cooled by means of heat exchangers, downstream of the rotameters. For avoiding heat losses from the tube after filling with the heated or cooled mixture, the tube could be thermostatised. The pressure inside the tube was registered with quartz transducers. The homogeneity of the mixture was ensured by mixing fuel and air far upstream of the tube. Ignition was performed immediately after filling the tube. The resulting flame then travelled the distance up to the foam specimen; here it was either arrested or passed through the foam, in the latter case igniting the combustible gas volume downstream of the obstacle. The appearance or non-appearance of this downstream ignition was again registered optically by a foto-transistor.

The tests were carried out in such a way that for given conditions (fuel mixture-ratio, pressure, temperature, cell size of the foam) the thickness of the foam specimen in the direction of flame propagation was varied from test to test until no ignition of the combustible mixture downstream of the specimen was observed. Each test point was repeated 10 times.

For the tests 7 foam qualities with different cell sizes were available, each of which was characterized by the number of cells per unit length (cm). In order to count the number of cells a very simple procedure was applied; the specimen was immersed into a opaque liquid, the color of which has to give enough contrast to the color of the foam. If the surface of the liquid and of the foam specimen are located in the same plane, it is possible to count the number of cells without interference from the adjacent cell layers. The cell sizes of the foams investigated ranged between 3 and 24 cells per centimeter.

TEST RESULTS

Fig.2 shows the results on the necessary specimen thickness depending on the number of cells for stoichiometric, fuel-rich and fuel-lean propane air-mixtures at a pressure of 1 bar and a temperature of 293 K. Two different values of the flame speed, 1,2 m/s and 8 m/s have been chosen. For the lower velocity the flame was ignited at the open end of the tube; the higher velocity could only be obtained with ignition at the closed end. As expected in this case the flame speed showed some fluctuations [2]. The distance between the ignition point and the specimen was chosen so that the prescribed value of the flame velocity could be reproduced with a scatter of approx. 10 - 15 %.

For all mixtures investigated the specimen thickness necessary for the suppression of the flame has a tendency to decrease with increasing cell numbers. This tendency is most pronounced for stoichiometric mixtures. For fuel-lean and fuel-rich mixtures the

thickness of the specimen is only slightly dependent on the number of cells. This seems to indicate that the total surface of the foam material exposed to the flame, at which radicals can be deactivated and which can absorb heat, is a controlling factor. Furthermore, for mixtures close to stoichiometric ratios the necessary specimen thickness increases with the speed of the travelling flame. From this it can be concluded that the time interval which the flame is in contact with the foam structure, is another controlling factor. However, this effect is not observed with fuel-rich mixtures.

It must be mentioned that with mixture ratios containing excess oxygen inspection of the foam specimen after a successful test always showed that the foam structure was partly burned at the upstream surface. This means that chemical reactions between the foam material and the oxygen can be induced by thermal effects.

Fig.3 shows the influence of different fuels and of pressure on the necessary specimen thickness; the results are valid for stoichiometric mixtures. The change in pressure showed no significant influence on the flame speed; however the scatter of the measured speeds at different pressures increased. Whereas the flame velocities for C_3H_8 resp. CH_4 were in the order of 8 to 9 m/s, for ethylene due to its higher reaction rate a value in the order of 20 m/s was found. In order to compare the results of all three fuels on the same base the foam thicknesses for ethylene have been corrected to the same velocity level as measured for propane and methane; assuming a linear relationship between foam thickness and flame speed, approximately.

The foam thickness h necessary for the suppression of the flame increases with pressure for all three fuels; the dependency can be described approximately by a power law

$$h = h_1 \cdot (P/P_1)^n,$$

where h_1 is the foam thickness at $P_1 = 1$ bar. The exponent n is nearly the same for all three fuels and has a value of 1.66. A first explanation is possible, if one assumes that a purely thermal process was responsible for the flame suppression. The solid surface of the foam structure necessary for the absorption of heat is proportional to the heat produced and inversely proportional to the heat absorbed by unit area of the surface. Assuming a constant temperature difference between the burnt gas and the surface, the heat produced increases with P^n , where n is the reaction order. The heat absorbed is proportional to the heat transfer coefficient which should be $P^{0.38}$ in the prevailing range of very small Reynolds numbers. Keeping in mind that for a constant cross-section of the foam plug, the active surface A of the structure increases with the thickness h of the plug, we have approximately

$$A \sim h \sim P^{n-0.38},$$

which for a reaction of approx. 2 leads to

$$h \sim P^{1.6}.$$

This compares very well with the observed experimental value of 1.66.

If one crossplots against the laminar burning velocity the measured thickness h for the three fuels at 1 bar, one finds that h increases like

$$h \sim S_L^{1.73}.$$

This could be explained similarly if one assumes that for constant heat transfer pro-

erties the necessary length h is approx. proportional to the heat Q produced in the flame. A simplified consideration of the propagation of a wrinkled laminar flame front shows, that Q should vary with S_L^2 , which is not very far from experimental observation. One should however bear in mind that the above treatment is a strong simplification of the real physical process of flame suppression and can therefore yield only qualitative results. Especially, radical recombination on the finely distributed solid surface in the way of the flame should play a major role.

A number of experiments has been carried in order to study the influence of the gas temperature before ignition on the necessary foam thickness. The first results have shown that there is some inconsistency which is rather difficult to explain without more insight into the process. Measurements have been carried out at gas temperatures of 353 K, 293 K, and 233 K. They show a distinct minimum of the foam plug thickness h around 293 K, and an increase of the necessary foam thickness both with decreasing and increasing gas temperature. The increase of h with gas temperature can be understood from an increase of the heat release rate for nearly constant heat transfer conditions. However, the reason for the increase of h at lower temperatures is not clear, presently. Some influence has to be expected surely from the change of the wave propagation patterns which occurs with varying temperature. Further experiments have to be carried out before firm conclusions can be drawn.

TEST IN AN EXPLOSION VESSEL

The experiments described in the previous section were intended to get basic information on the behaviour of flame-suppression foams under simplified conditions, which allow a comparison of different foam structures. The physical conditions in a flame propagating through the gas-filled space of a fuel tank differ however to some extent from those prevailing in a flame tube. Therefore, some experiments have been carried out on the extinction of flames propagating through an explosion vessel (Fig.4). Its diameter was 300 mm, its length 1 m. The purpose of the investigation was to find out how the results of the small diameter flame tube can be carried over to larger dimensions and what flame-suppressing qualities could be expected from different geometrical arrangements of foam layers. The filling of the vessel with combustible mixture took place in the same way as described in the previous chapter. For all tests stoichiometric propane-air mixtures were employed. The pressure at the wall of the vessel was measured half way between both end flanges. The extinction of the flame could be observed through a window.

Two kinds of tests have been performed, the first using the explosion vessel like a short flame tube of large diameter. The combustible mixture was ignited at one end flange, and foam plugs of 300 mm dia. and length of 100 to 900 mm were placed in the vessel at different distances from the ignition point. Foams with 4, 6 and 7 cells per cm have been used. Foams with 4 cells per cm or less cannot prevent flame propagation through the vessel at all, even if the vessel is completely filled with foam. However, the propagation process was considerably slowed down; also the pressure measured after combustion was completed is lower than in a vessel without foam inserts. It decreases from 12 bar in the latter case to 2 bar, if the whole vessel is filled with foam. For foams with 6 and 7 cells/cm the flame could not be prevented from passing through a foam layer of 100 mm thickness if the distance of the foam from the ignition source was larger than 400 mm. For smaller distances a passage of the flame through the foam cannot be excluded with certainty; the reason for this is not yet understood. From the fact that the foam shows severe destructions on the surface opposite to the ignition source and that the vessel is filled with dense white acid smoke after the test one can suppose that some reactions between the foam material and the hot gases take place, which were not observed in the flame tube.

The second kind of tests in the explosion vessel dealt with the size of cavities in-

side the foam structure necessary for flame suppression. These tests are not yet complete at the time of writing. Up to now only two cavity sizes have been investigated, one with 200 mm dia, 200 mm length, surrounded by foam walls of 100 mm thickness, the other with 80 mm dia, 80 mm length and foam walls of 80 mm thickness. The number of cells/cm were 6 in the first and 6 and 7 in the second case.

The respective specific gravities of the foams were 40.1 and 15.0 kg/m³. Ignition was performed by sparks in the center of the cavity. When using foam with 6 cells/cm, passage of the flame through the foam was observed in every case. This holds also for the foam with 7 cells/cm and the smaller 80 mm dia cavity. In this case the already mentioned destruction together with the appearance of white smoke was observed. A possible reason for this may be that the 7 cell/cm-foam with its very small specific mass of 15 kg/m³ has been heated more intensely than the heavier 6 cell/cm-foam. It is planned to continue these tests down to smaller cavity sizes.

SOME PHYSICAL PROPERTIES OF THE FOAM

Fitting of the fuel tank with foam rises some questions concerning fuelling and emptying the tank. Furthermore the fuel retainment of the foam is of great interest. The use of foam also leads to a decrease in sloshing of the fuel.

FLOW RESISTANCE OF THE FOAM

The measurements were carried out in a tube, with a foam plug of 500 mm length in order to ensure uniform flow conditions in the foam. It is obvious that the wall friction is much smaller than the flow resistance of the foam structure, hence the flow velocity inside the foam structure should be uniform over a large part of the tube cross-section. The wall friction losses have been subtracted from the measured total pressure drop across the foam plug. The measurements have been carried out using two tube diameters, 18 and 59 mm, thus Reynolds numbers in the laminar and in the turbulent flow range were obtained. As can be seen the flow resistance coefficient increases with increasing number of cells/cm, and decreases slightly with increasing Reynolds number (Fig.5). After these tests the fuel velocity was increased until the foam plug showed noticeable signs of compression. This limiting velocity was nearly the same for all foams investigated and amounted to approx. 0.5 m/s. If this velocity is exceeded the flow resistance increases sharply and the foam acts as a stopper.

FUEL RETAINMENT

The foam structure holds back fuel in its network. That means, that the fuel tank cannot be emptied fully. For the measurement of the fuel loss two tank configurations were used. The volume of the tanks was equal, but they differed in the height (1 : 3) and hence in base area. From this followed, that the bottom areas of the tanks differed. The test results are shown in Fig.6. As can be seen, the fuel retained in the tank increases with decreasing cell numbers. The tank geometry has an influence too. The fuel retainment in a flat tank, e.g. with the larger bottom area is larger than in the tank with the smaller bottom area. The foam layer immediately adjacent to the horizontal bottom wall withholds a fuel layer, which cannot be drained without further measures. It seems, however, possible to reduce the quantity of fuel retained to a large extent by suitable design of the tank bottom including the geometrical arrangement of the foam.

REDUCTION OF SLOSHING OF THE FUEL IN THE TANK

This question is mostly important for tank lorries. Under acceleration and

deceleration forces, the fuel or liquid in the tank sloshes. The uncontrolled movement of the liquid mass can lead to dangerous situations during braking or changes in the course. This sloshing can be suppressed to a large extent by the foam. For example under certain circumstances the maximum amplitude of the sloshing fuel inside the tank under the action of a deceleration force of 0.4 g was reduced to 10 % by the foam. This did change only slightly for different cell sizes.

DISCUSSION

The first part of the work has verified, that reticulated foam is basically able to act as a flame-arresting device. The length of a foam plug, necessary for extinction of the flame depends on the number of cells per cm, as well as on pressure and fuel type. Taking into account some simplifying assumptions, the quenching properties of the reticulated foam can be explained, at least qualitatively, by an energy balance on a purely thermal base. This assumes that the heat produced by the chemical reaction in the combustion volume must be, to a certain degree, absorbed by the solid surface of the foam structure.

In view of an optimization of the flame-suppressing properties of a foam it must be kept in mind, that there is not much freedom for changes in the geometry of the foam structure. First of all, only few different types of foams are available on the market; second, the geometrical shape of the foam network (number of cells/cm, uniformity) depends on the manufacturing process and mostly varies from one type of foam to the other. This of course makes an interpretation of the results difficult.

For the flame suppression in aircraft fuel tanks not only the dimensions of such a foam plug but also its weight is of interest, because this quantity influences the decrease in payload involved. For a given cross-section and a given specific mass of the foam the weight of the foam necessary for extinction is proportional to the length of the flame-suppressing plug. The results of Fig.2 (replotted in Fig.7 mass against cell/cm) therefore suggest to choose foams with large cell numbers per cm, surely above 10. However, this means that the quantity of fuel retained in the foam structure increases, too. Hence, the use of a foam with a smaller specific mass and smaller numbers of cells per cm is advisable. The following table compares results for two foams with a ratio of specific masses of 2 : 1:

ρ_{sp} (kg/m ³)	cell number (1/cm)	plug length (cm)	mass of plug (kg)	fuel retainment (%)
30	17	5	15	10 - 11.5
15	7	10	15	6.7 - 8.5

It can be seen that the reduction of the specific mass by a factor 0.5 together with a nearly twofold increase in cell number/cm results in the same mass of foam necessary for extinction combined with a lower fuel retainment.

Furthermore, as could be expected the flame-suppressing qualities increase with decreasing pressure. This would mean that the tank protection in low level flight is the critical condition. From a fire-protection point of view the pressure inside a fuel tank should therefore always be kept as low as possible, e.g. by connecting the exits of the venting tubes to areas on the aircraft surface where low pressures prevail during flight. The influence of temperature is not quite clear, presently; deserves further study.

Although the experimental results obtained with a flame-tube have clearly demonstrated

the flame-suppressing properties of reticulated foams, it is difficult to apply them to different geometric boundary conditions, as is shown by the experiments in the explosion vessel. It seems that further influences have to be considered. This limits the validity of the above mentioned results to some extent. Especially, if one introduces void cavities in the foam structure one finds that free convection flows can be generated which lead to local destruction of the foam. Such an effect was not observed in the flame tube experiments; therefore, presently, the scaling of the flame tube results to larger dimensions is rather difficult. One possible way to solve these problems is to decrease the hollow spaces in the foam; this however, needs further investigations.

If one uses foams with small cell numbers/cm (< 4), flame propagation through the foam cannot be suppressed in the explosion vessel. This is in contrast to the flame-tube results; however the reasons for this observation are not understood, presently. The pressure rise in the vessel during such a test is rather slow, indicating that during the time interval of flame-spreading a large quantity of heat is transferred to the walls. Applied to aircraft fuel tanks, this would mean that as long as the burst pressure of the tank is not exceeded, the damage to the tank should remain limited. From a practical point of view this already is one of the effects which was sought for. Furthermore, if one considers a tank penetrated by a hot shell, the pressure arising from a slow combustion in the tank could be relieved more easily by the bullet holes. However, it has still to be checked whether this effect also occurs to the same extent if the walls of the vessel are made from plastics or have a plastic coating.

From the above discussion it follows that further investigations have to be carried out in order to get a clear picture on the flame-suppressing qualities of reticulated foams and its application to fuel tanks.

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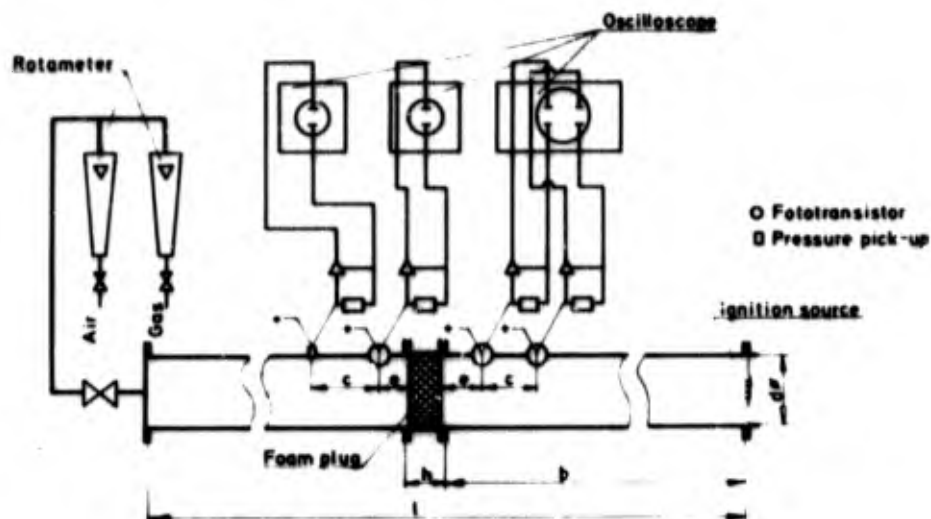


Fig.1 Schematic of the test-apparatus

$l=2000\text{mm}$, $b=500\text{mm}$ resp 1100mm , $e=50\text{mm}$,
 $d=60\text{mm}$, $h=\text{foam thickness}$ $c=100\text{mm}$.

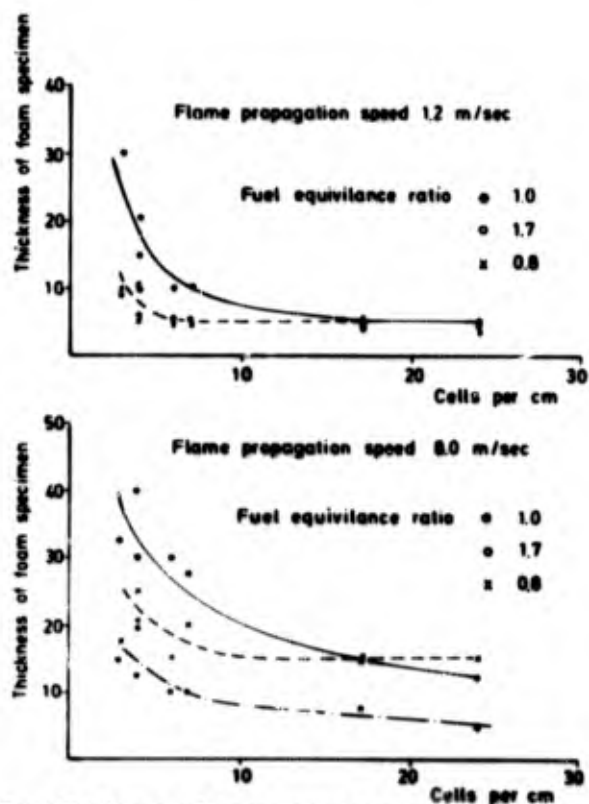


Fig.2 Thickness of foam specimen necessary for flame suppression, depending on the number of cells/cm, for two flame propagation speeds Propane - air mixture.

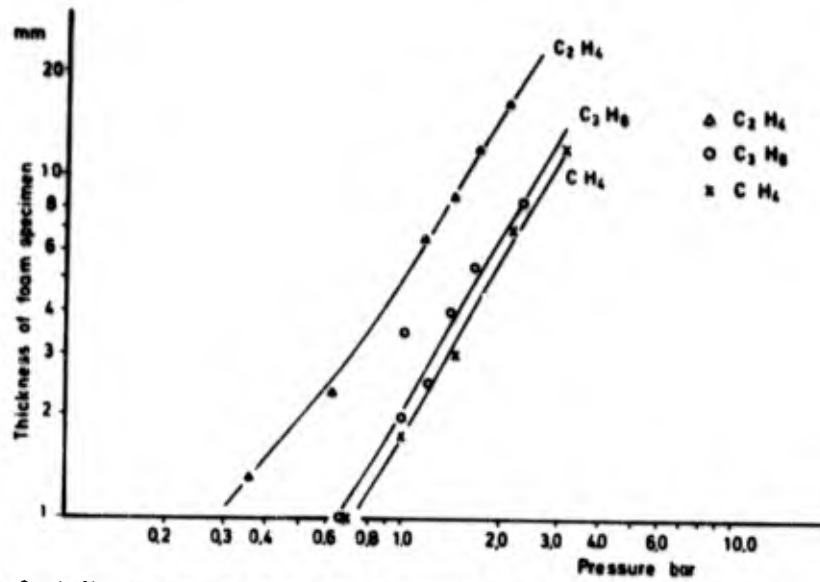


Fig. 3 Influence of pressure on the thickness of foam for stoichiometric methane - ethylene - and propane-air mixtures. Foam : specific mass 15 kg/m^3 , 7 cells/cm. Flame speed : 8 m/sec

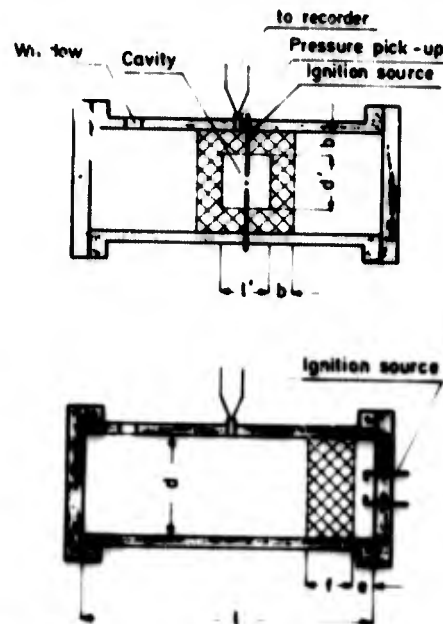


Fig. 4 Schematic of explosion vessel showing foam arrangement

- $d = 300 \text{ mm}$ d' = Diameter of cavity
- $l = 1000 \text{ mm}$ l' = length of cavity
- $f =$ Thickness of foam plug $b =$ Thickness of foam layer
- $e =$ Distance of foam plug from wall

Foam manufacturer	Cells/cm	Spec. gravity kg/m ³	Fuel retainment [high tank] %	Fuel retainment [flat tank] %	Volume l/m ³
A	3	43.4	6.2	7.1	49.5
A	4	47.5	8.5	8.7	48.0
B	4	30.0	4.8	6.3	39.5
A	6	40.1	6.5	7.8	49.5
B	7	15.0	6.7	8.6	33.0
A	17	37.8	10.1	11.5	90.0
A	24	35.4	15.0	18.1	115.0

Fig. 6 Fuel retainment of reticulated foam for two tank configurations

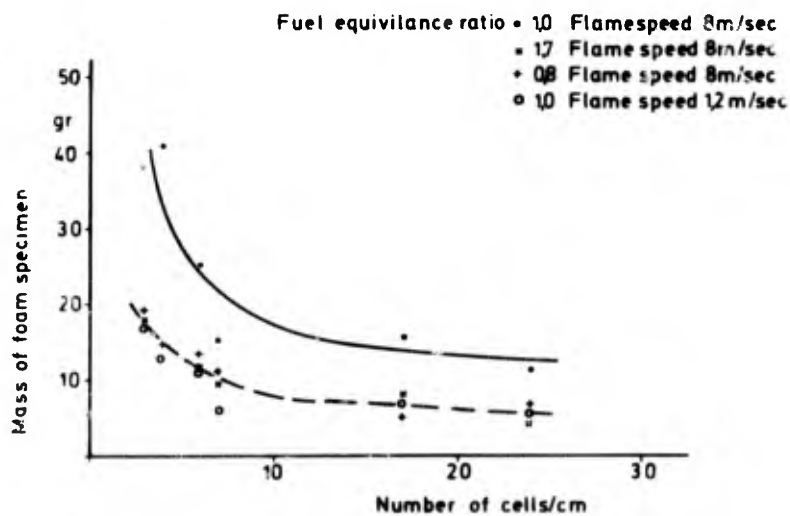


Fig 7 Mass of foam specimen necessary for flame suppression, depending on the number of cells/cm, for two flame propagation speeds. Propane-air mixture

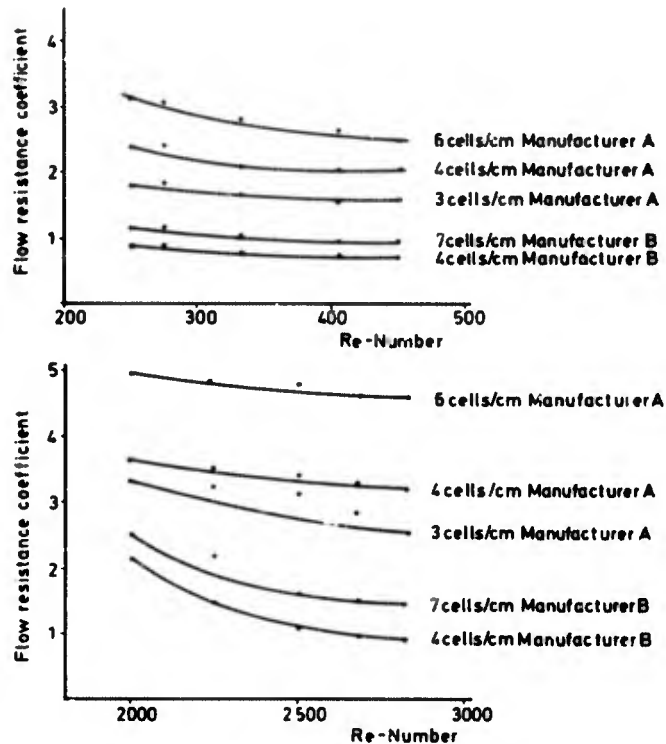


Fig.5 Flow resistance coefficient for reticulated foam

DISCUSSION – PAPER 16

Mr Pinkel: Regarding the use of reticulated polyurethane foam, some years ago we were working with metallic flame arrestors which are similar in action. We found that if the vessel on the protected side was closed as compared to open, the effectiveness was enhanced when the flame arrestor was wet with fuel. I wonder if on your flame tube tests you left an opening on the protected side, the results would be more comparable with the results in your vessels where the large volume gives you the effect of openness.

Mr Winterfeld: We are quite aware that pressure wave effects should occur in the flame tube and should influence the results to some extent. We did not try this case that you mentioned because in the tank you always have a solid surface bounding the space volume in which the flame can travel.

Mr Glassman: Could you clarify the exact manner in which the foam is used in the tank?

Mr Winterfeld: Yes, we use a system of small cavities in the body of foam which fills the whole tank. This gives us a weight saving and reduces retention. There are actually a series of compartments.

Mr Botteri: The US uses both solid fill and compartmented gross voided approaches. The key to the latter approach is the sizing of the compartments to keep the resulting overpressure in the overall cell in cases of ignition from exceeding structural limitations.

FIRE PROTECTION OF FUEL SYSTEMS IN COMBAT AIRCRAFT

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SUMMARY

A large proportion of the total volume of a military aircraft (fixed or rotary wing) is used to accommodate the fuel load. It is therefore important to consider the risk of ignition of the fuel together with the resultant fire or explosion that may arise from combat action. Evidence compiled from various theatres of war has shown that the major cause of aircraft loss arises from this risk and therefore its reduction or elimination would undoubtedly contribute to improved survivability.

Studies have been made to ascertain the conditions which affect fire and explosion probability within aircraft fuel tanks and surrounding bays. Particular attention has been given to the effect of fuel type, target construction and other environmental conditions.

From a knowledge of the physical effects following projectile attack, systems are suggested which could significantly reduce the risk of fire and explosion.

1 INTRODUCTION

A large part of the total volume of military aircraft is, of necessity, used to accommodate fuel. Investigations have been made at the RAE to ascertain the conditions which affect fire and explosion probability within aircraft fuel tanks and surrounding bays. Recently the fire raising potential of small arms ammunition against fuel tanks has been determined with the object of obtaining survivability and lethality data and to assess the effectiveness of a number of safety devices. Particular attention has been given to the effect of fuel type, target configuration, projectile and some environmental conditions.

Two aspects of fuel systems vulnerability are the risks of (a) fuel tank internal explosions and (b) fires in bays or voids adjacent to the tanks. The latter risk is undoubtedly the greater in terms of frequency of occurrence probably of the order of 10 to 1 but the former can have immediate and serious consequences to the aircraft and crew. We consider the fitment of internal protection to be a necessary adjunct to fuel system protection since an explosion within a tank could lead to a fire in the surrounding structure and therefore should be assessed when considering aircraft survivability. Successful systems have been developed⁽¹⁾ for fuel tank internal protection and this aspect will therefore not be dealt with in this paper, which will concentrate on fires external to the fuel tank, but within the aircraft structure.

It is fundamental to ignition that the liquid fuel be vaporised either by expansion following high shock pressures or by the thermal energy of ignition source. In this respect the target and ammunition are important factors in obtaining the appropriate spark or incendiary initiation, in preparing the fuel at projectile penetration and determining the spatial relationship between the flesh and fuel vapour or mist ejection. A distinction must be drawn between primary fires which are a direct consequence of projectile impact and secondary fires which follow from fuel leaking into regions containing ignition sources such as hot engine parts or electric sparks. It is imperative that designs be arranged to minimise this risk since little would be gained if primary fires were suppressed only to be followed by a secondary fire.

2 FIRE RAISING POTENTIAL

The chance of a fire in combat depends upon many parameters such as fuel type, fuel and air temperature, degree of void ventilation, ammunition and target configuration. The last condition presents one of infinite variability, since the chance of two paths being identical is minimal. However, provided functioning of a purpose built incendiary round is achieved the path then becomes less significant. In our trials we have endeavoured to separate the variables in order to establish the significance of individual parameters. For this purpose, simplified targets were constructed with the dual purpose of simulation of aircraft fuel tank structures and of functioning the rounds under consideration.

2.1 Effect of Fuel Type and Temperature on Ignition

Fuel for aircraft can vary from kerosine to gasoline, the main fuels at the present time being Avcat (JP5),

Avtur (JP1) and Avtag (JP4) of which the latter is the most volatile, therefore the one most likely to produce fires, since on release it can vaporise readily in normal ambient conditions and with ample supplies of air result in situations most favourable to ignition.

Investigations using a kerosine type fuel and an incendiary round, yielded the probabilities of fire shown in Figure 1, which illustrates clearly the significance of temperature of fuel and ambient air on ignition. Other conditions monitored were humidity, air disturbance and wound size but these all had statistically small negative influences on the risk of fire. Investigations against this and other fuels showed that the risk of ignition depended significantly on fuel temperature particularly its relation to the flash point of the particular fuel. An apparent deviation from this concept appeared in a limited number of tests made with an anti-misting kerosine. The reduced fire risk as shown in Table 1 is attributed to the very high apparent viscosity in this treated fuel following high shear rates produced by the projectile and possible suppression of atomisation and vaporisation. There are, no doubt, other fuel treatments that can be made to inhibit ignition but these will almost invariably introduce system and logistic problems.

2.2 Mechanism of Ignition

2.2.1 Inert Fragments or Bullets

The sequence of events is roughly as follows. The fragment or bullet penetrates the aircraft structure and a spray of incandescent metallic particles appears at entry and exit lasting for approximately 2 milliseconds, the temperature of the flash is about 2500°C. The fragment traverses the intervening air gap, penetrates the metal tank wall and produces further incandescent particles see Figure 2. On penetrating the tank a very high shock pressure is built up in the fuel around the projectile in fractions of a millisecond, the intensity of pressure increasing with fragment velocity and size. A typical trace is shown in Figure 3. Pressures in the fuel close to the projectile have been assessed as high as 10^9 KN/m², in consequence of which work is done on the fuel in addition to heat imparted by the hot projectile. If consideration is given to the fact that the pressure in the wake of the projectile is sub atmospheric then there is the distinct probability of a rapid phase change from liquid to vapour at the first ejection pulse even with the less volatile kerosine fuel since it is a complex mixture varying in carbon number C₆ to C₁₆, as illustrated in Figure 4. If the ignition phenomenon were purely one of atomisation one would expect the three main fuels to exhibit the same degree of fire risk since their viscosities are essentially similar and they therefore atomise with equal facility. In addition, the energy required to ignite sprays of atomised fuel is greater than required for vaporised fuel.

2.2.2 Incendiary and HE Projectiles

In this form of attack there is considerable ignition energy available to vaporise the atomised fuel and thereby assist the ignition process. The ease with which the fuel is ignited depends not only upon the kinetic energy of these rounds but upon the ability of their fillings (incendiary or high explosive mix) to vaporise the fuel and this is illustrated by the results shown in Figure 1.

3 FUEL SYSTEM FIRE RISK

The low pressure fuel system consists of many parts besides the fuel tanks themselves, each with its own degree of risk. For example, pipe runs which contain fuel at pressure and other components external to the fuel tanks could if struck give rise to a higher fire-risk than the fuel tanks but the relative risk depends largely on their presented area to given directions of attack. The vulnerability of fuel pipes could be reduced if routed through the fuel tanks.

3.1 Effect of Fuel Tank Design

The risk of ignition depends upon the tank design and location within the aircraft. For example, if tanks are of the integral type, the surfaces which form the external part of the aircraft should not be a fire risk since a fire cannot be sustained on the 'clean' aircraft surfaces at speeds above 100 knots. However, for tank surfaces within the aircraft structure the risk should be high.

It is fairly common practice to use self-sealed bag tanks for the purpose of fuel containment. Those surfaces of the tanks which are in close contact with the aircraft skin should not be vulnerable to fire for the reasons given above. However, trials have shown that self-sealing materials adjacent to internal bays do not reduce the primary fire risk significantly, a reduction of something less than 10% is possible. Pressurised fuel tanks if holed increase the rate of loss of fuel and consequently increase the fire risk.

3.2 Attack of Fuel Filled Pipes

In our studies, referred to above, we have dealt with fuel tanks in their own right but it is common for compartments adjacent to tanks to contain many items of equipment including fuel and hydraulic pipes which are in themselves a fire risk. These pipes are usually pressurised and therefore the fluid release is more immediate than in the case of fuel tanks which are larger and have a free liquid surface. Moreover, puncture of the pipe will generally occur before puncture of the tank and hence fire may occur before tank fuel is released. Studies have shown that when protecting fuel tanks due consideration should also be given to equipment in adjacent bays, the degree of congestion, ventilation, flammables present and their pressures. Trials against pipes containing various substances showed that the damage to pipe and surrounding structure varies with fluid the pipe contains. This is illustrated in Figures 5 and 6 which show the explosive effect when the pipe contains Avtag fuel even at normal atmospheric pressure.

4 FIRE SUPPRESSION

4.1 Previous Methods

Systems have been employed in recent years to extinguish fires in voids adjacent to fuel tanks. These

were primarily used to reduce the risk of crash fires but were later modified for automatic operation using a thermally sensitive wire to sense the fire and to trigger the release of extinguishant into the protected bay. This system is similar to that used in engine bay fire protection; however, it is not possible, as in engine bays, to shut off the fuel or air supply. The combined thermal sensing/ extinguishant system is not primarily for protection against combat fires and some firing tests with HE shell showed limited success in dealing with this risk.

The drawbacks of the system would appear to be due to:

- a. Doubtful effectiveness due to long delays (5 to 10 secs) before fire is signalled. Severe fires can develop in 4 to 5 seconds. Evidence in more recent tests indicate that the best time to extinguish a fire is within a few milliseconds after impact.
- b. Unreliability - The sensing system, which is not a robust item, requires external power and can give inadvertent operation.
- c. The system is itself vulnerable to attack.

Alternative methods which overcome these objections have been sought, in particular systems which are rapid acting. At the same time they must be judged for their weight and bulk, cost, logistics, compatibility with aircraft materials and ease of installation.

4.2 Fire Hazards Detection

On the assumption that a penetration of the fuel system leads to a fire and that it starts within a few milliseconds after impact then the hazard indication must come from the projectile penetration and not from the fire itself.

There are two main categories of fire as revealed in trials; these are (a) flash fires which may last a number of milliseconds detaching from the tank attack face before expiring, and (b) sustained fires which eventually envelop the target. The latter is the serious menace to the aircraft, however, the former is a potential fire raiser and although the flash fire is of short duration, experience has shown it should be considered when designing the safety system. The mechanism of a flash fire is illustrated in Figure 7.

4.3 New Suppression Systems

New developments can be divided into 4 classes, for example:

- | | | |
|-----------------------------|---|-----------------|
| a. Foam fillers | } | Passive Systems |
| b. Vapour packs | | |
| c. Powder packs | | |
| d. Active Dispersal Systems | | |

4.3.1 Foam Fillers

Various plastics foam fillers have been placed between aircraft skin and fuel tank surface, including low and high density, flexible and semi-rigid, reticulated, open and closed pore.

The preferred foam is a flexible lightweight polyurethane polyether having a density of 15 to 22 kg/m³ and a porosity of 25 pores per cm, (Figure 8) cut oversize to give a 10 per cent compression fit. Firing trials have shown the material to be effective against inert and incendiary rounds provided it completely fills the space, ie intimate contact between filler and bay walls. In the case of a high explosive round the effectiveness is dependent on the proximity of the burst and the resultant damage to the foam.

To minimise moisture and fuel pick up, ultra-violet degradation and oxidation of the foam, the material can be housed in a coated polyethylene polyvinylidene chloride bag, filled with low pressure nitrogen. Plastics foams are ideally suited to narrow uncongested voids often found between backing board/self sealed bag tanks and aircraft skins.

Prior to installing the foam within the compartment the suitability of the material for the environmental conditions prevailing must be carefully assessed together with its subsequent effect on ventilation and drainage.

In "situ" filling of bays during build or as an emergency fit has been considered. This method has been shown to be feasible provided the bay surfaces are free of contamination. Problems are foreseen with control runs or other moving parts, also in removing the material should the need arise.

4.3.2 Vapour Packs

Pressurised inert gas or extinguishant vapour (eg halogenated hydrocarbon) can be contained in a lightweight pack located against the fuel tank wall and is released by the projectile.

The pack is designed to provide the desired shape for intimate contact against the protected attack face of the tank. It may consist of (a) drop-stitch rubberised or plastics bag (b) reticulated plastics foam bonded to a plastics bag or (c) interconnected plastics honeycomb bonded to a plastics or metallic cover. A typical pack is shown in Figure 9.

Firing trials have shown the packs to be effective against inert and incendiary rounds.

4.3.3 Powder Packs

Fire extinguishant powders can be contained in a relatively thin lightweight pack located against the fuel tank wall and disrupted by the projectile. The selected extinguishant is hermetically sealed within the pack, which is designed to provide the desired shape for intimate contact against the protected attack face of the tank. The pack may consist of a thin small cell honeycomb core with a plastic or metallic film covering.

Although superficially similar to the vapour packs, they are considerably less bulky and the powder does not automatically escape through a wound but is in fact distributed by the direct shock produced by the projectile in traversing the pack and the hydraulic shock from the fuel caused by projectile deceleration. In the case of an external high explosive burst additional pack break up is caused by the blast pressure wave. A typical pack is shown in Figure 10.

Firing trials have shown the packs to be effective against inert, incendiary and high explosive rounds.

4.3.4 Active Dispersal Systems

These systems differ from foam fillers and powder/vapour packs in that they are not completely passive.

A self-powered system is based on the use of a piezo-electric sensor to detect the hydraulic shock by the projectile within the fuel and utilises the power developed from the sensor to activate a fuse of a detonator which in turn disrupts the diaphragm of a pressurised extinguishant bottle. Repeater units or pyroamplifiers may be incorporated within the circuitry to amplify the signal should this be considered necessary where a single sensor is used to operate a number of extinguishers or long lengths of cabling are employed. The complete system including the amplification is independent of external electrical supplies.

A typical sensor is comprised of two piezo-electric crystals with a common electrode intersurface. The pressure wave either transmitted through the fuel direct to an immersed sensor or through fuel and associated tank wall with bulkhead mounted sensors, acts on the flexible welded end diaphragms where the loading is transmitted via an intensifier stud to the crystal stack. The resultant signal is transformed and rectified prior to being fed to a repeater unit. The latter is based on the same principle but with the pressure wave induced within a small chamber by a detonator.

The amplified signal is then fed to one or more pressurised bottles containing a vapour or powder extinguishant, activating a further detonator within the container rupturing the diaphragm and releasing the extinguishant into the selected bay. A diagrammatic arrangement of a complete system is shown in Figure 11.

An alternative solution is based on surrounding the volume to be protected (ie tanks, pipes and bays) by a wire cage or strike mat, which when severed by the projectile completes an electrical circuit, activates a fuse and releases fire extinguishant into the selected compartment. This system will require an external electric power supply.

Firing trials have shown that active dispersal systems are effective against inert, incendiary and high explosive rounds.

4.3.5 Selection of Fire Suppression System

The choice of system for fuel tanks is dependent on many factors, particularly its effectiveness against the threat, but also on system weight, complexity, reliability and maintainability. The protection of pipes containing flammable fluids will require adaptation of the fuel tank fire suppression system.

Foam filling satisfies most of these conditions in uncongested voids with gap widths up to 50 mm, vapour packs up to 150 mm, powder packs up to 300 mm; semi-active or active dispersal systems may be tailored to suit larger voids.

The passive systems are more appropriate when considered in the early design stages of an aircraft than as a retrofit.

Foam filling can be used in the additional roles of support to flexible fuel tanks and thermal insulation. Powder packs could be built on to tank bay panel materials.

The selection of extinguishant depends upon the threat and compartment configuration. Powder extinguishants have excellent fire 'knock down' and flame inhibiting qualities in smaller compartments, while vapour extinguishants have good penetration and suppression in larger spaces and persist longer, particularly where ventilation is of a low order.

CONCLUSIONS

Firing trials and theoretical studies have shown that unprotected fuel tanks in combat aircraft are a high fire risk and this is confirmed by combat evidence in various theatres of war.

The risk of primary fuel fires can be reduced by using integral tank construction to limit the number of bays or voids around the tanks. Fire risks can be reduced by using less volatile fuels or by fuel treatment. The risk of secondary fire following combat damage can be reduced by suitable drainage overboard of escaping fuel and by the separation of flammables from ignition sources.

Improved survivability can be obtained by the application of both fuel fire and explosion suppression systems. In the latter fully developed systems are available, while in the former successful prototype devices have been tested.

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H W G Wyeth
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Agard Conference Proceedings No 84 on Aircraft Fuels, Lubricants and
Fire Safety.
AGARD-CP-84-71 (1971)

TABLE I
 FIRING TRIALS AGAINST ANTI-MISTING KEROSENE

Air Temperature Range °C	15 to 20		20 to 25		25 to 30		30 to 35		35 to 40		40 to 45	
	A	B	A	B	A	B	A	B	A	B	A	B
15 to 20	6	0	-	-	9	11	5	0	4	25	-	-
20 to 26	6	0	9	0	9	11	-	-	6	0	6	17

A - Number of Shots

B - Percentage Fires

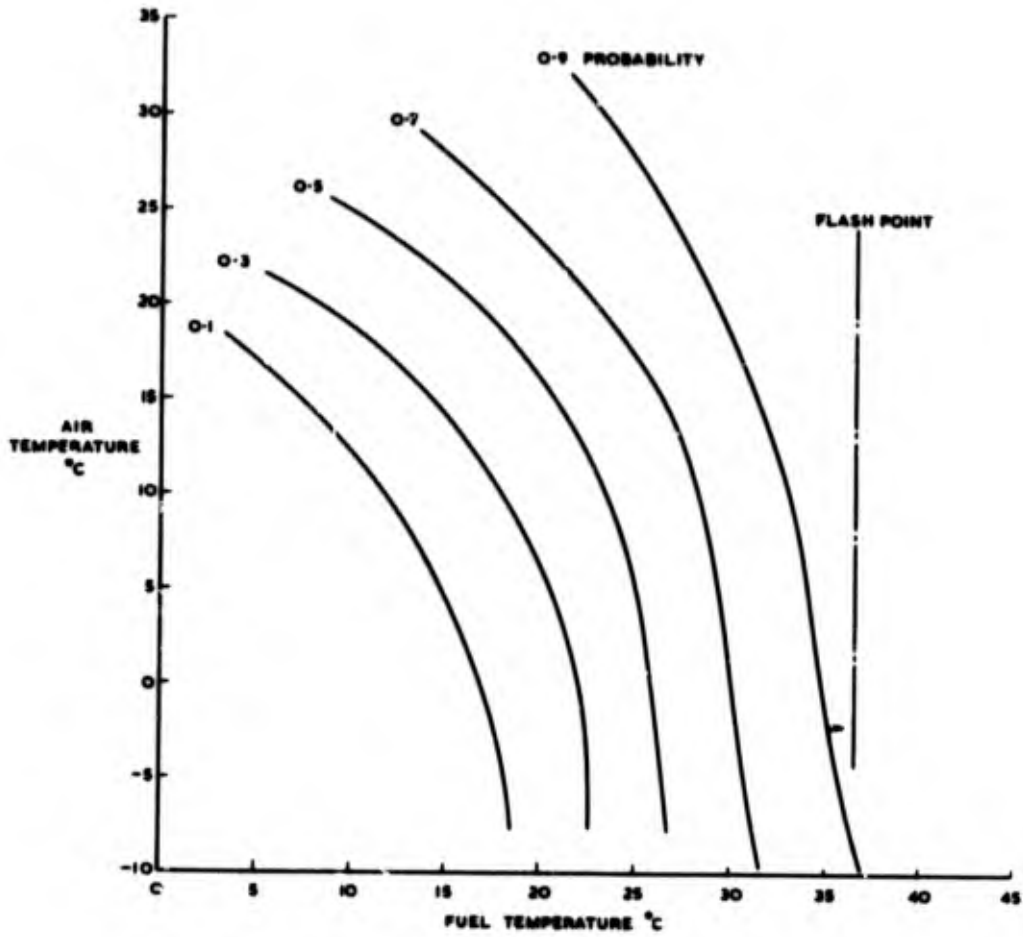
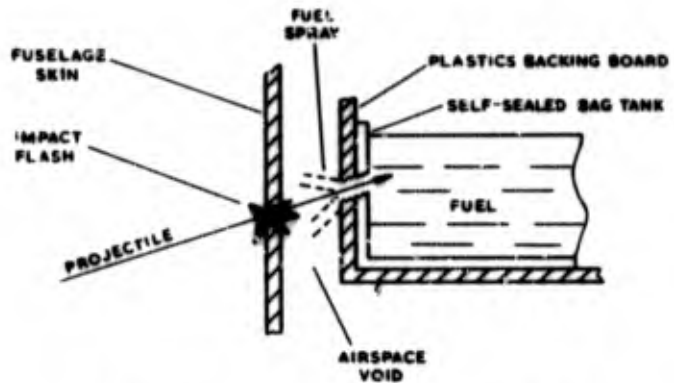
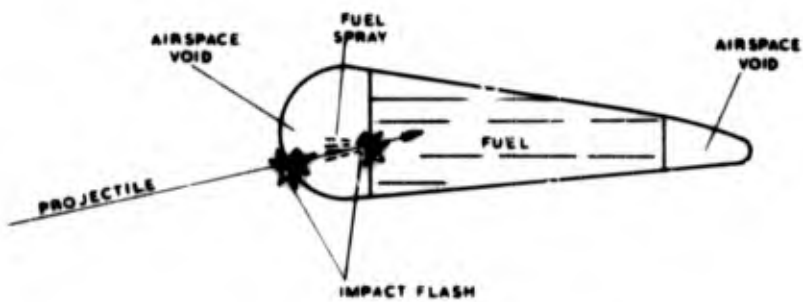


FIG.1 PROBABILITY OF FUEL (AVTUR JPI) FIRES
 [AVTUR (JPI) WITH INCENDIARY ROUND]



FUSELAGE SELF-SEALED BAG INSTALLATION

INERT ROUND - IMPACT FLASH
 INCENDIARY ROUND -
 INCENDIARY POWDER ALSO
 RELEASED WITHIN VOID



**WING INTEGRAL TANK INSTALLATION
 FUEL TANK FIRE PROBLEM**

FIG. 2 MECHANISM OF IGNITION

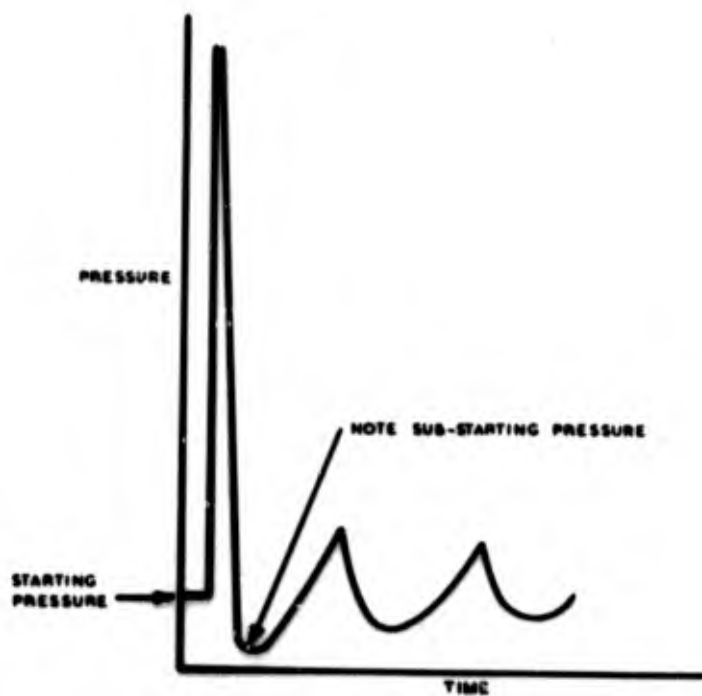


FIG. 3 TYPICAL PRESSURE-TIME CURVE DURING BILLET PENETRATION

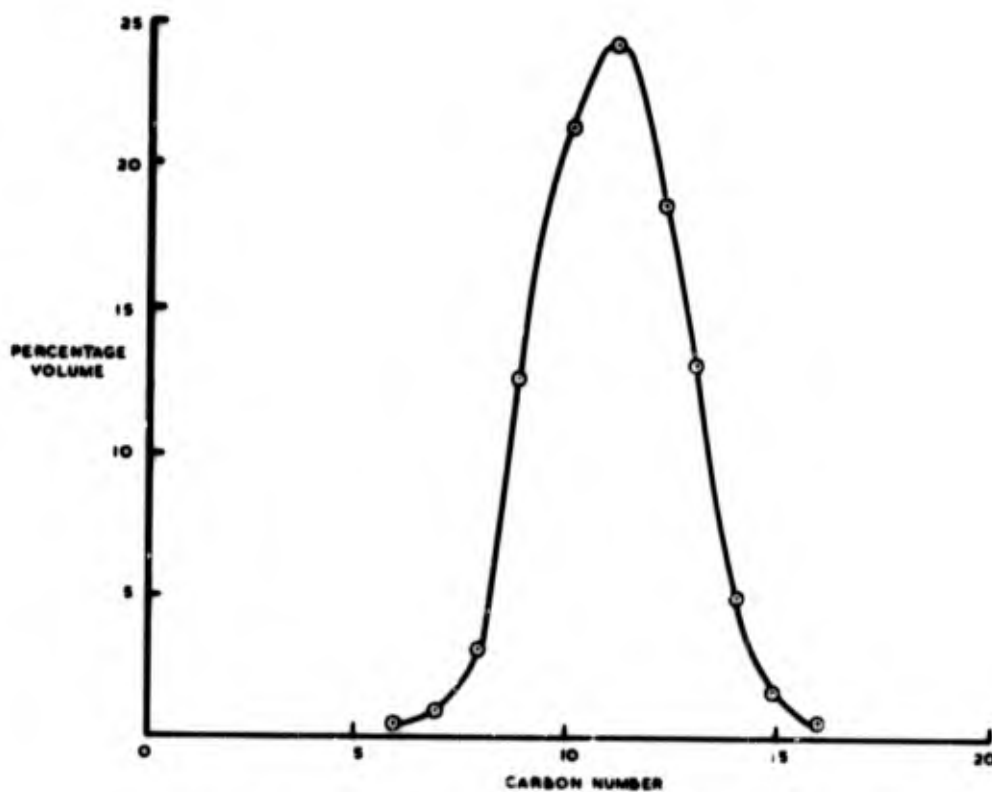
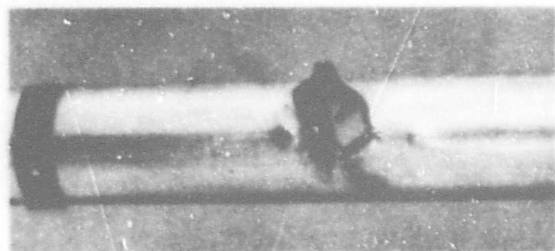
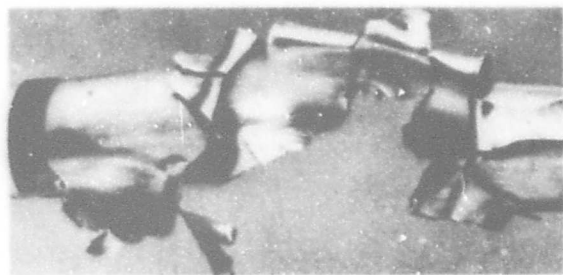


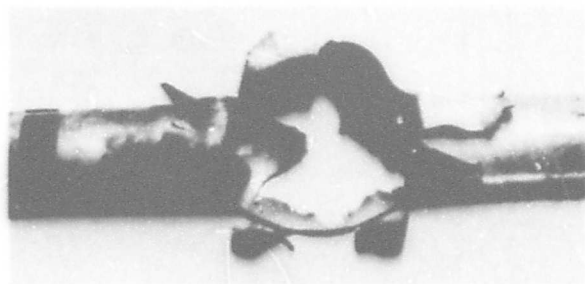
FIG. 4 PLOT OF THE CARBON NUMBER IN A HYDROCARBON (KEROSENE TYPE) FUEL



AIR FILLED PIPE



WATER FILLED PIPE

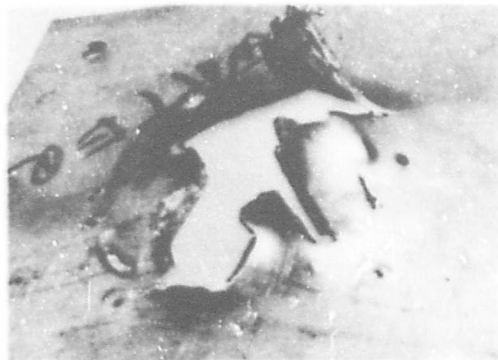


AVTAG FILLED PIPE

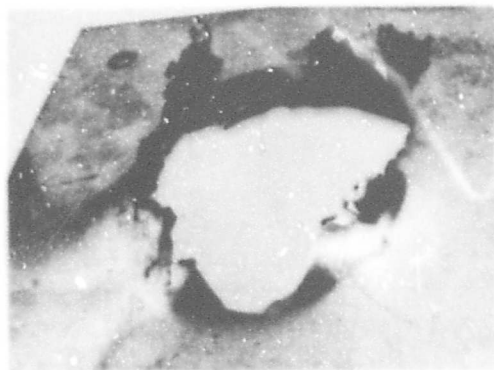
FIG.5 DAMAGE TO PIPES (38mm DIA) BY AN INCENDIARY ROUND



REAR PLATE BEHIND AIR FILLED PIPE



REAR PLATE BEHIND WATER FILLED PIPE



REAR PLATE BEHIND AVTAG FILLED PIPE

FIG.6 EXIT FACE DAMAGE TO 3mm AL ALLOY PLATE MOUNTED 150mm BEHIND PIPE

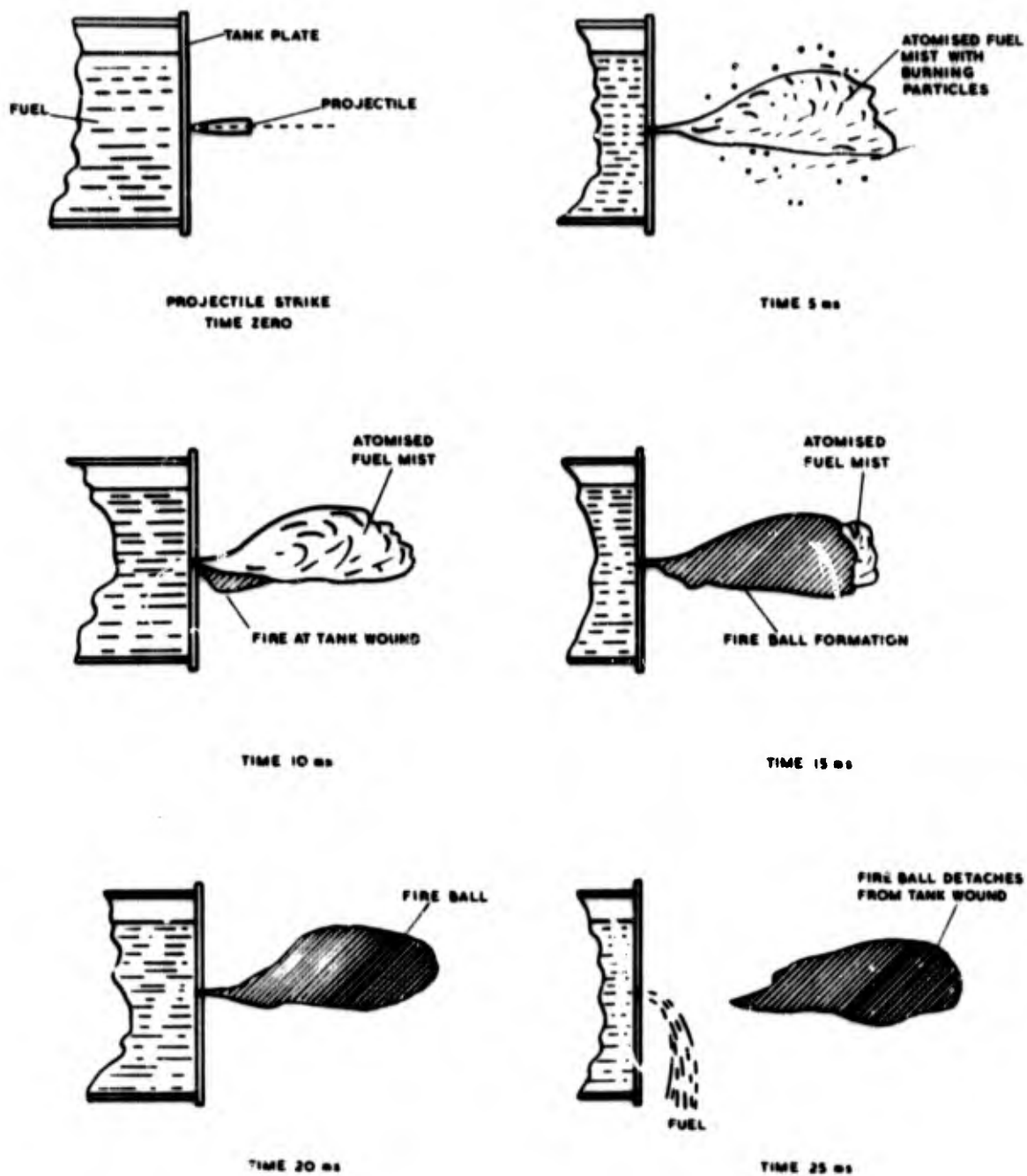


FIG.7 MECHANISM OF FLASH FIRE

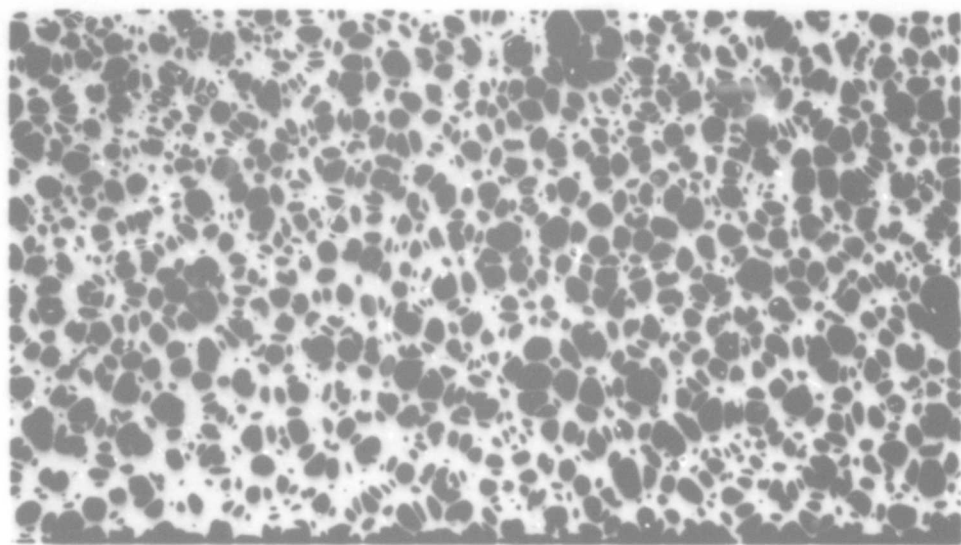


FIG.8 RETICULATED POLYURETHANE ETHER

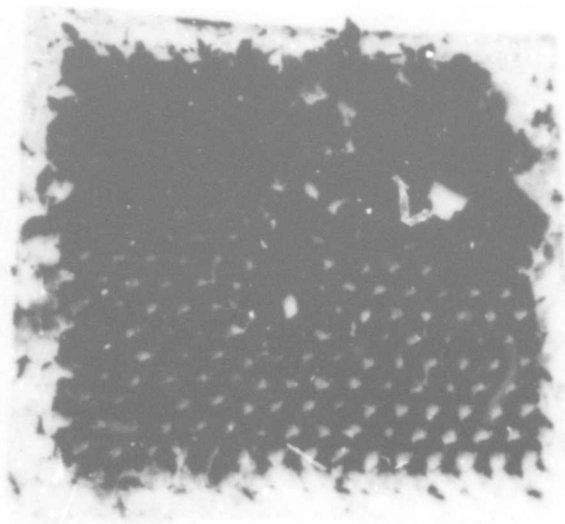


FIG.9 VAPOUR PACK, INTERCONNECTED HONEYCOMB

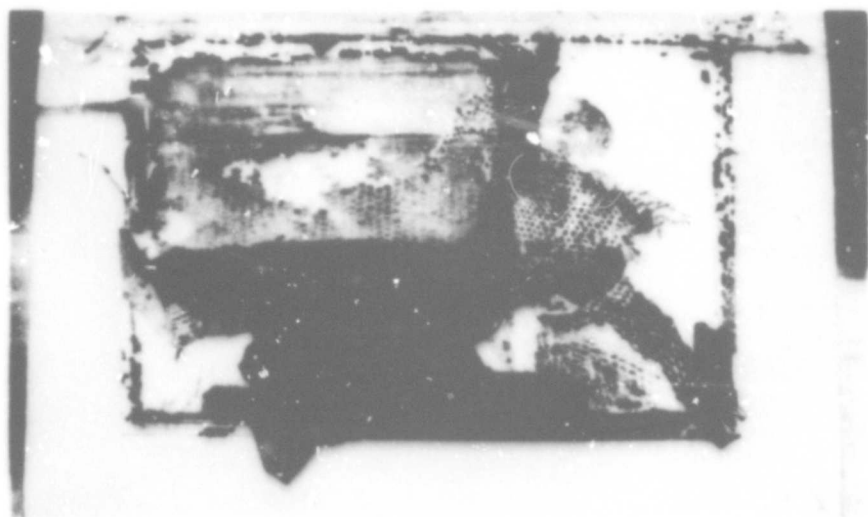


FIG.10 POWDER PACK

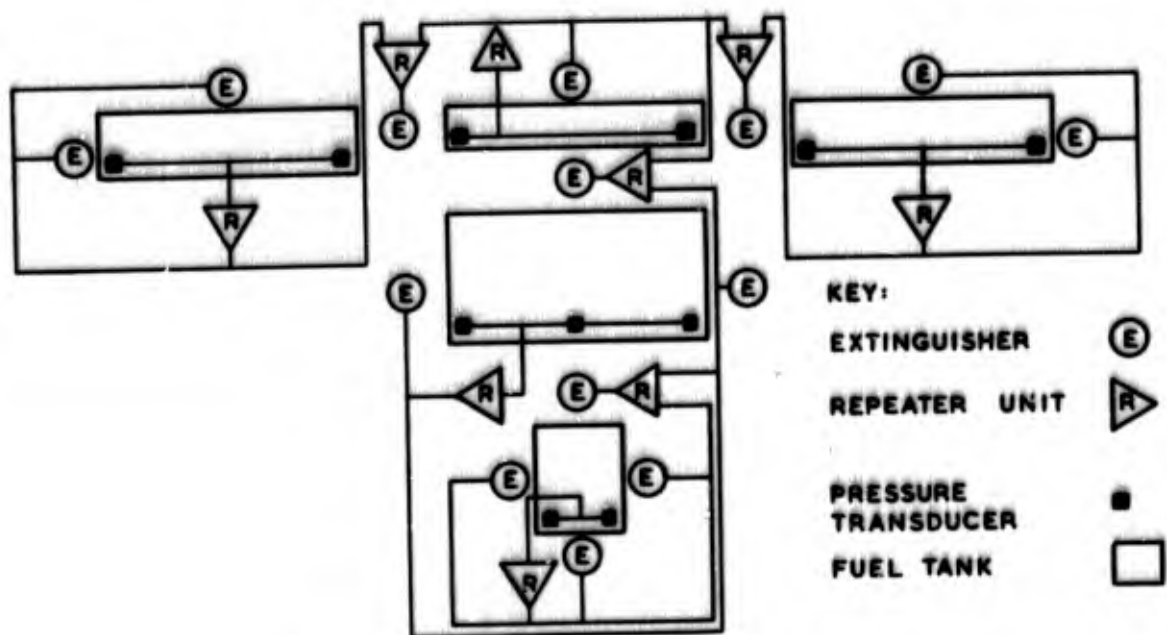


FIG.11 SCHEMATIC EXTINGUISHER INSTALLATION

DISCUSSION - PAPER 17

Mr Jackson:

- (a) Is the Piezo system available or is it still under development?
- (b) Are the reticulated foams available?
- (c) Are vapour and powder packs available?

Mr Macdonald:

- (a) The piezo-electric sensors and associated devices are available but further work is in hand on the optimisation of the extinguishing system.
- (b) Reticulated foams are available. Their application depends upon bay depth and on the upper temperatures encountered in the particular aircraft fuel system.
- (c) Vapour and powder packs are in an advanced state of development. Fitting to aircraft would require some degree of tailoring to suit the particular application.

Mr Parker: You have talked about flexible open cell polyether foams being applied externally to the tank, as a defeat mechanism. In the last few years in the US we have been developing closed cell semi-rigid fiber reinforced foams which can be applied external to the tank. An important point to consider is that in addition to the thermal mechanical interactions with the foams, there is also chemistry which can occur. Your suggestion to use the solids as quenching agents or solid extinguishants which are disbursed is a great one. I have been advocating this for five years, that is, to take advantage of the foam's breakdown to provide quenching by grabbing off the chain carriers of the combustion process. I would recommend a serious reexamination of the high speed chemistry which occurs at the wall.

Mr Previn: During the damaged pipe tests shown in Fig.5, were the effects of pressure and flow rate considered?

Mr Macdonald: No, not during these tests; fuel was at ambient pressure and zero flow, but we are now doing tests investigating variations in pressure and flow.

Mr Mahood:

- (1) Were explosive-type overpressures encountered in any of your fuel tank void space fire tests, (e.g. SOCAL, API)?
- (2) Won't categorical elimination of flash fires tend to needlessly penalize the aircraft, say in the case of void filler foams? In this case, for certain installations much more material would be necessary to eliminate "flash" compared to "sustained" fires.

Mr Macdonald:

- (1) In the particular trials referred to in the paper, the incendiary rounds produced no overpressures destructive to the simulated void. However, one side of the box external to the tank was open for camera viewing purposes. Other limited trials with a closed box showed no evidence of explosive effects.
- (2) Flash fires (which we define as combustion of fuel that can last many milliseconds, see Figure 7) are potentially dangerous, but in our assessment in Figure 1 only sustained fires were accepted. With regard to void filler foams, we have found it necessary to completely fill the void with consequent severe weight penalties in some situations. If the void is partially filled with foam, the flash fire may be of sufficient duration to ignite the subsequent fuel pulses. In the other suppression systems referred to in our paper, the flash fire is dealt with in the quick acting extinguishing systems.

Mr Livermore:

- (1) Can an exit wound which forms a flap act as a flame holder?

(2) Have the "hot and wet" decomposition problems of reticulated foam that were evident a few years ago been overcome?

Mr Macdonald:

(1) The quick answer is that outward petalling can act as a flame holder. However, the success in this respect must depend on the shape of the petals. When assessing the risk at exit, one must consider many other probabilities not necessarily associated with entry wounds such as penetration distance through liquid fuel, exit above fuel associated with direction of attack and the persistence of incendiary flash. The product of all these probabilities reduces the risk at exit significantly.

(2) The appropriate external foam should present no problem up to 100°C. There could be problems for the polyurethane ester foam used inside fuel tanks, but recent foam developments could overcome the hydrolytic and temperature problems.

Mr Parker: I would like to comment on the environmental question which was raised. This has been critical to the US for Vietnam and we have been simulating and studying it, with large tanks containing the ester foams. We expect to have significant deterioration after a year to a year and a half. The problem involved is primary chain scission of the urethanes to give both particulate matter as well as loss of tensile strength and modulus. The degree of loss in these areas which is acceptable has not yet been determined.

The answer seems to be use of an ester foam in the tank which is hydrophylic and is not swollen by the fuel as opposed to ether foams which are hydrophobic which reduces fuel carrying capacity up to 20% when it is swollen. There are two approaches being examined: one is coating of the ester foam with a barrier. This is not desirable for long term stability. Second is hydrophobic grafting. In the long term we will probably use a completely different foam.

AIRCRAFT FIRE PROTECTION TECHNOLOGY

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SUMMARY

The United States Air Force has pursued a modest but, nevertheless, continuous technical development program to enhance aircraft fire protection under natural and hostile (combat) flight environment conditions. Achievement of fire protection capability is initially dependent upon a knowledge of the ignition, flammability, and reaction severity characteristics of the combustible materials present. This information must then be utilized early in the design of an aircraft to prevent the presence of ignition sources proximate to combustibles and to maximize the margin of safety by judicious application of fluid drainage and ventilation provisions. Where a significant fire risk still exists, preventive measures must be supplemented with effective, reliable, and minimum performance penalty active and passive protection measures. The combat environment greatly complicates the fire protection problem. This paper will review the technical progress of the USAF program during the past seven years. Specific areas which will be addressed include fire and explosion hazard assessment (including fire safe fuels), fire prevention design measures, advanced fire and overheat detection systems, void space and dry bay fire suppression techniques, and fuel tank fire and explosion protection systems.

INTRODUCTION

The recipe for effective aircraft fire protection capability entails the application of fire prevention considerations during the initial design and throughout the engineering development phases of the vehicle, supplemented as necessary with appropriate fire containment, detection, and suppression and control provisions. An aircraft is comprised of a number of subsystems which must be integrated in a manner that provides a mission effective, reliable, economical, and safe operational flight vehicle. For normal flight operations, application of this approach has not unduly penalized aircraft performance and has resulted in an overall excellent civil and military safety of flight record. Extension of the fire protection capability goal to enhance crew, passenger, and vehicle survivability under crash impact conditions and, in the case of military aircraft, to combat (gunfire) environment conditions is much more difficult to achieve and in most instances imposes potentially serious additional system performance and cost penalties. Protection under the aforementioned threat conditions requires considerably greater emphasis on aircraft fire hardening and fire and explosion suppression and control techniques. In the final analysis the extent to which additional fire protection technology is incorporated into a vehicle is dependent upon a variety of tradeoff studies which consider the threat scenario, the vulnerability of the particular aircraft to the threat, the capability of available fire protection techniques to cope with the threat, and cost and performance penalties associated therewith. This paper will endeavor to summarize fire protection technological developments which have evolved from Air Force and Joint Air Force-other agency cooperative programs during the period 1967 through 1974. Where the technology has been transitioned to operational use, field experience will be interjected. In cases where technological development is still in progress, the potential benefits of the advanced techniques compared to state-of-the-art approaches will be discussed.

AIRCRAFT HAZARD ANALYSIS

The most important initial step toward the realization of a fire-safe aerospace vehicle is the application of fire prevention criteria during the design and development stages. Basically, this requires a continuous and conscientious hazard analysis effort to identify potential fire and explosion threats and to trigger design modifications to minimize or eliminate such risks. The hazard analysis must encompass the entire vehicle, provide specific attention to the operating characteristics of specific equipments located in various compartments, evaluate the possible failure modes associated with these equipments, consider the possible interaction of such failures with other subsystems that are in the same area, establish the relative criticality of such failures to vehicle survival, and endeavor to eliminate all single point critical failure modes by appropriate design modification or in the case of fire and explosion by additional protection provisions. An approach which has been successful in assessing the fire safety of recently developed Air Force aircraft is to classify discrete internal compartments of the aircraft into four categories:

1. Ignition Zone - Equipment offering ignition threat present but two failures are needed to cause fluid leakage.
2. Flammable Zone - Area in which flammable mixtures are normally present but two failures are needed to cause an ignition source.
3. Flammable Leakage Zone - Areas in which a single failure is needed to cause combustible fluid leakage, a single failure is needed to cause an ignition source, and two failures are required to cause fire potential.
4. Fire Zone - Area in which presence of ignition sources is normal and only one failure is required for combustible fluid leakage and generation of fire/explosion potential.

Where the aircraft compartment can be expected to be subjected to external ignition threats such as lightning strikes and gunfire, the hazard assessment must include these threats in the definition of the preventive and protection countermeasures required for aircraft survival.

FIRE PREVENTION

The ability to perform a credible aircraft internal compartment fire and explosion hazard assessment and to determine the appropriate engineering direction to minimize or eliminate the fire risk requires comprehensive data on the ignition, flammability, and flame propagation characteristics of the combustible fluids and materials present under representative environmental use conditions. In recognition of the importance of such information to safe vehicle design, the Air Force has maintained a technological activity in this area spanning a period of 20 years. Much of the data has been generated through a cooperative contractual program with the U. S. Bureau of Mines, Pittsburgh, Pennsylvania. References 1 and 2 are examples of recent useful reports pertaining to this problem.

In general, two types of combustion property data are required. The first type involves the conduct of controlled Laboratory scale experiments under somewhat idealistic conditions to yield information of the minimum spontaneous (autogenous) ignition temperatures by various types of thermal energy sources, the minimum electrical spark ignition energy requirements for various flammable vapor-oxidant mixtures, quenching distances, flame propagation velocities, and fuel-oxidant concentration explosion limits, and combustion severity (flame temperature, energy flux, combustion overpressure, etc.). These data provide the baseline from which specialized or more practical fire prevention engineering test evaluations can depart. These departures encompass the second, dynamic configuration oriented type of testing which is often required to establish permissible deviations from the baseline data while still assuring an adequate margin of safety.

Specific fire prevention measures which can be applied for example include:

1. Routing of combustible fluid lines outside of compartments where ignition sources are present.
2. Insulating equipment and bleed air lines to limit external surface temperatures below the ignition temperatures of combustible fluids likely to be present in the area.
3. Providing unidirectional ventilation at sufficient velocity to enable purging of the compartment and reduce flammable vapor-air mixture dwell time, thereby increasing the temperature required for ignition.
4. Incorporating adequate and controlled drainage capability for combustible fluid leakage zones to limit duration and extent of potential fire and explosion hazard.
5. Utilizing explosion proof equipment in all combustible fluid leakage zones.
6. Selecting the combustible fluid offering maximum fire safety margin where other fluid performance properties are acceptable.
7. Assuring double barrier combustible fluid leakage path to all ignition zones.

Fire prevention engineering design considerations are the most important and the initial mode of defense against the operational fire and explosion threat to an aircraft. Areas categorized as FIRE zones must be provided with additional fire containment, fire and overheat detection, and fire extinguishment and control protection features.

FIRE CONTAINMENT

Fire zone isolation is essential to prevent the spread of fire and to enable effective detection and control actions to be implemented. Isolation is accomplished through the use of appropriate fire walls, fire shields, or the skin and structure. Fire walls are generally stainless steel or titanium at least 0.038 cm (0.015 inches) thick and must withstand a 1094°C (2000°F) flame for 15 minutes without penetration. When the firewall is a load bearing structural member, titanium should not be used. It is imperative that the firewall provides a vapor tight seal; accordingly any penetrations through the firewall for lines, etc. must be sealed with materials possessing similar fire resistance capability. Where penetration of fire into other internal compartments or other vital structure is not likely fire shields and normal structural materials can be utilized. No significant advancements in fire containment technology have evolved in recent years. Intumescent coatings, however, are receiving greater attention as a means of enhancing fire hardening capability and reducing damage to costly components in the event of fire. In some instances the use of intumescent coated aluminum walls has been proposed in lieu of standard firewall materials. The latter approach is considered unacceptable because of their reduced fire resistance capability as well as the questionable long-term performance of the coated panels when subjected to cyclic environmental aging and damage from maintenance actions.

Achievement of the fire containment goal also requires provisions for shut-off of combustible fluids, as well as the use of stainless steel fluid carrying lines and bleed air lines in the fire zone area. All shut-off valves should be located outside the fire zone to further preclude thermal damage.

FIRE AND OVERHEAT DETECTION

Reference 3 provides an excellent review of United States Civil Aviation and Air Force experience with operational fire and overheat detection systems and the research and development efforts directed toward achieving an improved detection capability. The fire and overheat detection systems used in the engine nacelles of present day operational USAF aircraft have a very poor reliability and performance record. Figure 1 summarizes pertinent data for the time period between 1965 and June 1973. Over 80% of the reported fire alarms were false and resulted in four fatalities, six aircraft being destroyed and one receiving major damage. In addition, the detection system failed to provide an alarm in 52% of the accidents/incidents involving aircraft engine nacelle fires and contributed to several additional aircraft receiving major damage or being destroyed.

Table IA summarizes the state-of-the-art types of fire and overheat detection systems employed on Air Force aircraft. Most of the older aircraft (C54, C97, B52, KC135) use the unit detector. The false warning problem has been so acute with this system that it has been deactivated or significantly reduced in some aircraft. The remainder of the operational USAF aircraft have fire detection systems which use a continuous element cable. This system provides much greater detection coverage; however, it

is susceptible to false warnings due to electrical shorts. These shorts can be caused by the presence of foreign material in electrical connectors, defective control boxes and damaged sensors or electrical cabling. The use of a short discriminator in the electrical circuit of some systems (i.e., C-5A and F-111 aircraft) has significantly reduced this problem. However, this fix will not eliminate false warnings from partial short conditions.

The problem of false warnings can be significantly reduced or eliminated by using either systems which operate on entirely different principles which are inherently reliable or by using redundant or backup components with the conventional system to increase reliability. The AFAPL has been working for several years to solve the false warning problem. The dual loop overheat system used on many of the commercial aircraft today and some recent USAF aircraft is an outgrowth of the redundancy features of the Integrated Fire and Overheat Detection System conceived by Mr. T. Trumble of the AFAPL in the early 1960's.

Several advanced thermal sensing type detection systems developed by the USAF are listed in Table IB. In addition, to correct the "missed" fire problem technological effort was directed toward development of infrared and ultraviolet radiation sensitive sensors capable of reliable operation in the engine nacelle environment while providing volume coverage, fast response and specificity to fire. The status of these sensor developments is also shown in Table IB.

The AFAPL is in the final development phase of the Integrated Fire and Overheat Detection System which should provide optimum performance and reliability for engine nacelle applications. The Integrated System will consist of six radiation type detector heads (each containing two ultraviolet sensors and a test source), dual loop overheat sensors, a crew readout unit, a computer control unit, and a maintenance warning unit. The system uses separate sensors for overheat and fire detection. The system logic is such that a signal is required from two sensors (two UV for example) in order to provide either a fire or overheat alarm to the crew. In addition, each system acts as a backup in the event the other systems fail.

In addition to redundancy, the Integrated System provides for continual checking of the radiation and overheat sensors. If one sensor in the dual loop or in a detector head is defective, then only one signal is required by the computer control unit to provide a fire or overheat alarm. Appropriate readouts on condition of detector systems and computer are given on the crew readout. In addition, information on defective elements is transmitted to the maintenance warning unit where it is retained for display to the aircraft maintenance crew. This maintenance information system is similar in concept to the Central Information Test System (CITS) on the C-5A aircraft.

The Integrated System development is under contract to Thomas A. Edison and will be completed in the fall of 1975 with three flight qualified systems being delivered to the Air Force. A flight evaluation of this system is being planned.

FIRE ZONE FIRE EXTINGUISHING SYSTEMS

In military aircraft (Ref. 12), generally speaking, single engine aircraft are not fitted with fire extinguishing systems. On some Air Force aircraft such as the B-51 and KC-135, the engines are located in pods below the wing and separated from the rest of the aircraft by a pylon. The engine compartment is isolated from the pylon with a horizontal firewall. These aircraft have no fire extinguishing system installed on the basis that it is improbable that a nacelle fire would be totally destructive to the aircraft. There are also other military multi-engine combat aircraft such as the F-4 which do not incorporate fire extinguishing systems on a "calculated risk" basis. However, almost without exception fire extinguishing is provided in all military transport and cargo type aircraft engine nacelles.

Modern aircraft engine installation fire extinguishing systems generally employ a halogenated hydrocarbon type fire extinguishant because of its greater effectivity and attendant reduced system weight penalty. Table 2 illustrates the two types of systems currently in use. The conventional and high rate discharge (HRD) systems are very similar with the exception of the method of agent distribution. The HRD system utilizes open-end nozzles and relies on the high velocity of the agent discharge for proper dispersal within the nacelle. Consequently, high vapor pressure agents such as CF_3Br are best suited for HRD applications. In contrast, the conventional system utilizes perforated tubing for agent distribution with consequent penalties of restricted flow and generally higher total system weight. Low vapor pressure agents such as CH_2BrCl are best suited for the latter application. CF_2Br_2 , an intermediate volatility extinguishant, has been used successfully in both types of systems. Recently developed aircraft utilize the HRD type system.

The USAF has had excellent experience with the various halogenated agents. A review of accidents and incidents over a six-year period (1964-1970) showed that these fire extinguishing system installations have been more than 90% effective. In cases where the system has failed, extenuating circumstances were usually involved such as lack of rapid fire detection, utilization of improper fire emergency procedures, and mechanically damaged nacelles.

Air Force technical development activities in this area in recent years have been very limited. A successful effort was completed in 1969 for the development of a Pyrotechnic Gas Discharge Fire Extinguishing System capable of effective performance in the operating temperature range from $-54^{\circ}C$ ($-65^{\circ}F$) to $238^{\circ}C$ ($450^{\circ}F$) (Ref. 13). This system utilizes CF_2BrCF_2Br as the extinguishant and was developed primarily for high performance aircraft applications (Mach 2.5+) where high environmental operating temperatures will be experienced. To date this type of system has not been applied.

FIRE AND EXPLOSION VULNERABILITY OF FUELS

During the past 7 years the AFAPL has investigated the vulnerability of conventional and various modified turbine engine fuels to fire and explosion under ballistic impact conditions. The bulk of the testing was accomplished with 50 caliber API and single high energy fragments. Several different types

of test articles were employed depending upon the nature of the ballistic response being evaluated, for example external fire susceptibility due to liquid space hits versus ullage explosion hazards due to vertical upward liquid-vapor penetrations. In addition, the effects of tank volume, tank materials of construction, initial pressure, dry bay volume and ventilation were explored. Early testing also evaluated the effect of initial fuel temperature on the probability and severity of fire/explosion response for each of the conventional baseline fuels. In addition, various series of tests were often conducted to obtain immediately essential engineering data for vulnerability assessments or to quickly evaluate the survivability enhancement potential offered by various modified fuel formulations. As a result, many of the tests were limited in scope to satisfy the specific need at the time. Consequently, many gaps exist in the overall hazard characterization of a particular fuel. It is the intent of the subsequent discussion to summarize pertinent findings and/or trends observed from the testing conducted. Detailed discussion of test articles, test conditions, and test results is available in published technical reports (Ref. 14, 15, 16, 17).

Vertical Gunfire Response of JP-4 and JP-8 (Similar to JET A-1) Fuels

This test program was conducted in two phases: (1) "non-equilibrium" tests conducted with a 92 l (92 gallon) cylindrical tank to determine effects of fuel temperature, initial ullage pressure, tank volume, fuel depth, etc., and (2) equilibrium tests conducted with various rectangular tank configurations having capacities from 379 l (100 gallons) to 1136 l (300 gallons) to determine effects of initial ullage fuel-air mass ratio on ignition and reaction overpressures. All testing was conducted at the Air Force Flight Dynamics Laboratory's Ballistic Impact Facility located at Wright-Patterson AFB, Ohio. With the exception of eight tests conducted with 14.5 - 113.8 mm API, all other tests were conducted with 50 caliber API, type M-8 rounds fired at a service muzzle velocity of approximately 853 m/sec (2800 ft/sec). Results of the non-equilibrium tests are shown in Figure 2. Both JP-4 and JP-8 can be ignited over the temperature range of -12°C to 54°C (10 to 130°F) and reaction overpressures with JP-4 were generally higher than those from JP-8. In the case of the equilibrium tests, mixtures with initial fuel-air mass ratios as low as 0.002 and not exceeding 0.11 could be ignited. The normal rich fuel-air mass ratio for hydrocarbons is 0.28. The generation of the mist and sprays due to ballistic impact has the effect, as should be expected, of driving the fuel-air mass ratio in the zone of potential ignition above the rich fuel-air mass ratio, resulting in an overall apparent depression of the rich flammability limit. With respect to the vulnerability of fuel tanks to vertical upward projectile hits, a potential explosion hazard exists with both JP-4 and JP-8, but in general the severity of the reaction is lower with JP-8.

Vertical Gunfire Response of JP-4 and JP-8 Fuels Containing Anti-Mist Additives

At the Aircraft Fuels, Lubricants, and Fire Safety 37th Meeting of the AGARD held in THE HAGUE, Netherlands in 1972, the Royal Aircraft Establishment reported on their progress toward the development of anti-misting additives for reducing the aircraft crash fire hazard of Jet A type fuels. As a result, the Air Force made arrangements with the British Government to obtain a sample of their FM-4 additive for evaluation in JP-8 under vertical ballistic impact conditions. During the interim period several other promising anti-mist additives were also surfaced in the United States. The latter were also included in the test program. A detailed description of the test program is available in Ref. 15. Basically, the test article consisted of a 379 l (100 gallon) rectangular tank (0.9 m x 0.9 m x 0.45 m) (36" x 36" x 18") with replaceable entrance and exit plates made of normal aircraft type of aluminum (2024 T3) with thickness of 2.29 cm (0.90") at the entrance and 4.57 cm (0.180") at the exit. The threat for these tests consisted of the standard 50 caliber API, fired at a velocity of approximately 732 m/sec (2400 ft/sec) with 30° obliquity which assured maximum incendiary burning within the tank ullage. The total travel of the projectile through the liquid was 10.2 cm (4"). This test arrangement provided approximately 95% ignition of all the fuels tested throughout the program. All tests were conducted at 1 atmosphere initial pressure and bulk fuel temperatures in the 15.5-21.1°C (60-70°F) range. Test results are summarized in Table 3. In general, the anti-mist additive approach appears very promising for reducing the ullage reactivity of low volatility JP-8 type fuels. Additional effort is required to optimize fuel-additive blends from an overall fuel and engine system's performance viewpoint and to establish minimum effective concentration not only for 50 caliber threat but also larger weapon threats.

External Fire Vulnerability of Jet Fuels to Liquid Space Gunfire Hits

Incendiary and high velocity fragment penetrations into the liquid space of fuel tanks provide a principal means for initiation of external fires which if sustained can result in rapid destruction of flight vehicle structure and critical subsystems. If direct ignition does not occur, leaking fuel can be ignited by secondary ignition sources present within the aircraft. Analysis of aircraft combat loss data indicates that initiation of fuel fire rather than fuel tank explosion is the more prevalent cause of aircraft loss.

Several investigative efforts of the relative vulnerability of conventional jet fuels to ballistic external fire generation have been conducted utilizing various test articles to simulate typical aircraft fuel tank-dry bay configurations. These fuel tank simulators can be categorized into two basic types: (1) Striker Plate - Unconfined Void Space - Fuel Tank with static airflow, and (2) Confined Dry Bay - Fuel Tank with bay ventilation and external airflow.

Results of the Type 1 configuration indicate that the susceptibility to sustained external fire is a function of the volatility fuel. The bulk of the testing was conducted with fuel temperatures in the (4.4 to 26.7°C) 40-80°F range. JP-4 exhibited a high probability of sustained fires whereas the JP-8 type fuel was generally non-vulnerable, exhibiting only flash burning of the initial mist-air mixture and sustained burning in less than 5% of the tests.

The Type 2 confined dry bay configurations provided dramatically different response from JP-4 fuel. The bulk of these tests were conducted with fuel temperatures in the 29.4 to 35°C (85-95°F) range and 1.34 atm (5 psig) fuel tank pressure. A variety of dry bay volumes and ventilation rates were investigated. Sustained external fires occurred in only 11.28% of the tests with JP-4 and only 1.68% with

JP-8. In the majority of the tests, dry bay flash-reactions occurred with both fuels. In general, combustion overpressures of JP-4 were higher than for JP-8.

To date, a realistic test configuration capable of duplicating the combat fire vulnerability of aircraft to liquid space gunfire hits has not been achieved. However, it should be recognized that only a limited number of test parameters have been investigated.

AIRCRAFT FUEL TANK/DRY BAY FIRE AND EXPLOSION SUPPRESSION TECHNIQUES

Combustion involves the chemical reaction of fuel with an oxidizer resulting in the generation of heat, smoke, and radiation (usually visible and referred to as flame). Sustenance of the combustion process requires the continual resupply of fuel, oxidant, and sufficient energy to maintain activation of the chemical reactions involved. The combustion reactions for most materials occur in the gas phase, and accordingly a portion of the thermal energy release must be fed back to the unreacted fuel to precondition it by means of vaporization or pyrolysis to permit continuance of the gas phase oxidation reactions. The reactions occurring in the gas phase also involve the formation, consumption, and generation of free radicals which are intimately involved and essential to the overall combustion reaction. In summary, the requirements for combustion are fuel, oxidizer, energy and free radicals. The suppression of combustion involves the use of physicochemical actions capable of counteracting one or more of these combustion elements.

Several active and passive methods for counteracting the fuel tank/dry bay fire and explosion hazard exist. Only two methods, in-situ flame arrestors and nitrogen inerting, are currently in wide utilization. Various refinements of these as well as other methods are being investigated.

In-Situ Flame Arrestors

Reticulated polyester polyurethane foam has been in use by the Air Force for aircraft fuel tank protection for several years in both the fully packed and gross voided system application modes. Fully packed foam has exhibited 100% effectiveness in preventing fuel tank explosions. In addition, the foam appears to reduce damage from hydraulic ram, and blast overpressures and fragments from 23 mm HEI detonations within the tank. Enhancement of self-sealing bladder performance is indicated due to maintenance of wound alignment. Fully packed foam is currently installed on over 2000 aircraft. One of the problems encountered with polyester polyurethane foam has been poor hydrolytic stability. Experience has indicated that under a severe high humidity and temperature environment such as SEA, foam deterioration in the fuel tank ullage can be anticipated in 2-5 years of service. Under less severe conditions such as the United States type environment, service lives of 5-7 years have been experienced. The newer, lower density polyester polyurethane foams are susceptible to similar degradation problems. The Scott Foam Division has developed a polyether polyurethane reticulated foam possessing significantly superior hydrolytic stability. The physical properties of this material are similar to the polyester foam with two exceptions, its volume swell is higher (20% versus 7% in JP-4 fuel) and its tensile properties in fuel are lower, 62 kN/m² versus 103-172 kN/m² (9 psi versus 15-25 psi). The polyether foam is currently undergoing engineering evaluation by the Aeronautical Systems Division, Wright-Patterson AFB.

Through the use of gross voided foam concepts, significant reduction of the foam protection system weight and volume penalties can be achieved. Various configuration possibilities exist. Basically, the concept allows combustion to occur in a portion of the tank, contains the reaction within that volume element, and makes use of the adjoining voided foam array for relief of hot combustion products, thereby limiting overall peak overpressures below damaging levels. The gross voided foam concept is intended for incorporation into new aircraft designs where appropriate tradeoffs of fuel tank arrangement and structural strength versus extent of voiding and type of voided configuration can be conducted to establish the optimum for protection. Two models for predicting overpressures with voided flame arrestor systems have been developed (Ref. 18, 19). Unfortunately, these models do not provide a high degree of confidence for direct application to aircraft systems; and, consequently, full scale gunfire testing of selected configuration is required to verify suppression performance. Typical system weights for the fully packed and a 40% gross voided reticulated polyurethane foam configurations are shown in Figure 4 for fighter and larger transport/bomber type aircraft.

Fuel Tank Inerting

Maintenance of the oxygen concentration in the fuel tank ullage below that essential for flame propagation has long been known as an effective method for protecting against explosion. An inerting system utilizing Liquid Nitrogen (LN₂) as the source of inertant has been developed and flight tested for application to the C-5A aircraft. The entire C-5 fleet is scheduled to be equipped with this protection capability in the very near future. The total system weight for tank inerting as shown in Figure 4 is approximately 3000 lbs. In the case of the C-5, additional LN₂ will also be available to provide fire fighting capability in various non-habitable areas such as wheel bays and other bays adjacent to fuel tanks. LN₂ inerting is also attractive for fighter aircraft applications; actual system weight will be dependent on anticipated mission flight profiles.

The Air Force and more recently the Federal Aviation Agency have been pursuing technical efforts toward development of on-board inert gas generation (IGG) systems. IGG systems offer the potential advantages of mission profile operational flexibility, independence from logistics resupply requirements, overall reduced cost of ownership, and significantly reduced system weight, particularly for the larger aircraft. Two IGG techniques offer promise and are depicted by simplified block diagrams in Figure 3.

The first technique involves the catalytic combustion of jet fuel with air in controlled manner to generate combustion products possessing low residual oxygen content (less than 2 volume %), conditioning of these products to reduce temperature and remove undesirable ingredients such as water and SO₂, and utilizing the residual products as inerting gas. Activities in this area have been sponsored by the Air Force principally with AiResearch Manufacturing Company of California (Ref. 20) and have successfully progressed through the prototype catalytic reactor system evaluation stage. This reactor was operated at

an inert gas output of 0.454 kg/min (1 lb/min) with an oxygen concentration as low as 0.5 percent (average between 1 and 2 percent). In addition, the program demonstrated high oxidation reaction effectiveness, stability of operation, and effective thermal control. A fuel tank inerting system was synthesized to meet all flight requirements, including emergency descents. Preliminary engineering system weight estimates are indicated in Figure 4. Additional process technology and system development efforts culminating in aircraft flight test performance demonstration are required before this type of system can be considered a competitor to LN₂ for inerting applications.

The FAA has pursued investigation of other IGG techniques. The most promising involves hollow fiber permeable membranes. As depicted in Figure 3, this technique entails the passage of conditioned air through the membranes where the oxygen is preferentially separated, and the depleted oxygen source gas is utilized for tank inerting. The basic feasibility of this approach has been demonstrated by the AirResearch Manufacturing Company (Ref. 21) and preliminary engineering system weight estimates are shown in Figure 4. Technical development of the membrane separation technique has not progressed as far as the Catalytic Reactor approach. The Air Force and FAA are currently planning a joint program to develop the membrane technique to the same point as the catalytic reactor system. One of the techniques would then be selected for advanced development and flight demonstration.

CONCLUSION

Significant progress has been made toward achieving a superior aircraft fire protection capability. The process must begin with the rigorous implementation of fire prevention measures during the design of the vehicle. These must then be supplemented by appropriate fire containment, hazard detection and fire and explosion protection capabilities. Technological advancements have been made in the development of detection systems which provide rapidity of response, specificity and false warning free operation. Additional understanding of the ballistic vulnerability of aviation fuels to fire and explosion has been developed. In general, the results indicate that all conventional fuels pose a significant threat under combat conditions. Specific additional protection measures are required to enhance Aircraft Survivability from fuel tank gunfire hits. In this respect, reticulated polyurethane foam and LN₂ inerting are attractive for fighter, close-support aircraft applications, whereas LN₂ inerting is the most attractive for large aircraft applications. Finally, anti-mist fuel additives and IGG systems offer technological potential for future year applications.

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TABLE I
FIRE AND OVERHEAT DETECTION SYSTEMS

A. STATE-OF-THE-ART (Air Force Aircraft Applications)

<u>Type</u>	<u>Principle of Operation</u>	<u>Application</u>	<u>Advantages</u>	<u>Disadvantages</u>
Unit Detector	Bimetallic switch which closes when temperature exceeds preset limit.	Engine nacelle Fire & overheat C-54, C-97, B-52 KC-135	Inexpensive Simple	High failure rate High false alarm rate Slow response Does not distinguish between overheat & fire
Continuous Cable (Resistance Type) (Single Loop)	Continuous element coaxial cable. Filler material resistance varies as a function of temperature. When resistance reaches a pre-determined value an electronic circuit triggers an alarm.	Engine nacelle Fire & overheat F-4, F-111, C-133 Bleed air lines overheat C-130	Most inexpensive of the cable type systems	High failure rate High false warning rate due to cable shorts Slow response May not detect small fires or engine burn through Does not distinguish between overheat & fire
Continuous Cable (Resistance Type) (Dual Loop)	Each cable same as above. System consists of two cables mounted side by side. Both cables required to sense overheat before crew warning is given.	Engine nacelle Fire & overheat F-15, C-5A, B-1 (Prototype)	Not prone to false warnings from cable faults.	Slow response Does not distinguish between overheat & fire May not detect small fires or engine burn through
Continuous Cable (Pneumatic Type)	Sealed cable with a core or trapped gas. When temperature increases above preset value, desorbed gas causes sufficient pressure to close a switch and activate an alarm.	Engine nacelle Fire & overheat T-37 and T-38 Retrofit Cargo Bay and Dry Bays & wheel well Fire & overheat C-5A	Not prone to false warnings Self checking (with a second set of electrical contacts)	Slow response May not detect small fires or engine burn through Does not distinguish between overheat & fire
Optical (Visible Light)	Uses ratio of two wavelengths (colors) of light emitted from combustion flame.	Engine nacelle Fire detection Sikorsky Helicopter Cargo Bay Fire detection C-5A	Fast response Provides true volume coverage for fire detection	Can false alarm under certain sunlight conditions Becomes insensitive to fires in bright light
Smoke Detector	Detects scattering of light by smoke particles.	Crew & cargo compartments C-5A	Early detection of some types of smouldering fires before actual flame	Sensitive only to smoke. Will not detect black type smoke. Susceptible to false warnings from cigarette smoke and dust.

TABLE I - Continued

FIRE AND OVERHEAT DETECTION SYSTEMSB. TECHNOLOGICAL ADVANCEMENTS (USAF R&D PROGRAM)

<u>Type</u>	<u>Principle of Operation</u>	<u>Performance Advantages</u>	<u>Status</u>
Continuous Cable (Self-Generating Type)	Continuous element thermocouple which generates an EMF when heated. Electronic circuit triggers an alarm when EMF reaches a pre-determined value.	Will not false warn from shorts in the cable. Can also detect an overheat when shorted although alarm temperature will be higher. This system was developed primarily for overheat detection, but will also detect fires (with the limitations inherent with overheat cables for this application).	Two prototype flight qualified systems have been successfully flight tested for over 500 hours each. No false alarms or failures have occurred. System development is complete. (Refs. 4, 5)
Continuous Cable (Time Domain Reflectometry, TDR)	Determines the location of an overheat along a coaxial cable by sending electrical pulses down the cable and measuring the reflected pulse from the overheat zone.	Detects location of overheat and also differentiates between true overheats and short and open circuits in the cable. Developed primarily for overheat detection	Breadboard system developed, however it is limited to 15.2m (50 feet) of cable length due to cable losses. (Ref. 6)
Infrared Fire Detector (CdTe)	Detects infrared radiation in the near IR spectrum (0.7 to 1.5 μ m) emitted by combustion flames.	Provides total volume coverage for flame detection and thus is a true fire detector. Can be operated at temperatures from -54°C (-65°F) to 399°C (750°F). Applicable to engine nacelle, APU, cargo, dry bay applications.	Sensor developed to final hardware stage. Presently, undergoing evaluation testing. Flight hardware control unit is being developed. System will then undergo flight test evaluation. (Ref. 7)
Ultraviolet Fire Detector	Detects ultraviolet radiation in the 2000Å to 2800Å spectrum region which is emitted by combustion flames.	Provides total volume coverage for flame detection and thus is a true fire detector. Will detect engine burn through. Solar blind feature permits operation in open areas. Temperature range from -54°C (-65°F) to 260°C (500°F).	A 500°F sensor has been developed to hardware stage and is used in the integrated system described below. (Refs. 8, 11) A 538°C (1000°F) sensor has been developed to breadboard stage and is presently being evaluated. (Ref. 9)
Integrated Fire & Overheat Detection System	Combines any of the cable overheat sensors with any of the fire detectors into a self checking system.	Provides both fire & overheat detection for engine nacelle applications. Self checking feature will simplify crew checking and maintenance requirements. Dual sensor feature eliminates false warnings.	Three flight qualified systems are being fabricated. Two systems will be flight tested. System development is complete. (Ref. 10)
Smoke Detector	Utilizes difference in scattering by smoke particles at two ultraviolet wavelengths.	Can be designed to detect specific types of smoke and not false alarm from other sources. Provides volume coverage.	Three systems are presently being fabricated. These will be further evaluated.

Table 2

TYPES OF AIRCRAFT FIRE EXTINGUISHING SYSTEMS

SYSTEM TYPE	AIRCRAFT	AGENT	AGENT ⁽¹⁾ QUANTITY FORMULA	NACELLE NET VOLUME		AGENT WT/SHOT		TOTAL SYSTEM WT		DISTR. RQMT. COMPLIANCE
				l	ft ³	kg	lbs	kg	lbs	
Conventional	C-130	CH ₂ BrCl	(Design Guide)	1726	61	6.13	13.5	27.24	60	Motion Pictures
	B-57	CH ₂ BrCl	0.56 Wa + 0.16V	1189	42	6.13	13.5	23.61	52	
	C-97	CH ₂ BrCl		3396	120	14.98	33.0	54.48	120	
High Rate Discharge	DC-9	CF ₃ Br	W = 0.05V or	3679	130 ⁽²⁾	3.81	8.4	16.84	37.1	Agent Concentration Analyzer
	C-141	CF ₂ Br ₂	W = 0.02V + 0.25 Wa	3255	115	3.18	7.0	32.69	72	
	C5-A	CF ₂ Br ₂	(Whichever is greater)	3934	139	3.41	7.5	39.59	87.2	

(1) V = Net volume of zone in cu. ft.

Wa = Air flow (normal cruise) in lbs/sec.

(2) Includes APU and both engines

Table 3

SUMMARY OF ANTI-MIST FUEL ADDITIVE BALLISTIC EVALUATION

Fuel/Additive*	No. of Tests	No. of Reactions	Avg. Pressure Rise		Maximum Pressure		No. of Reactions Over 69 kN/m ² (10 psi)
			kN/m ²	psi	kN/m ²	psi	
Neat JP-4	16	14	378	54.8	496	72.0	14
Neat JP-8 (Flash Point 45.6°C (114°F))	15	13	262	38.0	379	55.0	13
JP-4 + FM-4	15	12	465	67.5	545	79.0	12
JP-8 + ESSO A	16	16	219	31.7	427	52.0	14
JP-8 + FM-4	16	14	59	8.6	276	40.0	2
JP-8 + AM-1	15	12	68	9.8	228	33.0	3
JP-8 + XD 8132	15	15	90	13.1	207	30.0	6

* Fuel additives at a concentration of 0.3% by weight, except XD 8132 at 0.7%.

		FIRE ?	
		YES	NO
Warning Light ?	ON	330	1396 (8 A/C Destroyed) (4 Fatalities)
	OFF	355 (2 A/C Destroyed) (4 Major Accidents)	No Reported Problems

Figure 1 USAF A/C Fire and Fire Warning Experience for Period 1965 - June 1973, 2081 Total Incidents

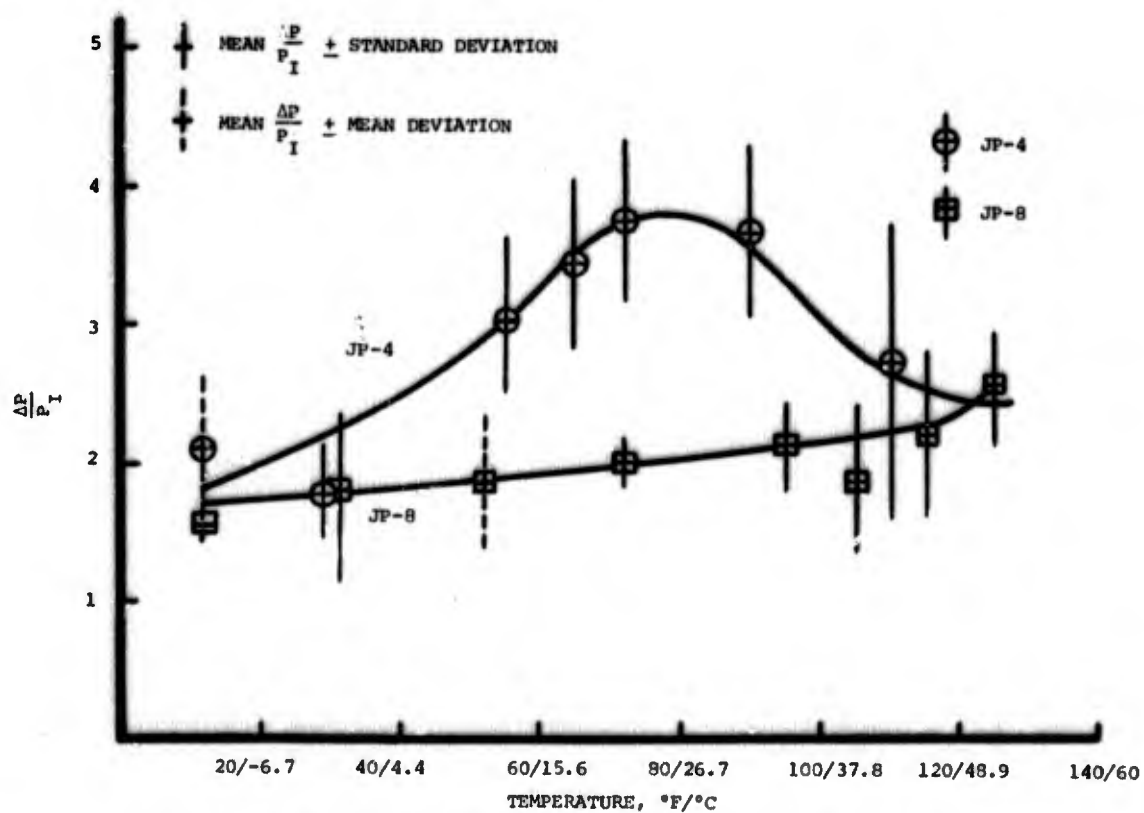


Figure 2 Effect of Fuel Temperature on Reaction Over-Pressure in Tests Conducted with JP-4 and JP-8 10.2 cm (4 inch) Fuel Depth, and Atmospheric Ullage Pressure [348 l (92-Gallon) Tank]

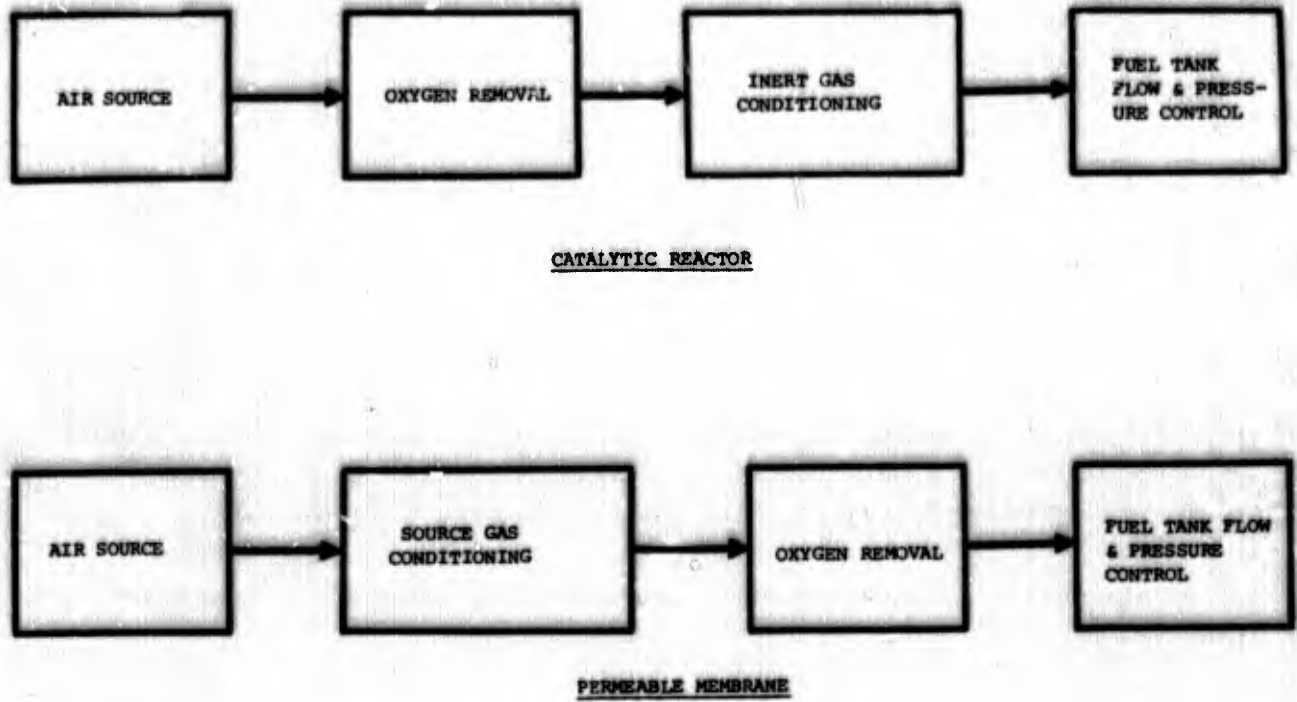


Figure 3 On-Board Inert Gas Generation (IGG) Fuel Tank Inerting Systems

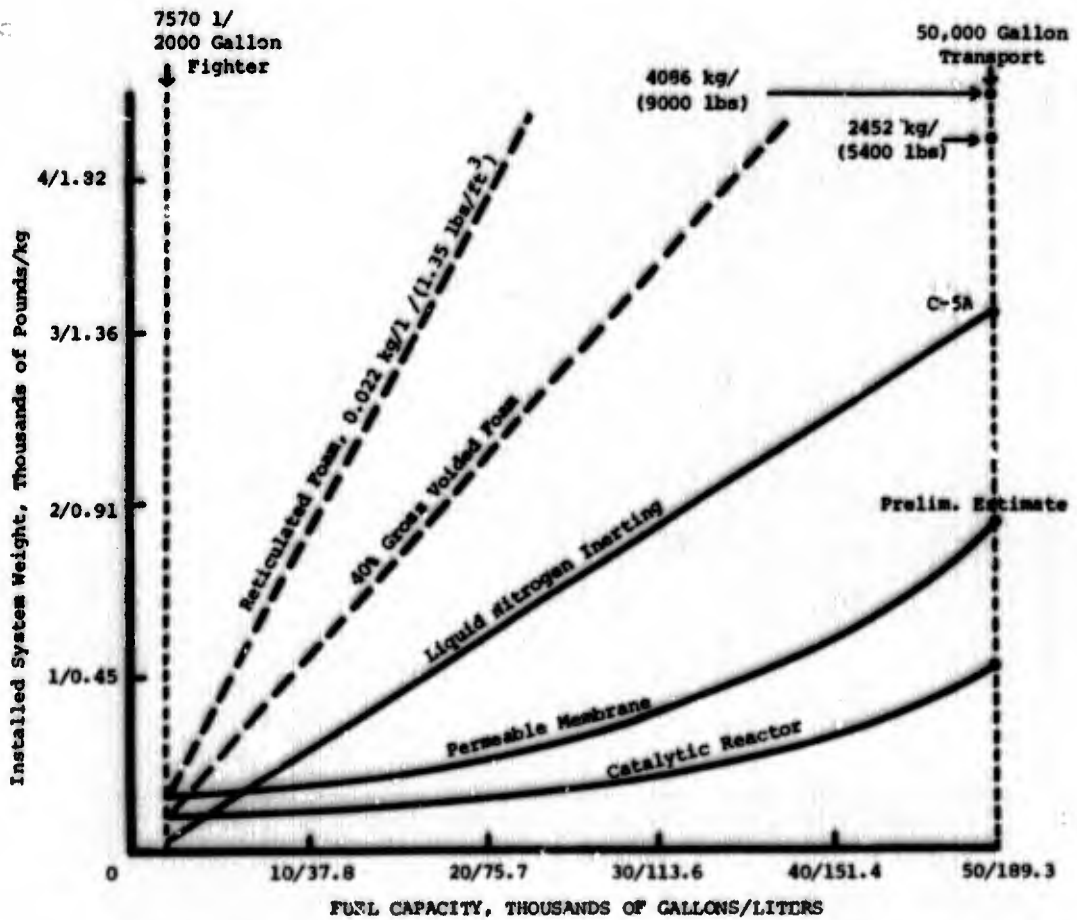


Figure 4 Fuel Tank Explosion Protection Systems, Weight Comparison

DISCUSSION -- PAPER 18

Mr Leathley:

(1) Do the weight estimates for the catalytic system include penalties for particulate matter and sulphur dioxide removal?

(2) Since the catalytic combustion system is acknowledged to have a potential fire risk, what is the objection to using an orthodox, higher temperature combustion system in which it should be possible to obtain an even lighter weight system due mainly to the greater temperature differences resulting in smaller, and hence lighter, heat exchange equipment?

Mr Botteri:

(1) The preliminary weight estimates do include penalties for conditioning the product gases from both a thermal and chemical quality standpoint.

(2) The catalytic reactor system is designed to provide inertant gases having a residual gaseous oxygen content of 2 volume percent. This is accomplished by near-stoichiometric reaction in a catalytic bed in which maximum system temperature is approximately 1200°F. An orthodox combustion system would also require near-stoichiometric operation with a much higher system temperature. The problem of oxides of nitrogen formation would require attention with the latter approach. The orthodox approach is worthy of consideration. Currently, however, technological emphasis is being put on an inert gas generator technique that would not pose the inherent fire risk potential associated with both the catalytic reactor and the orthodox combustor approach. The most promising alternative approach is the use of semi-permeable membranes.

Mr Marriette: Does the LN₂ system in the B1 aircraft offer as good protection against projectile penetration as reticulated foam?

Down to what size of aircraft does an LN₂ system show a weight advantage over foams?

Mr Botteri: The choice was strictly on a weight basis, though liquid nitrogen is as effective if not better.

There are several ways of operating; you could use it strictly on a demand basis at high hazard times. The quantity of nitrogen required could then be reduced.

Mr Macdonald: On the question of foam vs. nitrogen I would have thought that foams were applicable on fighters roughly up to 2,000 gallons; beyond that capacity it would lose out on a weight basis. Of course foam gives protection at all times. Also nitrogen involves logistics problems for military aircraft.

Mr Botteri: I agree with you entirely; that is one of the reasons we are pursuing the inert gas generator system. In addition to the potential weight savings, there is a substantial logistics advantage in operational use.

Mr Macdonald: I was interested in your success with the pneumatic detectors. Would you have any further comments on their performance. I have found them to have a much higher electrical energy output, and therefore are less prone to false warnings.

Mr Botteri: Air Force experience is limited but the records show very good results in commercial use.

Mr Bourgeat:

(1) Quels sont les types d'extincteurs portables mis à bord des avions de transport de l'USAF?

(2) Si j'ai bien compris, des extincteurs halon 1301 sont montés à bord des cabines équipage et passagers. N'y a-t-il pas un danger de toxicité élevé pour les occupants de ces avions en cas d'utilisation d'extincteurs de ce type. En effet, par pyrolyse certains gaz très toxiques sont libérés pouvant entraîner des troubles graves tant sur le personnel de cabine que sur les passagers.

Mr Botteri: USAF transport A/C carry 1 quart capacity A-20 type hand portable fire extinguishers, charged with approximately 4 lb of Bromochloromethane (CB or Halon 1011). The 1 gal. capacity, D-1 extinguisher charged with CB has been authorized for use in cargo compartments of A/C such as the C-130.

Halon 1301 is not currently used in hand extinguishers in AF A/C. An extinguishing system, using Halon 1301, for the cargo/passenger and avionics compartments of the C-5 A/C, is being test flown. This system is permanently installed and is coupled with a fire/overheat and smoke detection system to warn of a fire situation. Mode of operation is total flooding of the compartments requiring protection with approximately 6% by volume of 1301.

Halon 1301 is the least toxic of the available halogenated by diocarbons in the neat state. All extinguishants have some level of toxicity as do all products of combustion to be anticipated in any closed compartment, be it A/C or not. The modern materials used in A/C passenger compartments produce products of combustion as hazardous to personnel as those from a pyrolyzed extinguishant such as 1301 and in greater concentrations if extinguishment is not accomplished quite rapidly. The key to survival from a fire in confined space is the rapidity with which the fire is detected and can be extinguished.

Mr Lewis: Regarding powerplant areas of fighter aircraft given good fire protection features in the initial design, i.e. component standards, bay drainage, and bay and fluid isolation, have you shown benefit of the fire extinguisher on fighter aircraft taking into account:

- (a) possibility of high ventilation airflows
- (b) that projectile damage could alter ventilation and hence extinguisher flow paths.

Mr Botteri: Propulsion compartment fire extinguishing system protection is required on all Air Force multi-engine fighter aircraft unless a specific waiver is granted. Present day turbofan installations, as you have indicated, do provide a much reduced fire risk potential. In many instances engine/accessories have been segregated into separate compartments. Although the fire risk has been reduced, in view of the nature of the equipment/environment involved, these compartments are still treated as fire zones. Extinguishing system provides coverage for all engine/accessories compartments. Considering the cost of advanced fighter aircraft, the inclusion of a fire extinguishing system for multi-engine installations provides low cost additional insurance against in-flight fire and certainly enhances combat survivability. Recent experience with modern installations has confirmed the advantage of this capability.

In a combat environment, projectile damage certainly can alter ventilation paths and consequently affect fire extinguishing system performance. Obviously, the projectile also increases the likelihood of fire and consequently the need for effective fire control. Although not indicated in the technical paper, the problem of effective fire control under battle damaged propulsion compartment conditions is an area which is being addressed by the Air Force in conjunction with Joint Technical Coordinating Group for Aircraft Survivability. The latter activity includes investigation of improved extinguishants which provide better-permanency of action.

Mr Mariette: I notice that you have used smoke detectors in the crew compartment on the C-5; we have seen in previous papers that the toxic gases seem to be more critical.

Mr Botteri: The performance experience in the C-5 has been very good and it is possible to cite examples where they have alerted the crew and allowed them to get out safely as well as saved the aircraft by aborting the mission in time. The smoke detectors of course, represented the state of the art at the time the C-5 was developed.

Mr Parker: On the question of what comes off first; smoke, toxic gas, or can one sense heat, we currently have research under way at Stanford Institute to study the various types of detectors shown as well as the NASA light scattering particulate detector developed for the shuttle-aircraft. The first thing to appear in a fire is not smoke but the small particulate matter which seems to spill from the surface as soon as heating occurs. I believe this is the important thing to detect. If we can make this type sensor reliable, it should be the best solution. We have found that they are quite sensitive to the material being ignited. Some do not see urethanes at all, for example. Others see poly-vinyl chloride. One must be very careful in selecting the detector for the particular fire scenario.

Mr Taylor: In an earlier paper Mr. MacDonald had not been hopeful of military aircraft being able to standardise on low volatility fuels. However, you have suggested, I believe, that the USAF and NATO may be changing to a Jet A1 type fuel in the foreseeable future. Could you please enlarge on this giving some idea of the item scale involved.

Also, could you say if there is any possibility of going to a fuel of even lower volatility, for example JP5, as still used, I believe, in the US Presidential aircraft.

Mr Botteri: The United States Air Force is re-assessing the advantages/disadvantages of utilizing JP-8 fuel (similar to commercial Jet A-1 fuel) in lieu of JP-4, the current operational fuel. More recently the Department of Defense via a Joint Technical Coordinating Group for Fuel Standardization has been assessing the same problem with the further goal of achieving international standardization of a single type jet fuel. Obviously the problem of fuel standardization involves a number of considerations, including availability, cost, and operational utility. Principal benefits for a JP-8 type fuel are considered to be in the areas of flight fire safety and combat survivability. The committee's recommendations are to be made in 1975. A decision on these recommendations should follow in 1976. If approved, a conversion period of 5-10 years is visualized. The lower volatility, JP-5, fuel is not suitable for standardization purposes because of poor availability. This fuel will probably continue to be utilized on-board Navy aircraft carriers for safety reasons.

It is possible, in view of the current Energy Crisis and the activity that has been generated on production of alternate and synthetic fuels, that in the distant future a fuel possessing superior safety properties than JP-8 may be feasible.

Mr Mariette: Does the LN₂ system in the B-1 aircraft offer as good protection against projectile penetration as reticulated foam?

Down to what size of an aircraft does an LN₂ system demonstrate a weight advantage over foams?

Mr Botteri: The choice was strictly on a weight basis, though liquid nitrogen is as effective if not better for explosion protection.

There are several ways of operating with LN₂. You could use it strictly on a demand basis at high hazard times. The quantity of nitrogen could then be reduced significantly making it potentially attractive for smaller close-support aircraft. Selection of the best LN₂ protection approach for a particular aircraft must tradeoff duration of protection desired and mission flight profile considerations.

FIRE PROTECTION OF MILITARY AIRCRAFT

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SUMMARY

The paper is in two parts, first it examines some of the problems associated with "classical" engine bay fire detection and suppression systems and airframe design constraints. In the second part the primary and secondary fire problem is considered. Statistical evidence from modern war shows that the highest proportion of aircraft kills is due to primary and secondary fire, and the author discusses the application of possible fire suppressant methods. The current structural and system design philosophy is questioned with respect to achieving improved fire protection of military aircraft.

PART 1

ENGINE BAY FIRE PROTECTION

1. INTRODUCTION

During the past 10 years there have been few major productionised developments of engine bay fire protection for military strike and fighter aircraft. This section of the paper therefore outlines the current fire detection and suppression systems currently used with comment on the interface problems for the engine bay designer.

2. ENGINE BAY ZONING

When jet engines were first used in military aircraft it was possible to provide a fire-proof bulkhead aft of the combustion chamber area which separated the cool forward zone containing fuel system components from the hot surface of the exhaust pipe. As the thrust outputs increased the hot surfaces moved steadily forward until it became extremely difficult to separate the fuel sources from hot surfaces. With the advent of the by-pass engine for military use it is again possible to position a fire-proof bulkhead towards the rear of by-pass mixer casing such that all surfaces forward of the bulkhead are below the spontaneous ignition temperatures of fuels. The engine manufacturer is assisting the aircraft designer in keeping all the fuel system components for reheat and nozzle operation in the forward cool zone. This simplifies bay cooling, fire detection and suppression system problems and, in the writer's opinion, is the most significant recent development contributing to improved military aircraft fire protection.

3. FIRE DETECTION

Two distinct types of fire detection systems are currently used; point detector heads usually operating on high resistance caused by opening contacts with rising temperature, and firewire systems activating control units monitoring either co-axial wire resistance or capacitance.

The typical point detector head is shown in Fig. 1 and systems utilising these have several disadvantages.

- (a) Because they sense temperature rise locally, many heads on a ring main must be used to adequately cover a fire bay and obviously depending on fire source position the system may not sense a small fire early enough to prevent a major conflagration.
- (b) The interconnecting wire must be cleared to withstand fire attack for at least 10 minutes to maintain system integrity.
- (c) The detector heads can give spurious warnings if damaged and a lengthy process of fault diagnosis may ensue to calibrate each head for trigger and reset settings.
- (d) Because of their size the detector heads have limitations on positioning in bays, this itself is found to restrict bay coverage. The positioning problem is becoming more acute with the reduced airframe/engine clearances currently employed.

Temperature sensitive firewire is preferable to the writer in that it has the following advantages:

1. More complete bay coverage is achieved.
2. The firewire is itself proof against normal fire attack.
3. No serious space envelope limitations.
4. Engine mounted loops can form part of the aircraft system.
5. Well proven pilot pre-flight check facility.

However in-service problems are experienced too frequently with spurious warnings caused by moisture ingress and mechanical damage sustained during general servicing.

Both the above detector types have a common failing; because they are temperature sensitive devices they cannot differentiate between bay overtemperature and fire conditions. This has led to the design and development of detectors which monitor ultra-violet rays. Considerable difficulty has been experienced in making them discriminate between solar and fire U.V. wavelengths and in making the detector head itself fireproof. The only practical aircraft applications known to the writer are for monitoring engine reheat light-up and combustion chamber break-out. Continued development is aimed at providing a viable engine bay fire detection system.

4. FIRE SUPPRESSION

4.1 Types of Suppressants

Most current fire suppression systems use one of the following vapour/gas halogens;

Methyl Bromide (M.B.).

Bromotrifluoromethane (B.T.M.).

Bromochlorodifluoromethane (B.C.F.).

There is little to choose between them in their fire suppression capabilities and choice is usually made by Government agencies on some other feature, e.g. toxicity. In addition different countries have slightly varying views on the concentration level and timing required, therefore the writer does not intend to comment further in the short paper.

Fire suppressant powders have recently been developed which lend themselves to aircraft usage. However most difficult problems remain to be overcome, such as distribution within the bay, powder compacting due to vibration, etc.

4.2 Installation Problems

Several major installation problems present themselves to the aircraft designer.

- (a) The extinguishants stored in a metallic bottle under pressure give rise to weight problems, since in addition to the bottle being heavy, its supporting structure is also heavy to withstand 'g' forces, etc.
- (b) A system of pipes and indicators must be installed to give ground crew notice of flight activation or pressure relief.
- (c) The extinguishant distribution pipework must give complete bay coverage and allow no pockets behind any equipment.
- (d) Bay ventilation flows can conflict with extinguishant concentration/bottle sizing limitations.

5. FIRE-PROOF BULKHEADS

The first consideration of the engine bay is that it should be fire-proof to obviate fire transgression to adjacent parts of the aircraft. Obviously all electrical, pipe and control runs passing through the fire-proof wall must be fire-proof. In some military aircraft the walls of the engine bay are used as fuel tank structure, these must be adequately insulated to prevent fire causing the structure to reach the spontaneous ignition temperature of the fuel. All equipments on the engine and within the engine bay must be fire-proof and the most difficult problem for the engine and airframe manufacturers to resolve completely is the engine mounted engine/airframe fire-proof bulkhead. Two aspects have proved extremely difficult:-

- (a) To allow for engine/airframe relative expansions the bulkhead must have lateral movement which is usually achieved by interlocking sliding metallic surfaces. In the majority of cases these are not fuel proof hence a fuel leak in a forward cool zone can ignite in the aft hot zone. This is not assisted by there usually being a differential bay pressure from front to rear zone across the bulkhead caused by exhaust ejector effects.
- (b) To cater for longitudinal engine/airframe movements the bulkhead is usually fitted with a fire-proof flexible seal which can be wire filled or, more recently, inflatable. To date these have not achieved all the installational requirements and one usually has to compromise. These requirements can be generally detailed as follows:

(1) The bulkhead shall be proof against fire attack for 10 minutes minimum.

(11) It shall be vapour-proof in one direction when subjected to differential pressures of +14 kPa to -7 kPa. On certain fan engine installations this range can increase to +35 kPa and -7kPa.

- (iii) It shall be sealed throughout a temperature range of -26°C to $+180^{\circ}\text{C}$ and undamaged when subjected to -56°C for long periods.
- (iv) The seal shall be of minimum cross section but capable of a nominal compression of 3.8 mm and a maximum of 7.6 mm to cater for adverse engine and airframe tolerances.
- (v) The seal shall be capable of sliding slowly laterally 7.6 mm on the airframe land without losing its sealing capabilities.
- (vi) It shall be cleared for vibration levels normally associated with modern jet engines.

6. BAY VENTILATION AND DRAINAGE

Ventilation flows are kept to a minimum for several reasons;

- (a) High flows from ram intakes give high aerodynamic drag.
- (b) High flows increase fire extinguishant size requirements.
- (c) High forward bay pressures cause high bulkhead differentials.

There is obviously an optimisation required on each installation between the above aspects and cooling/insulation requirements, etc.

Bay drainage is generally provided to cater for small leaks and seepages. The very high fuel flows used in modern military reheated engines make it unrealistic to provide drainage systems which would cope with fuel quantities from fractured pipes. It can be argued that with a major spray leak the probability of initiating and maintaining fire is very low due to the bay becoming fuel over-rich.

7. GENERAL

On military aircraft the standard of fire protection in the engine bay is generally satisfactory. Extinguishant systems act effectively when required and bay fire containment is usually achieved. However spurious fire warnings still test the pilot and must be eliminated completely. Continued research must find a fire-proof bulkhead design which is both fuel and fire proof. When these two problem areas have been eliminated engine bay fire protection will be very satisfactory.

PART 2

PRIMARY AND SECONDARY FIRES

1. INTRODUCTION

Statistical evidence of aircraft losses during combat shows that fire losses accounted for the major proportion during all the major wars. It has been quoted between half and two-thirds are fire kills. This is not surprising if one considers that on most modern military aircraft the fuel tanks cover between half and two-thirds of the area presented to projectile attack. Obviously if fire suppression devices and aircraft design changes can markedly reduce this high kill rate for reasonable weight and cost implications they will fully justify incorporation.

This part of the paper discusses the aircraft implications of fitting primary fire suppression devices and comments upon some of the areas requiring investigation for reducing secondary fire risk.

2. PRIMARY FIRE

The mechanics of primary fire initiation have been fully explained by Messrs. MacDonald and Wyeth in Paper 19 "Fire Protection of Fuel Systems in Combat Aircraft" where it is shown that fire generation occurs within milliseconds of fuel tank or pipe rupture by shell fragments. With the types of ammunition currently providing the aircraft threat, existing aircraft design philosophy provides large areas of tankage and high pressure fuel and hydraulic pipes which are vulnerable.

Fire suppression methods considered by the above referenced report can be collected under the following headings.

- 1. Foam fillers.
- 2. Sandwich packs containing powder extinguishants.
- 3. Vapour packs.
- 4. Self-generating active systems using gaseous or powder extinguishants.

Each of the above systems has been assessed by the writer for use on typical modern military strike and fighter aircraft. It must be stated that suppressant methods discarded by the investigation may be more applicable to other existing designs, for example, helicopters, or on future strike/fighter aircraft where design changes are made

to facilitate their incorporation.

3. INSTALLATION ASPECTS

Figure 2 is a diagrammatic representation of a typical military strike aircraft showing fuel tankage, and equipment bays.

Analysis of the bay types has shown there are two types requiring different fire protection methods:-

- (a) Small Voids - equipment free volumes generally up to 100 mm in width.
- (b) Equipment bays and large voids.

3.1 Small Voids

Small voids can be further classified into three types:

1. Interspaces between fuel bag tanks and the containing structure. By definition they are peculiar to aircraft fitted with bag tanks but can account for up to 90% of the small void volume.
2. Structure bounded cavities having no routine access or dis-assembly. These voids are typically found at transportation joints and in corners between frames and stringers.
3. Structure bounded cavities requiring occasional access or dis-assembly; for example, between external access panels and fuel tank structure access panels.

3.2 Equipment Bays

The following observations can be made with regard to equipment bays from investigations made on several modern military aircraft.

- (a) Nearly all the bays are interconnected and subject to ventilation air flows.
- (b) Bays generally contain fuel, hydraulic and electrical systems.
- (c) Bays are generally congested from the point of equipment fit. Therefore suppressant dispersal is difficult.
- (d) Routine maintenance will be carried out in the bays. Fragile components of suppressant systems will be liable to accidental damage.
- (e) Some bays have equipments which are heat generators and may have internal temperatures above fuel spontaneous ignition temperature.

4. APPLICATION OF SUPPRESSANT SYSTEMS

4.1 Design investigation of the application of the suppressant systems quoted in para. 2 shows that foam fillers and self-generating active dispersal systems are most suitable for small voids and equipment bays respectively. The main reasons for this decision are as follows:-

- (a) The bays and voids invariably contain complex structural members and many equipment mounting brackets, therefore there are no large plain panels bordering fuel tanks. Since vapour, gas or powder packs require to be in intimate contact with the fuel tank skin it will be necessary to have numerous dissimilar small packs. This is considered impractical from both installation and weight aspects.
- (b) Small voids are in general inaccessible, except during build or major overhaul hence an active dispersal system would be impractical. It is considered that foam filling is the only practical protection.
- (c) In highly congested bays having regular maintenance accidental damage to vapour, gas or powder packs would cause extensive system dis-assembly for replacement and high servicing penalties in system functional testing following rebuild.
- (d) Due to the varying standards of congestion, size, ventilation flows, etc., in equipment bays, a system is required which provides a certain amount of versatility in size and positioning of extinguishant container throughout the bay. This is only possible with an active dispersal system.
- (e) Some bays, for example undercarriage bays, can have several fuel tanks providing the wall of the bay. Thus a projectile rupture of one tank protected by vapour, gas or powder packs would only release the extinguishant from those packs in intimate contact and could be insufficient in the large bay volume.
- (f) Dependent upon the theatre of action it may be necessary to provide a system having a "two-shot" capability, each time providing complete coverage for a bay or series of interconnected bays. This is possible with an active dispersal system.

It must be stated again, the choice of suppressant methods enumerated above may not be applicable to other aircraft designs, in which case one of the other methods may be more suitable.

Figure 3 shows a typical application of foam filler and active dispersal systems to the diagrammatic typical aircraft. It will be noted that system coverage varies and each suppressant system will now be discussed in more detail.

4.2 Foam Fill

Small voids require two distinctly different types of foam fill material.

- (a) Cavities between fuel bag tanks and structure require a semi-rigid foam having certain structural load bearing properties.

Figure 4 shows a typical application where it will be noted that the foam fill has been incorporated in a fuel tank having self-sealing fuel bags. The foam completely fills the interspace between the aircraft structure and the bag tank anti-petal backing board. The typical environmental conditions the foam could be subjected to are as follows:-

Pressure

Ambient pressures between 7 kPa and 140 kPa.
The maximum pressure rising due to 'g' loads and/or system failure conditions to 350 kPa.

Temperature

Operating range of -40°C to +120°C.

Contamination

Contamination by the full range of aviation fuels, sea water, hydraulic oils, etc.

Life

The operating life and characteristics must not be unduly affected by vibration, humidity, sand and dust and ideally should be equal to the life of the aircraft.

It is envisaged that the foam would be cut from blocks and installed during tank build. As bag tanks are occasionally replaced it is feasible to adopt a foam inspection procedure in specific possible problem areas. Such inspection requirements could only be determined by experience of an individual aircraft installation and are obviously dependent upon structure complexity, vibration levels, fuel cell drainage paths, etc.

It should be noted that without 100% foam filling between structure and bag tank/backing board, the primary fire risk remains within the interspace.

- (b) Cavities bounded by structure whether having routine access requirements or not may be filled with flexible foam as they have no load bearing requirements.

Figure 5 shows typical foam application in a void having routine access. The foam between the access panels could be cut from blocks and partially compressed on fit. Voids having no access may allow in-situ foaming however the problems of obtaining 100% foam fill with intimate structure to foam contact will require development of in-situ foaming techniques.

Some development testing of foam used in non-access voids is still required to determine whether there are corrosion and water absorption problems. This could necessitate the foam being encapsulated in a protective film. It is currently envisaged that the foam would be cut from block or sheet and installed slightly compressed with no outer skin sealing.

Generally the requirements for the flexible foam are as in para. 4.2(a) except the maximum pressure due to 'g' loads and system failures is not applicable. The contamination fluids are however increased to include engine and gearbox oils, fire extinguishing fluids, sealants, corrosion inhibiting fluids, etc.

4.3 Self-Generating Active System

4.3.1 System Installation

Full system details are given in Paper 19 - "Fire Protection of Fuel Systems in Combat Aircraft" by Messrs. MacDonald and Wyeth. Briefly, with this system the extinguishant is stored in small canisters mounted at several positions within the equipment bays. The extinguishant is discharged on receipt of an electrical signal generated by pressure change sensors mounted within the fuel tank or to the tank wall. Figure 6 shows the application of the system to a self-sealed bag tank and adjacent bay.

In general, the following sensor installation features are worth noting.

- (a) The sensor can be tank wall mounted on integral tanks or fully immersed in all types of fuel tank.
- (b) Signal strength due to the hydraulic shock is not affected by sensor orientation.
- (c) Hydraulic shock strength will not be significantly affected by use of backing boards, self-sealing materials, etc.
- (d) All the sensors can operate on either rate of pressure rise or pressure level they can be set within a range which is above that due to refuel surge, fuel sloshing, etc.
- (e) In tanks of large or complex shape more than one sensor can be installed to activate one or a number of extinguishant cannisters.
- (f) Failure of one sensor in a series system will not affect system operation.

Of the aircraft used in the design investigation the sensors could be installed either as initial or retrospective fit. Provision of mounting brackets within bag tanks can best be achieved at access panels, however depending upon the tank detail design and fuel tank level over the target area this may not be possible and special provision is then required.

Extinguishant cannister location is dependent upon several considerations:-

- (a) Equipment bay size and shape.
- (b) Equipment type, size and fit.
- (c) Ventilation air flow.
- (d) Type of extinguishant.
- (e) Access requirements.

The cannister must discharge the extinguishant directly into the bay without pipe distribution in order to meet the short timescale requirements for extinguishing primary fire. Therefore the bay size, shape and equipment fit play an important role in determining the size of the extinguishant cannisters and their location to give full bay coverage.

The air mass flow for general bay ventilation in unconditioned bays should obviously be kept to an acceptable minimum in order to restrict the cannister total size. Extinguishant concentration levels must be designed for the worst combination of air flow, temperature, volume, etc.

All design studies and trials to date have assumed standard vapour-gas extinguishants. The disadvantages of using these are, firstly, the cannister must be pressurised to aid extinguishant dispersal and meet time/concentration requirements which necessitates a thick-walled vessel giving a heavier weight than that required for powder extinguishants.

Secondly, in order to discharge all the extinguishant the cannister must be mounted vertically unless recuperator type flexible diaphragms or similar devices are employed. The latter would have cost and reliability implications.

Use of vapour/gas extinguishant is already undertaken on aircraft in engine bay suppression systems therefore their properties are well known. However powder extinguishant dispersal and operating characteristics, and corrosion effects are not yet fully investigated. When this work is completed it may show that powder extinguishants are more advantageous from system weight and installational aspects.

The design study has shown that all equipment bays are capable of being adequately protected using a combination of a limited number of "standard" cannister sizes. The sizes are such that they can be installed in bays and retain the equipment access for routine servicing.

4.3.2 Active System Grouping

The grouping of sensor positions and number of extinguishant cannisters is dependent upon the individual aircraft disposition of fuel tanks and equipment bays, however the following points should be noted:

- (a) Where several tanks form the boundary of a bay, all the tank sensors should be linked to activate all the cannisters within the bay.
- (b) It may be necessary to have a port and starboard system both covering a bay which traverses the fuselage.
- (c) System coverage will be dictated by the type and angle of attack of the threat.
- (d) System location will be dictated by fuel contents over attack area and bay

equipments and congestion.

4.3.3 System Safety

During design and development of the self-generating active system, careful consideration has been paid to the safety aspects of the system components during storage, installation, and aircraft maintenance. Detailed analysis of all failure modes and system vulnerability shows that there is considerably less risk of accidental operation than exists for other devices, such as, ejector seats or engine bay fire extinguisher systems.

It is difficult to imagine any maintenance operation which could cause the system to activate even assuming personnel mistakes. It would require a live conductor contacting the input to an extinguishant cannister when in the "primed" condition. This will be safe-guarded by provision of a basic electrical circuit shorting switch, and an internal shorting switch and discharge nozzle closing cap for the cannister. In the unlikely event of accidental operation of a cannister there is no danger to personnel even if hand held as the pressure is wholly contained within the unit.

5. OTHER PRIMARY FIRE SOURCES

The paper has so far concentrated on primary fire caused by fuel tank projectile penetration but there are several other sources, namely, fuel and hydraulic pipes. In many areas it is possible to predict that a projectile which penetrates a pipe would also penetrate a fuel tank, thus the fire extinguishing system protecting the tank would also protect the pipe. However in areas where this does not apply various methods of approach are possible.

5.1 Large bore fuel pipes can have provision made for a sensor within the pipe which can activate cannisters. Some detail work would be required to obviate valve and fuel system component positions affecting the hydraulic shock transmission. Alternatively protection could be provided in a similar method as detailed below for small bore and hydraulic pipes.

Many aircraft having twin engines located in the rear fuselage have fuel systems with the main engine fuel lines in close proximity and both near the bottom centre line. System features which are desirable and not difficult to achieve include the following:

- (a) Wherever possible large bore fuel pipes should pass through the fuel tanks as this provides the highest degree of shielding.
- (b) Where pipes pass outside the tanks they should pass through the aircraft spine or as high as possible within the fuselage to remove them from high risk areas.
- (c) The fuel pipes leading to each engine should be adequately separated and provided with protection.

5.2 Small bore pipes usually pass through every equipment bay and are generally routed in groups, the following methods of protection are possible:

- (a) Run several pipes within a sealed duct containing sensor heads.
- (b) Wrap a number of pipes with a suppressant filled pack.

These two schemes are shown diagrammatically on figure 7 however any protection method encapsulating a number of pipes has a high servicing penalty and, more often than not, high cost and weight implications. A more acceptable system would incorporate sensor heads acting as blast sensors within bays, and development of the sensor head is imminent.

Obviously small bore pipe protection is very difficult to provide in any practical way which does not have several penalties, and where there are areas involving few pipes supplying widely spread system components it must be accepted there will remain a primary fire risk. On existing aircraft this can be theoretically assessed however on new aircraft, system designers must be made aware of the slight changes in system design philosophy which can give real benefits.

6. SECONDARY FIRE

Secondary fire losses are caused by inflammable fluids leaking from tanks or pipes contacting spark sources or igniting spontaneously on hot surfaces. For measures taken eliminating primary fire to effect worthwhile reductions in overall aircraft fire kills it is mandatory that similar reductions are achieved in secondary fire vulnerability.

Most current equipments fitted outside existing fire zones are designed not to present ignition sources during flight, e.g. junction boxes, electrically operated valves, and pumps. However in the event of damage sustained due to projectile strike they can cause fire initiation and fuel should be kept away from these possible sources. Secondary fire prevention is therefore best achieved by a system of drainage and compartmentation resulting from a detailed analysis of fuel sources and paths.

6.1 Secondary Fire Prevention

6.1.1 Compartmentation

Following application of a primary fire suppressant system the fuselage will already have been zoned and compartmented to permit bay interconnection and ventilation flow. It will probably be found of value to further sub-divide the zones to obviate zone intercell fuel flow:

- (a) Fuel should not easily flow laterally within the fuselage.
- (b) There should be no structural pockets where wells of fuel will collect to be dumped later during aircraft manoeuvre.
- (c) Fuel leakage will be under pressure therefore intercell boundaries within a given zone should be reasonably proof against spray passage.
- (d) Ventilation air flows should be kept to a minimum as they assist intercell fuel passage and air inlet scoops can reingest previously drained fluids.

6.1.2 Drainage

It follows from above that drainage paths should be as large and unhindered as possible. For flight aerodynamic drag reasons the drain outlet positions generally also serve as ventilation air outlets, however they should be positioned so that drainage becomes detached from the fuselage and is not immediately upstream of any scoop intake.

Large bays having large fuel tank areas or complex high pressure pipe systems should have drainage panels fitted. It is feasible to incorporate fusible diaphragms which could be activated by the sensors triggering an "active" primary fire extinguishant system, but there could be a penalty in achieving correct extinguishant concentration levels with the larger drainage area.

6.1.3 Fuel Tank Sealing

It has been stated previously that fuel tanks incorporating bags do provide primary fire problems and the use of self-sealed fuel bag tanks must be carefully considered, for with larger calibre ammunition it becomes increasingly difficult to provide a reasonable degree of self-seal capability within acceptable system weights. It is the writer's opinion that self-sealed fuel tanks should only be used in those areas where alternative solutions are not available. Integral tanks can cause sealing problems however the gains on total aircraft survivability by eliminating interskin primary fires, allowing ease of running pipes through tanks, etc., plus weight saving on bags recommends the continued use of integral tanks.

6.1.4 Protection of Components

Commenting generally on component protection, it is recommended that only those components normally having internal temperatures in excess of fuel spontaneous combustion temperature should be protected or located in sealed bays. Where serious design problems would be involved it is worthwhile assessing the use of coats of intumescent paint. This paint in fire conditions, smoulders and forms a thick layer of carbon which acts both as a flame trap and heat insulation.

6.1.5 Fuel Tanks

Two extra actions are possible to decrease overall fire risk from fuel tanks.

- (i) Filling of the fuel tank with reticulated foams will eliminate the possibility of internal fire or explosion leading to external fires.
- (ii) Depressurisation of the fuel tanks over the target area will reduce the primary and secondary fire risk, however dependent upon the basic fuel system performance this action may cause re-assessment to meet full engine reheat fuel flows. Dependent upon the type of aircraft it may even be possible to eliminate pressurisation but it would need an evaluation against system increased weight and complexity.

7. CONCLUSIONS

Whilst the capability of engine bay zoning has been improved recently as by-pass engines are now used in military aircraft there are still two areas within an engine bay fire protection system which require further design and development :-

- (a) A fire detection system which does detect fire and not overheat condition. It must also have improved reliability from spurious warnings compared with current systems.
- (b) The current standard of engine to airframe fire-proof bulkhead is necessarily somewhat of a compromise of many requirements. It must be developed to provide a fire and fuel proof seal whilst still giving the necessary flexibility for engine/airframe relative movements.

Combat aircraft losses due to primary and secondary fire resulting from projectile penetration are the major proportion of all losses. On many military aircraft there is little or no protection other than self-sealing fuel bag tanks. In recent years several new primary fire suppression systems have been developed and the writer has assessed their application on typical modern strike and fighter aircraft. Some of these systems, notably foam fillers and self-generating active extinguishant systems are applicable to current designs. However to gain maximum benefit it is necessary that aircraft design should be amended slightly in the following main areas:-

- (a) Bag tanks should only be used where other protection methods cannot be applied. They should then be of the self-sealing type.
- (b) All major fuel pipes should pass through integral fuel tanks, and where outside, should be removed from the threat area or adequately protected.
- (c) On twin engined aircraft the engine fuel supplies should be well separated and protected.
- (d) Compartmentation and drainage of bays should be to a much improved standard.

It is mandatory that a primary fire suppression system is associated with secondary fire protection. In the writer's opinion the majority of existing equipments are satisfactory in normal operation and only provide ignition sources in the event of strike damage. Therefore efforts should be made to provide improved structural zoning and drainage with protection of "high risk" components by individual compartmentation, intumescent paints, etc.

Finally, it must be stated that both the agencies responsible for defining aircraft requirements, and, the aircraft structural and system designers should have increased awareness of the combat fire risk, and, what can and must be incorporated to reduce the overall aircraft loss rate.

Acknowledgement

This report has been written with the support of the Procurement Executive of the Ministry of Defence.

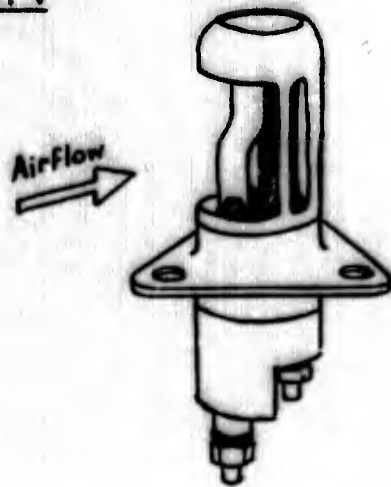
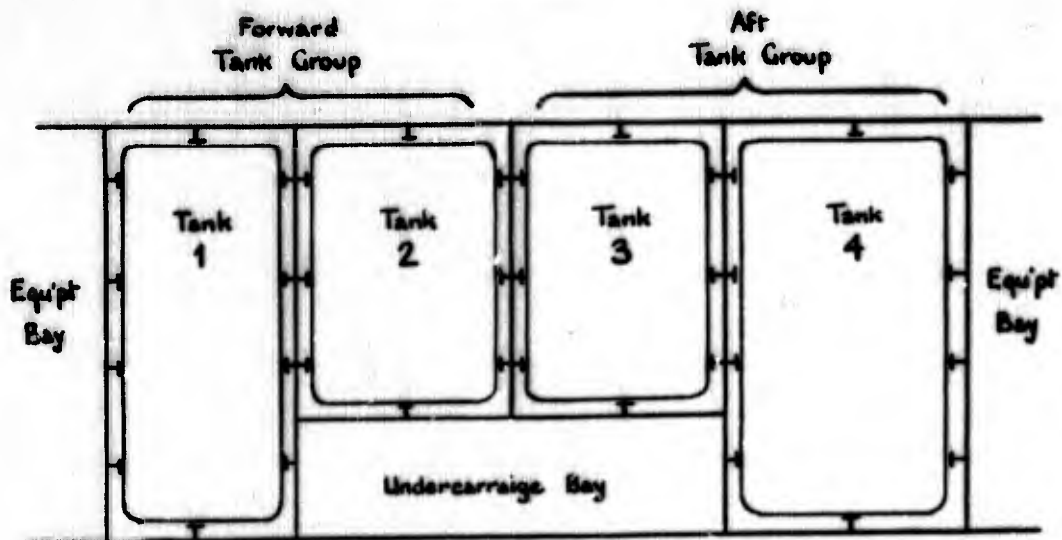
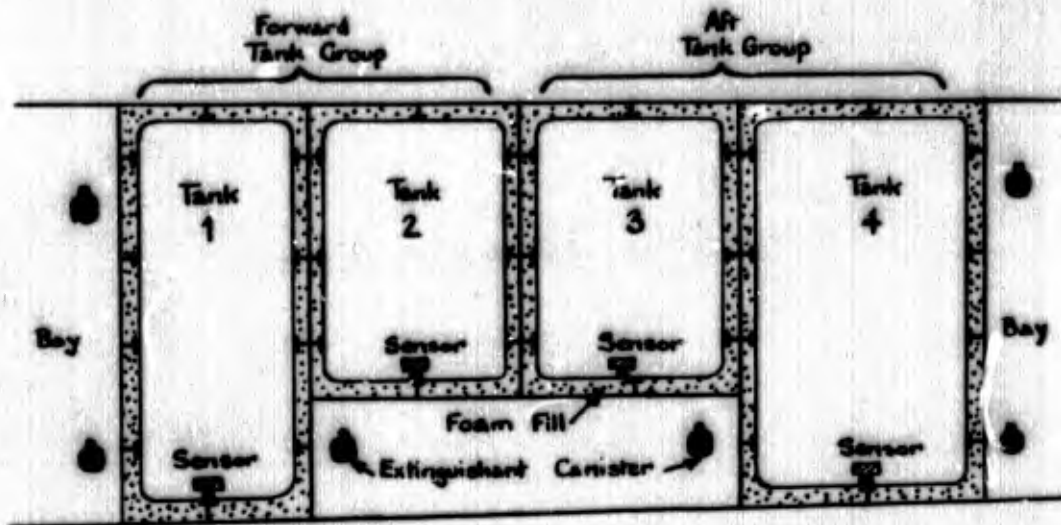
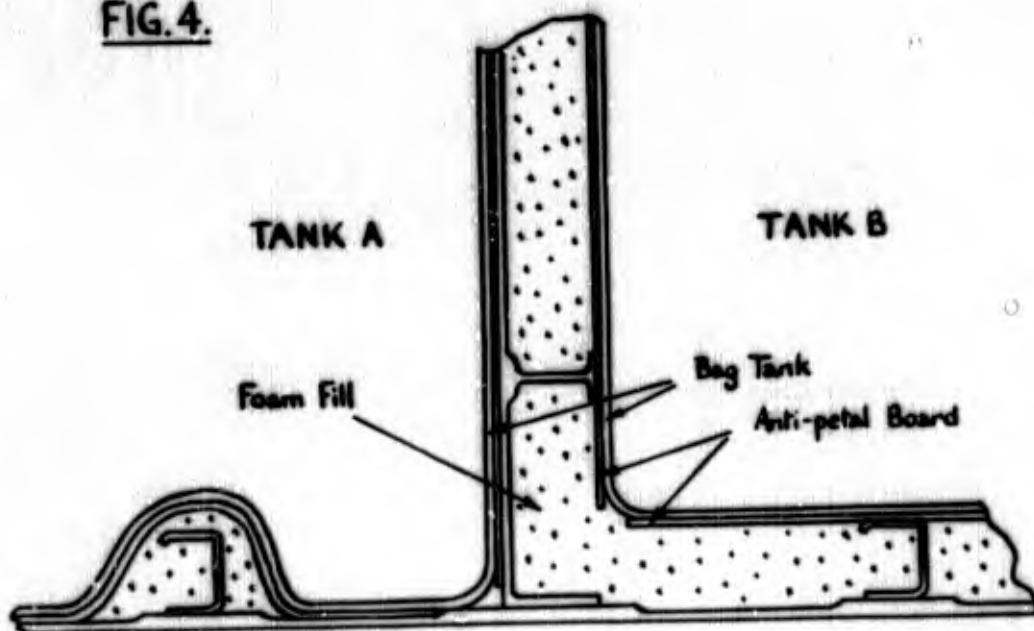
FIG. 1Typical Point Fire Detector HeadFIG. 2Diagrammatic Aircraft Section showing Fuel Tanks
and Equipment Bays

FIG. 3

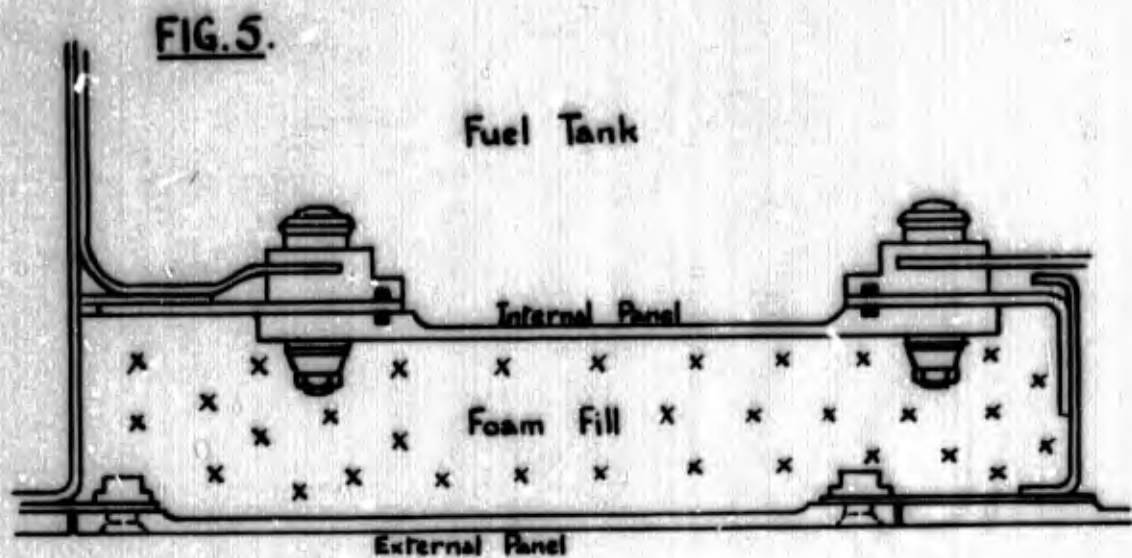


Diagrammatic Aircraft Section showing Primary Fire Suppression by Foam Fill & Self Generating Active System

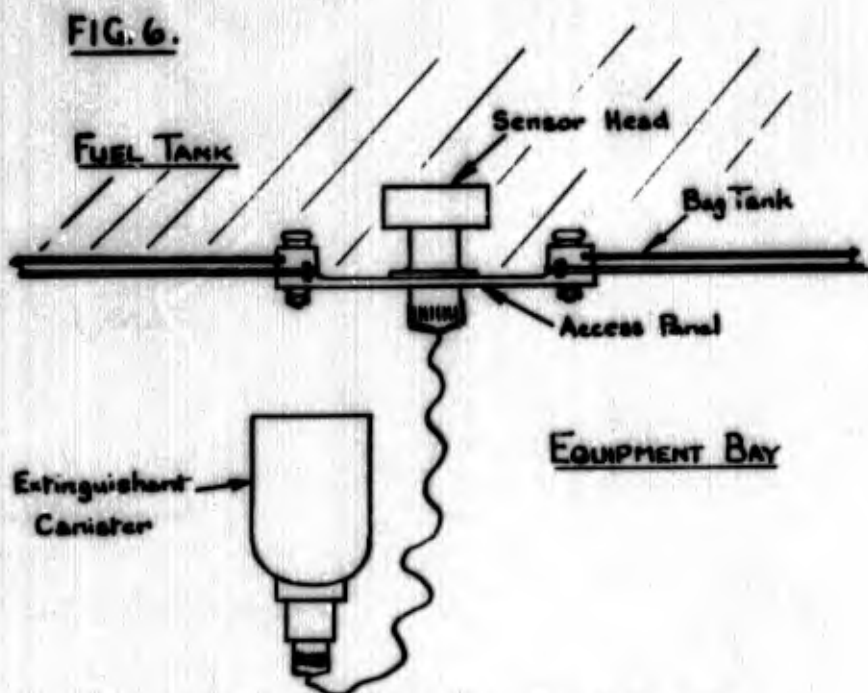
FIG. 4.



Typical Foam Fill in Fuel Bag Tank Interspace



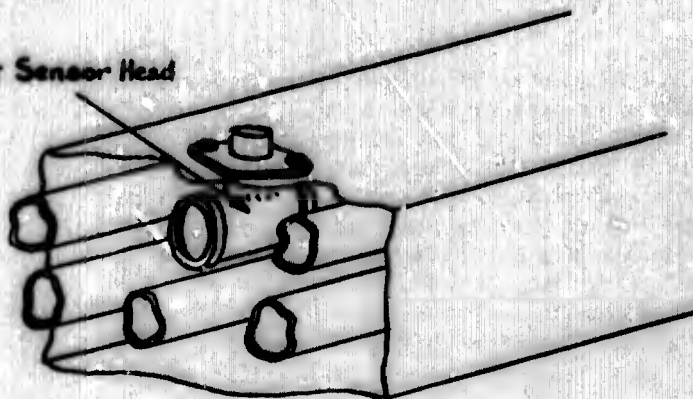
Typical Foam Application in Void with
Routine Access Requirement



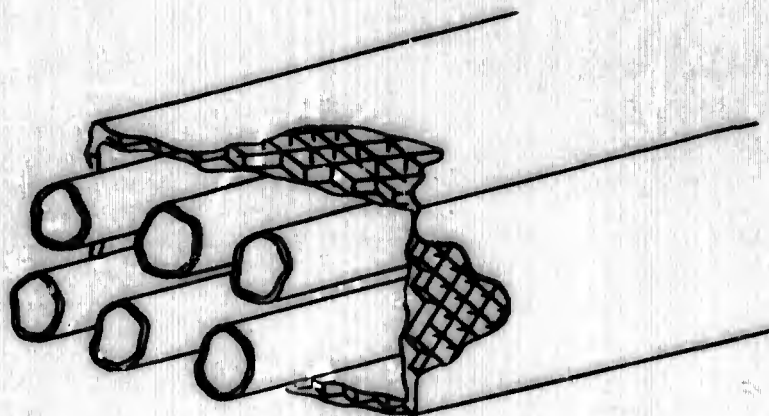
Simplified Installation of Self Generating Active Fire
Suppression System.

FIG. 7.

Blast Sensor Head



Small-bore Piping enclosed in Ducting with
Blast Sensor Head



Small-bore Piping enclosed with Powder Suppressant
Filled Honeycomb

DISCUSSION - PAPER 19

Mr Livermore: Could you comment on the effects of high energy torching flames that originate within the engine with respect to effect on structure and method of detection.

Mr Vincent: Our experience with pure jet reheated engines has been virtually free of high energy torching flames. We have had a few cases of jet pipe gas leakages caused by jet pipe material failures, but no engine break-outs apart from internal titanium fires originating in the later stages of the compressor. Molten titanium will obviously cut through most airframe structure in a timescale which makes it most difficult to detect or take any action. We have experienced one case where the fire wire system was cut by the titanium such that no warning was given. In all cases we did not suffer sudden catastrophic loss due to structural problems. The gearbox and accessories mounted on the engine did successfully stop most of the molten incandescent metal hitting the airframe.

In our experience combustion chamber breakout is a most infrequent defect. With the added protection of bypass ducts on recent military engines we do not believe that engine breakout will constitute an aircraft hazard.

Mr Taylor: I was a little surprised at your remarks about leakage of fuel through the engine bay fire proof bulkhead. I was under the impression that one always sought a pressure balance or preferably a slightly higher pressure in the rear bay to make quite sure that no fuel leakage could occur. Would you please comment on this.

Mr Vincent: It is obviously advantageous to have a higher pressure in the rear bay as you state, however on some of the recent engines this is difficult to achieve. Reheat nozzle operation is by a translating shroud arrangement which requires airframe clearance in addition to the shroud/nozzle clearance on the engine. The jet efflux causes an ejector effect at these circumferential gaps which in turn lowers the rear bay pressure. In our experience because of the large total area presented by these clearances, the supply of external air to counteract this depression would cause unacceptable aerodynamic drag penalties.

In my written paper I give some of the requirements for the engine bulkhead seal. United Kingdom seal manufacturers are currently attempting to design more advanced sealing arrangements to meet this specification.

Mr Lewis: Comments on two previous questions:

Combustion Chamber Burn Through

Combustion chamber burn through is not a frequent occurrence. On by pass type engines an incident is not as severe as a straight jet engine and on the former is contained within the powerplant area. With the advent of large fan engines at higher pressure ratios, such an occurrence could produce more damage and engine constructors are endeavouring to minimise any hazard by restricting critical structure or components in adjacent areas.

Detection of such an occurrence can be provided by monitoring deflected cases or by surveillance systems.

Engine Powerplant Bulkheads

Sealing of conventional powerplant bulkheads incorporating provision for axial and radial movements is usually assisted by providing a positive pressure differential from the dry bay area to the fluid carrying areas.

This positive differential has been difficult to achieve on some reheat installations incorporating translating shrouds in the dry bay areas. Current studies with additional sealing features on sliding members should alleviate this potential problem.

Mr Feltham: You have dealt with the problems of airborne fires only. What can be done by the aircraft designer to reduce the high rate of post-crash fires which occur following accidents in which no airborne fire existed?

Mr Vincent: The lost-weight penalty of fitting suppression systems for post-impact fires makes their introduction prohibitive on military aircraft. The civil case is, of course, somewhat different.

Military aircraft have provision of inertia switches operating engine bay fire extinguishers, isolating electrical circuits, etc., in the event of a crash landing. However, it should be appreciated that if the pilot knows an aircraft defect exists which will give a high degree of risk to a landing, then he is often instructed to eject.

Mr Mahood:

(1) Was the fuel tankage protected against the smaller explosive projectiles (20-30 mm)? Against both "super-quick" and delay-fuzed HE/HEI projectiles?

(2) Was the quantity of fire extinguishing material increased to provide adequate suppression even with ventilation caused by "super-quick" fuzed projectiles detonating on slipstream-wetted surfaces?

Mr Vincent: Yes, tests done by Mr. MacDonald's group at RAE have shown the protection to be effective against 23 mm projectiles, under simulated conditions.

Yes, currently most of the work is theoretical with limited testing to back it up. We are now in a phase where we are trying to vary the airflow based on the congestion level in the bay. This is to decide how much you must increase the cartridge size based on the projected conditions.

Mr Macdonald: Regarding military aircraft crash protection, we must keep in mind that some military aircraft are equipped with ejection systems which provide some degree of crew protection.

Regarding ventilation in bays, and fire extinguishing, we must keep in mind that the fire-extinguishing systems for combat aircraft act in milli-seconds so the ventilation is less significant under these conditions.

Mr Vincent: The area that I see as the biggest problem is the distribution of extinguishant within the bay, particularly getting adequate dispersion in a congested bay.

Mr Assart: Afin de déterminer les types, quantités et débits d'agents extincteurs nécessaires aux Services au col pour éteindre les incendies de moteurs, le Service Technique de la Navigation Aérienne (France) a entrepris une étude expérimentale sur une maquette à l'échelle 1/1 du moteur OLYMPUS (Concorde).

Il serait utile d'éviter la duplication de ces essais longs et coûteux.

Avez-vous entreprise de tels essais, ou en avez-vous connaissance?

Mr Macdonald: Tests have been done on a number of engine installations which have zoning of engine compartments and from them it is possible to read across to other similar designs. However, the Concorde engine installation is somewhat different in having straight through ventilation, high ventilating air mass flow through the power plant; it therefore required special consideration.

**THE USE OF ROCKETS
AGAINST CRASH FIRES IN AIRPORT AREAS**

by

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SUMMARY

A major problem in crash fire fighting in airport areas is that of reaching the fire sufficiently quickly. Studies of survival time in aircraft accidents followed by fire have indeed shown that fire fighting must initiate within some two minutes, on an average, in order to save fatalities and injuries to the passengers. Conventional airport fire fighting facilities most often prove unable to fulfill this critical demand. The use of rockets has been proposed as a possible solution, due to their intrinsic rapidity, easy operation and ability to reach sites not readily accessible by other means. A number of rockets, controlled by a computerized aiming system, could deliver an appropriate amount of extinguishing substance to the crash site in a very short time.

The paper gives an account of a continuing study undertaken for evaluating the feasibility of such a concept. Following a general discussion of some possible vehicle configurations and system operating modes, a specific solution basing on small ballistic rockets is considered in particular. Details are given of a simulation study being still in progress, intended for providing the major specifications for the system components performance with respect to efficacy, reliability and safety requirements.

Finally, a hint is given concerning the introduction of cost considerations; the need for a benefit-cost-analysis approach is underlined.

1. INTRODUCTION

It is virtually an axiom in current opinion that, apart from very special circumstances, the probability of surviving an aircraft accident is exceedingly small. This is certainly true for those cases in which an aircraft is completely destroyed by an explosion during the flight, or by high velocity impact with the ground. When the crash occurs at comparatively low speeds, typically in take-off or landing conditions, a number of fatalities may still result from partial destruction of occupied compartments and from structural missiles. In such cases, however, the primary intrinsic factor which determines passenger's chances of survival is represented by impact deceleration; and decelerative forces, even severe, can be tolerated fairly well by human beings, provided that they are adequately supported. Thus we have a large class of otherwise survivable accidents in which the main cause of death is represented by fire following the crash.

Several studies are currently being made along the line of crash-fire prevention, including studies on special fuels, fuel-system protection, interior materials and shieldings, structural features, etc. An alternative method of attack in fire fighting is based on improving the extinguishing technology. Here the principal efforts have been devoted to the study of extinguishing agents, on which considerable performance data and valuable results have been accumulated. But, when dealing with aircraft crash-fires, we have to face an additional difficulty concerning the extremely short time available for extinguishing the fire. Conventional airport fire fighting facilities most often prove unable to fulfill this critical demand since the crash-site is likely to be remote or not readily accessible, and the accident is generally sudden and unexpected.

To cope with such difficulties, the use of rockets has been proposed [1] as a possible solution, owing to their intrinsic rapidity, easy operation, and ability to reach sites not easily accessible by other means. According to this concept, airport fire protection facilities should include a number of ready operated rocket powered vehicles; in the event of a crash followed by fire in the airport area they could be used, in connection with a computerized aiming system, for delivering an appropriate amount of extinguishing substance on the fire site. The entire operation would require a very short time, thus providing an effective means of hindering the fire, at least for the time needed to begin fire fighting with more powerful means.

Undoubtedly, the proposal is such as to appear, at first, extravagant or even preposterous; one is likely to be immediately thinking of a host of reasons why it couldn't work. So did we. But what if, after all, it were just "crazy enough to be right"? The premium placed upon effective fire fighting in aircraft accidents is very high. Therefore, we decided that the thing should be considered seriously. We performed some preliminary evaluations which led us to the conviction that the concept deserved further analysis. Thus, some months ago, we undertook an extensive feasibility and evaluation study. Since this work is still far from complete, we shall not present definite answers. This paper is intended to give an outline of some important aspects of the problem, details of our approach and a feeling of our current orientation.

2. SURVIVAL TIME - FUEL FIRES AND EXTINGUISHING AGENTS

Several studies have been performed in the past for evaluating the characteristics of aircraft crash fires and related conditions for human survival. A classic NACA paper of some 20 years ago [2] was the first to report on extensive experiments aimed at appraising survival times as limited by thermal injury and respiratory damage. The data were obtained by crashing instrumented full-scale transport- or cargo-type airplanes in such a manner that a large fire resulted. Time-histories of cabin temperatures and toxic gas concentrations, obtained while the airplane was burning, were used for estimating the time interval during which occupants could attempt to escape from the fire. Results of that study indicated that, depending on the particular characteristics of the fire, the survival times ranged from 50 to 300 seconds. Subsequent developments in aircraft fuels, materials and design features have but little changed the situation. Tests made by NAFEC in 1965 [3,4] led to survival time estimates of about 140 seconds, well in line with the previous results. We can ultimately assume that in average conditions the time available for an escape action by the occupants or an external relief action, is only slightly larger than 2 minutes; that is a desperately short time. As we shall see later, a rocket based intervention is likely to require no more than some 75 seconds to be initiated; though it may not allow total extinction of the fire, it could nevertheless prove useful in two ways: by hindering the spread of the fire so as to lengthen the escape time available to the occupants; by providing additional escape avenues through the exterior flames or lengthening the time interval during which these avenues remain open.

The escape chances depend primarily upon the specific circumstances of how the fire starts and spreads. Generally, large volumes of fuel mist are formed when fuel tanks are ruptured while the aircraft is still moving rapidly. The resulting mist fires rise away from the airplane and burn out in a few seconds, so that they do not noticeably affect cabin environment temperatures. Subsequent fires develop from fuel on the ground, on the wetted structure and pouring from the tanks. The size and extent of these fires are the result of the details of the crash, the slope of the terrain near the airplane and the velocity and direction of the wind. In the worst circumstances, when there is direct contact between the flames and the fuselage skin, this may burn through in a few seconds, thus remarkably shortening the minimum survival times given above. Therefore the fire extinguishing action must essentially extend to the area immediately surrounding the aircraft structures; current assumptions, for today's aircrafts, are on an average of 5000 m².

With regard to extinguishing agents which might possibly be selected for this kind of applications, there's a vast literature concerning their properties and effectiveness as resulting from a number of different methods [5,6,7].

Several basic studies have been devoted to the inhibition process in premixed flames, which should be similar to that in turbulent diffusion flames, typical of crash fires. More direct evidence of the behaviour of extinguishing agents in fuel fires is provided by results obtained from standardized test fires [7]. Among the extinguishing agents which seem to be well suited to fuel-fires, namely halons and dry powders, we limited our attention to the latter, mainly because powders lent themselves to simpler and more effective solutions with respect to problems of storage in the rocket head and expulsion from it.

The amount of powder needed per unit surface obviously represents a very important characteristic, chiefly for our purpose. For one of the best powders, namely a cryolite (Na₃AlF₆), unitary amounts of about 1 Kg/m², obtained from a test on laboratory scale, have been reported [7].

This would mean that, to extinguish a surface of 5000 m², about 5 tons of powder, at least, should be delivered to the fire site, provided that they could be uniformly distributed.

Unfortunately, the distribution resulting from a dropping of separate charges would unavoidably be uneven. Another important factor affecting the choice of extinguishing agents is represented by their ability to prevent fire reignition by residual flames or hot parts. Since this depends primarily upon the particle concentration in the air (which, in turn, is affected by environmental effects, such as the wind) it seems advisable that the spreading of extinguishing agents be prolonged in time.

3. CONCEPTUAL SYSTEM EVALUATION

We shall now turn to the conceptual design aspects of our system; that is, an airport fire protection system relying on a number of ready operated rocket vehicles which, in the occurrence of a crash-fire in the airport area, would deliver an adequate amount of extinguishing powder to the crash site. Having so generally defined the objective of the system, a broad variety of solutions are possible with respect to the choice of vehicle configuration, trajectory, guidance, control, ground installation, system operating modes, etc. The following is a convenient, yet oversimplified, breakdown of possible choices:

a) Small ballistic rockets - These would be unguided fin-stabilized vehicles with quasi-parabolic trajectory (Fig. 1). The aiming at the target would be accomplished by ground-orientation. Deceleration sequence and extinguishing powder release would be controlled by a timer, suitably regulated soon before launching. All operations, apart from target sighting, would be accomplished automatically under computer assistance. Vehicles of this class could be designed for payloads of 50 to 200 Kg of extinguishing powder, therefore, a large number of them would be required for a single mission. Details of this concept will be discussed in the following paragraphs.

b) Missiles with autopilot - Vehicles of this type would be provided with a self contained control system intended for performing the various functions of motion data gathering, tilt program, stability, engine control, charge separation. Time functions would be regulated by a program device containing both standard built-in information and specific information supplied by the ground computer immediately before launch.

ching. Such missiles would be able to follow a well tailored trajectory (Fig. 2), consisting of three phases: i) Boost phase with terminal tilting on timed command; ii) sustain phase at constant height until timed charge separation; iii) standard diversion manoeuvre and parachute recovery. The aiming of the missile at the target could be shared in various ways between computer assisted ground orientation and autopilot guidance. A fully automated system operation is still conceivable. Being remarkably more sophisticated than rockets of the previous type, missiles of this class should be able to carry a comparatively larger payload in order to keep the number of vehicles required for a rescue mission within reasonable limits.

c) Missiles with command radio guidance - Vehicles of this type would continuously exchange navigational and guidance information with the ground system. Therefore they would exhibit a much higher mission flexibility than previous systems (Fig. 3). They could be launched from a fixed-orientation surface or subsurface launching pad, follow a complex target-seeking trajectory, release the powder load and finally accomplish fly back and landing on a specified site. Obviously, this would represent a very sophisticated system, requiring a specific team of highly trained operators. Vehicles of this class should be designed for carrying a very large weight of extinguishing powder, because it would be difficult to operate two or more of them at one time; therefore a maximum of two or three vehicles performing subsequent missions should be capable of delivering the total amount of needed powder.

Many further alternatives are conceivable, especially with respect to the guidance concept. Wire guidance techniques, for instance, are commonly used for close-range surface-to-surface military rockets. Optical sensing devices, especially suited for fuel-flame detecting, are well within the current state-of-the-art. In other respects, the conceptual evaluation work is somewhat facilitated inasmuch as several conceivable options can be reasonably ruled out on the basis of specific criteria, such as the need for contemporary operation of a large number of vehicles, and safety considerations concerning the environment, where avoiding target misinterpretation is mandatory.

Once the choice has been limited to the few major alternatives considered above, one is able to estimate the essential characteristic of the vehicles, and to define their performance, their operational characteristics and their required support systems. The result of this work is a summary of specifications concerning the vehicle and system elements. Additional information and data are obtained by considering safety requirements, maintenance requirements, personnel factors, etc. Finally, a preferable approach must be selected; and this obviously requires a preliminary operational analysis including development economics as well as operational economics.

Owing to the exploratory nature and limited aims of our study we indeed based our choice on a somewhat more intuitive philosophy. In short, we decided to follow the simplest approach, that is to go deeper into the study of an airport fire protection system based on small ballistic rockets. We felt that, owing to the unusual character of the matter, clear-cut incentives would be required in order that it may look worth developing; and we thought that a simple system of that kind, intrinsically cheaper than others, was more likely to offer such incentives, provided that its ability to accomplish the desired performance could be demonstrated.

4. SMALL BALLISTIC ROCKETS

We shall limit hereafter our attention to a specific class of vehicles, i.e. small fin-stabilized ballistic rockets, capable of delivering 50 to 200 Kg. of extinguishing powder to the crash-fire site. A preliminary design study was performed in order to estimate the major characteristics of such vehicles. As an instance, we give in Fig. 4 a configuration sketch of a typical rocket of this class, corresponding to the following specifications:

Diameter, m	~ 0.3
Length, m	~ 2.65
Mass of projectile, Kg	120.42
Mass of propellant, Kg	14.79
Mass of the round, Kg	136.08
Burning velocity, m/s	243.84
Effective burning time, s	0.91
Effective acceleration, m/s ²	252.86
Specific impulse, s	208
Deceleration coefficient, m ⁻¹	12.07 x 10 ⁻⁵
Thrust, N	~ 32,600
Max. range, m	~ 4,000

The vehicle consists of two main parts, the head and the motor; the former contains the charge of extinguishing powder, and the program device. Separation of the two parts occurs at the appropriate instant on timed command, and each of them is provided with its own parachute. The vehicle trajectory has 3 sections (Fig. 1):

- 1 - The burning phase, being nearly rectilinear and lasting about 1 second.
- 2 - The coasting phase, with a quasi-parabolic shape.
- 3 - The descent phase, which begins with the separation of the two main modules.

The head and the motor follow two separate descent trajectories, since the motor has a recovery parachute system, whereas the head is provided with a simple deceleration drag device acting, moreover, with some delay. Thus the motor is caused to land at a distance from the fire site and does not represent an additional hazard. The aiming of the rockets to the target is accomplished by means of launcher orientation (i.e. advance orientation and azimuth orientation) and by regulation of the timing device, in accordance with a set of equations providing the optimum mix of the relevant parameters with respect to the target direction and distance. Such equations may be given in a computer suited form by means of a number of curvilinear regression coefficients, to be determined previously on the base of theoretical and/or experimental performance data. Appropriate corrections must be applied in order to account for atmospheric conditions and wind characteristics. The system configuration is schematically illustrated in Fig. 5. Following an alarm, the whole system is activated; the sighting of the crash site is performed manually in one or more theodolite stations (A). Position data are then automatically supplied to the computer (C) together with meteorological data gathered by the instruments (B). Based on such data, the computer selects the batteries to be actuated, performs all calculations concerning orientation of the launchers and regulation of the program-device of each rocket, establishes the launch-succession, and automatically executes all preparatory operations on launchers and vehicles (E). A start up command from the control room (D) causes the computer to initiate and proceed with the sequence of launches until exhaustion of the rockets, unless stopped before by the operator.

Each rocket, after the burning phase, follows its ballistic trajectory until the timer causes the two modules to separate (Fig. 6). While the motor descends under the action of its recovery-parachute, the head is decelerated towards the fire-site by deployment of its drag device (Fig. 7).

Since it is advisable that the powder may spread in the air at some meters of height, the powder-bag is provided with a little explosive charge and with a suitable detonator; this could possibly be represented by a device hanging by a thin cable of appropriate length, released in the last nearly-vertical phase of descent and actuated by the impact with the ground (Fig. 8).

The flight time for a vehicle of this kind would typically be on an average of about 30 seconds; by estimating the time required for all preliminary operations, - that is, time elapsed since the crash instant till the alarm (~15 sec) -; fire recognizer and theodolite sighting of the fire site (~20 sec); computer controlled orientation of launchers and vehicles programming (~10 sec) - an appraisal may be attempted of the overall time needed to begin the extinguishment action. With the figures assumed above, this time turns out to be some 75 seconds; for a comparison, an optimistic estimate of the average intervention time for conventional means is on the order of five minutes. Therefore, the rocket system does indeed represent a convenient alternative provided that every thing goes the right way. We can obviously think of a variety of possible difficulties; for instance, a particularly unlucky position of the crash site, or unfavourable meteorological or light conditions. But it should be remembered, any way, that if difficulties of any kind were to cause a delay in fire recognition, any conceivable rescue means, not only this, would result unable to save the passenger's life.

5. SIMULATION PROGRAM

Based on the general operational and performance characteristics thus established, an extensive simulation program was undertaken; we shall give here an outline of this work, being still in progress.

The fundamental question we are to answer can be worded as follows: which specifications result for the components of our system, if we demand that certain conditions be satisfied, in terms of total weight and distribution of the powder within a specified area centered on the fire-site? In other words, how many the rockets, which the values of diffusion parameters of each charge, what the accuracy of each component performance should be in order to satisfy the desired conditions? This is an important question, because the resulting requirements affect not only a feasibility appreciation, but also, and more important, the quality needs and hence the related foreseeable cost upon which depends, ultimately, whether this may or may not appear as a viable approach to airport fire safety.

To carry out the simulation program an analytical model of the rocket trajectory was first developed. This model is now used for running complete trajectory simulations by means of numerical computer techniques. The simulation program is essentially intended for error analysis purpose. A number of trajectory simulations are required in order to simulate a single extinguishment operation. With an appropriate sample of extinguishment simulations, the statistical properties of the system performance relating to the assumed parameter values can finally be determined. The whole procedure must of course be repeated so many times as to cover the desired range of variation of the system parameters. Therefore, two sets of input variables are considered:

- variables assumed to exhibit statistical variation for each trajectory simulation (for instance, those relating to launcher orientation, thrust misalignment, burning time, weight data, timed events, powder spreading);
- variables held constant for the whole set of trajectories of a single extinguishment operation, and assumed to exhibit statistical variation for each extinguishment simulation (for instance, those relating to crash-site coordinates estimation, atmospheric data, wind characteristics).

The output variables are represented by the statistical properties of the distribution of extinguishing powder resulting from a specified number of launches, or else the number of rockets required in order to get a specified amount of powder within a certain area surrounding the target.

The system parameters are essentially represented by the standard deviations of all input variables. Since the statistical variations of these could be directly related to accuracy, repeatability and reliability characteristics for the system components, one can understand that systematic correlation of simulated performance with such parameters may prove useful not only for feasibility considerations, but also for introducing cost considerations.

Simulation programs are generally carried out by the Monte Carlo method, unless the necessary number of complete simulations is such as to make a Monte Carlo study prohibitively costly; and this was the case with us.

Several methods [8,9] have been developed for approximating the behaviour of errors with a reduced number of simulations when the Monte Carlo approach appears too expensive. The rrs procedure is still often used but it could not answer our purpose due to the restrictive assumptions that it makes. The method adopted in our study is based on a modified Monte Carlo procedure developed by Logsdon and Africano [8].

In short, the method makes a series of perturbations on the input variables at selected probability levels and then fit the effect on the output variables with a series of polynomial curves. Once these polynomials have been determined, the Monte Carlo samples are taken from these instead of from the simulation program; the computer time is thus drastically reduced. An additional advantage, especially in our case, is that the individual effects of input variables can be isolated, so that a limited change in one of the input statistics does not require a repetition of the entire analysis.

As previously noted, we are at present working along the lines above described with the aim of completing the parametric analysis.

To give a feeling of the kind of results we are currently accumulating we give in Figs 10 to 15 two series of computer generated plots of powder density distribution. As illustrated in Fig. 9, the plot field corresponds to a square of 100 m x 100 m centered in the target site with a mesh of 1 m x 1 m. The range-line is imagined as running from the upper right to the lower left corner of the square. The cases illustrated correspond to vehicles carrying a 200 Kg - powder charge, all launched by the same battery. The two sets of figures are intended for illustrating the effect of a change in a single parameter, namely the standard deviation σ of the powder distribution at the ground resulting from each charge. Figs 10 to 12, correspond to $\sigma = 3,5$ m, and illustrate the situation after 5, 10, and 25 hits. Figs 13 to 15 give the analogous situations for a $\sigma = 7$ m. A larger value of σ obviously yields a smoother distribution; on the other side, if σ is too large, the powder density at the ground may result too low; thus, given the amount of powder delivered by each rocket, an optimum value of σ can be established, which maximizes the extinguishing effect of a single charge; the importance of this parameter is somewhat reduced when the number of charges addressed to the fire becomes large. The dispersion of impact points about the target point, resulting from statistical variations in the input variables (for ease of comparison both series refer to the same sample), recalls a two-dimensional normal distribution with standard deviation of about 24 m in range and about 15 m in lateral deflection; in such a case the expected proportion of charges falling within a 5000 m² area circle would be about 90% - In other words, a 90% efficiency in rocket number and powder mass utilization would require that the overall effect of errors affecting the trajectory be limited to less than 1%, over a flight range of some 3000 m. The requirement for high accuracy and repeatability of the rocket trajectory must be tempered by consideration of possible errors in estimated target position; perhaps a certain predetermined degree of dispersion of impact points might prove useful. Anyway, the problem of accurately estimating the target position is of major importance, especially when considering the extremely short time available for sighting operations.

6. THE NEED FOR A BENEFIT - COST EVALUATION

As commonly happens in all fields of engineering, also in the present case the ultimate decision as to bring or not the envisaged concept towards full implementation will depend upon cost considerations. We are still in too a preliminary stage of our study to allow introduction of detailed cost considerations. Nevertheless, some remarks can be made concerning a convenient approach to this subject. We deal evidently with a case in which the investments required for a development and implementation program should be essentially justified by public utility considerations. In such cases, the only way to perform a suitable evaluation study is by adopting methods and techniques of benefit-cost analysis. There is no difficulty, on principle, with the statement of cost categories which will presumably be considered: development costs, production costs, installation costs, maintenance and repair costs, and so on. On the other side, the only important benefit to be considered is represented by expected savings in terms of human fatalities and injuries, over a specified period. The risk reduction allowable by the introduction of the new safety system should in turn be purged of additional risks relating to the use of rocket projectiles in the neighborhood of urban areas, and additional hazards to life and property in the airport. Here an old debated question arises: what monetary value is to be assigned to a human life? In benefit-cost studies carried out in recent years, mainly in the fields of nuclear power and civil aviation, a variety of approaches to such a ticklish problem have been attempted [10]. None of proposed methods looks completely satisfactory, what is quite natural. Nevertheless the problem is a real one, and it must be answered somehow. Some frequently quoted figures may help for an order-of-magnitude appraisal. In the U.S.A, a common value for life insurance is \$ 30,000. In the nuclear field the typical assumption of \$ 250 per man-rem corresponds to a value of about \$ 1,000,000 for a human life. As for the civil aviation domain, the compensatory damages awarded by U.S. juries to the victims of aircraft accidents often reach astronomic sums; for instance, figures

which were cited by Lloyds underwriter David Dunn at an SBAC symposium on Products Liability [11] include examples of \$ 2,000,000 for the death of one man, and \$ 3,800,000 in the case of a scientist who suffered severe burns; examples of compensation granted in cases of death which go well over \$ 500,000 are countless.

Such figures are rather impressive, so that it is not out of question to suppose that the expenditure required for developing the envisaged system may result sufficiently justified.

CONCLUSIONS

In the present phase of our work have not yet attained a definite conclusion as to the practicability of this particular approach to the problem of aircraft fire-safety. We have the feeling that the thing is feasible under a strictly technological standpoint; in other words, with an adequate development effort, we could make the system provide the desired performance. On the other side, the actual possibility of readily or practically operating the system whenever need arises is open to serious questions. Unfavorable meteorological conditions and other disturbing factors might drastically reduce the percentage of occasions in which the system could be successfully employed. In this case the balance of costs and benefits, intrinsically questionable for a project of this kind, would be irremediably impaired.

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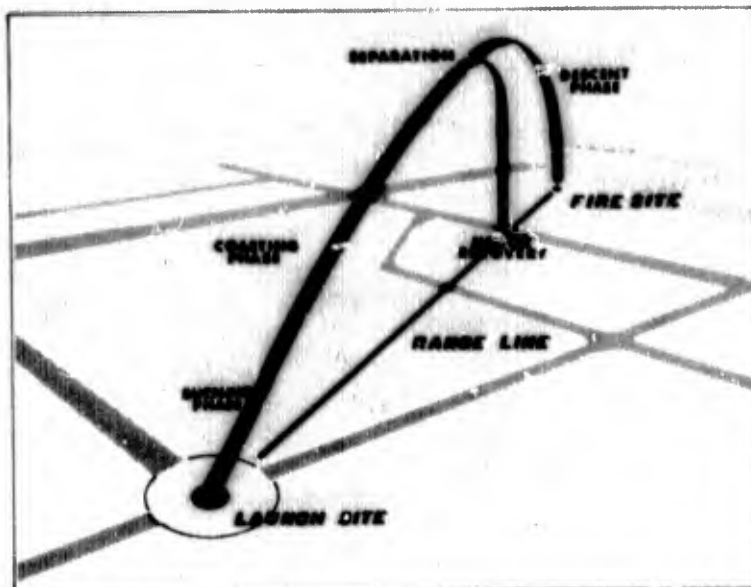


FIG 1

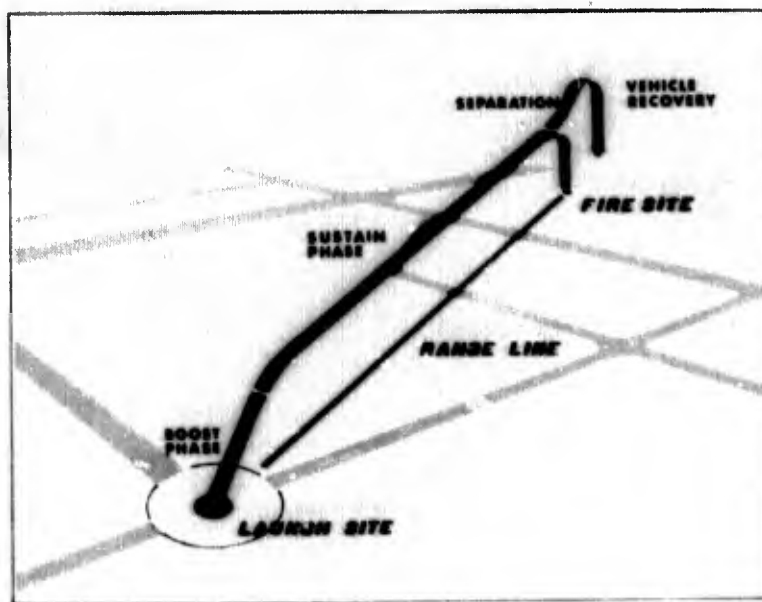


FIG 2

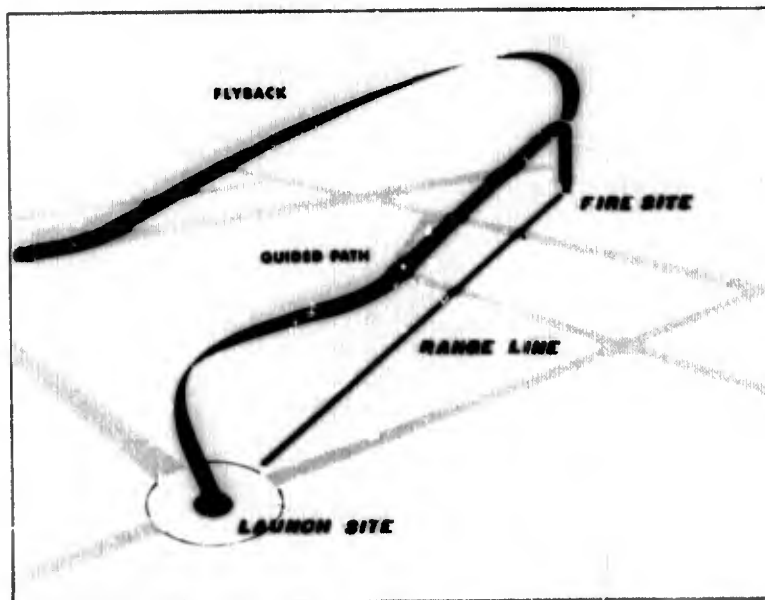


FIG 2

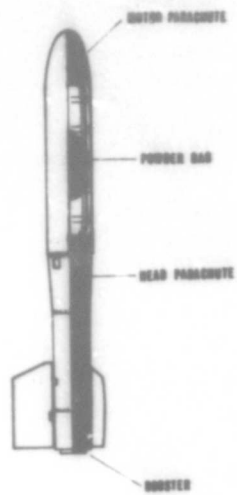


FIG 4

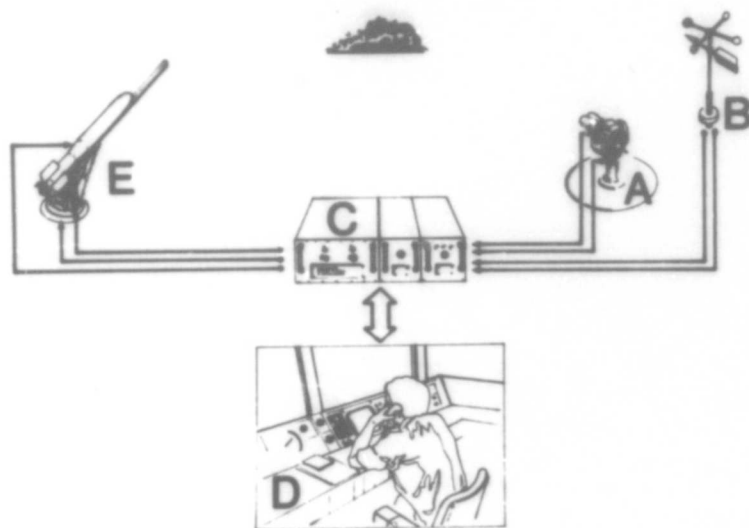
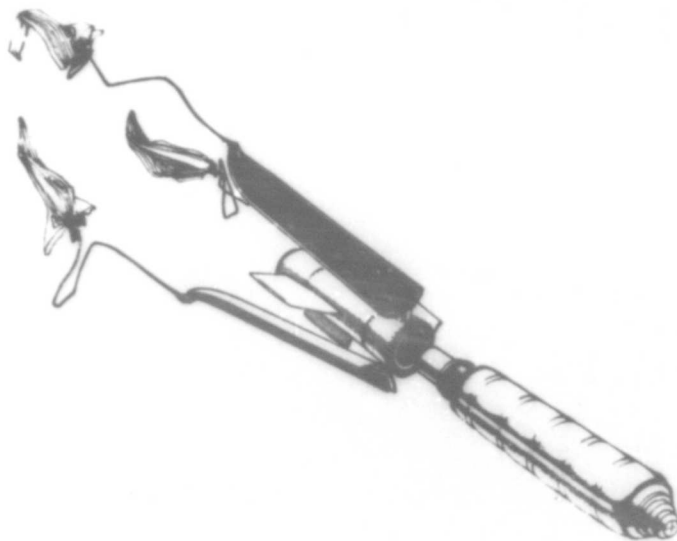


FIG 5



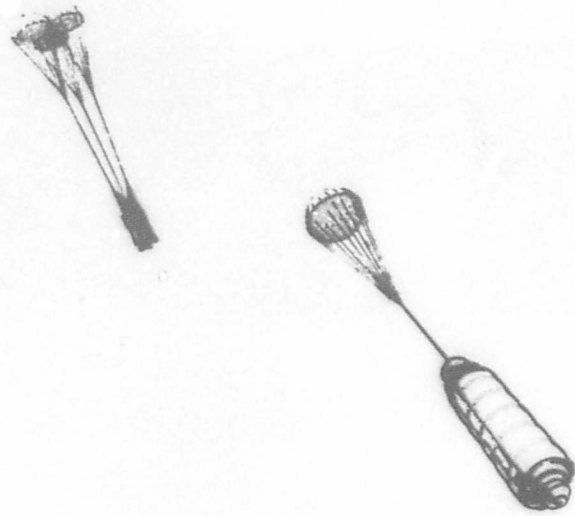


FIG 7

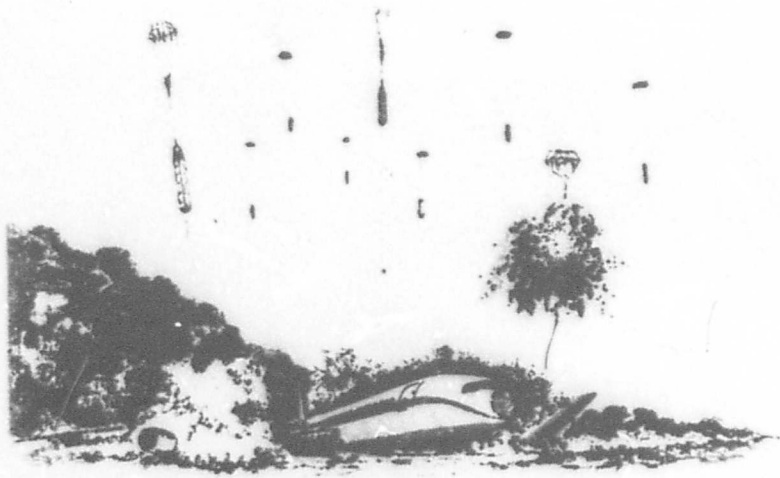


FIG 8

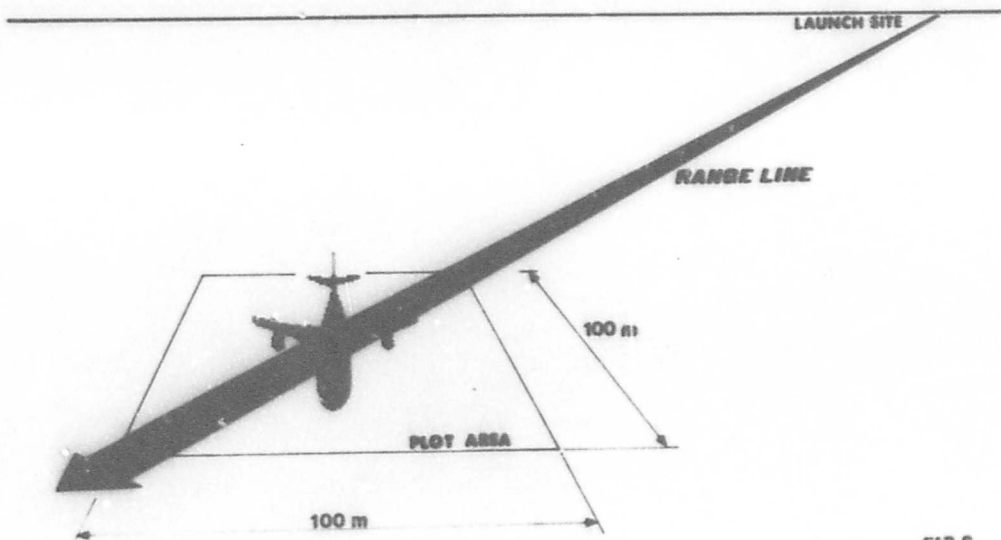
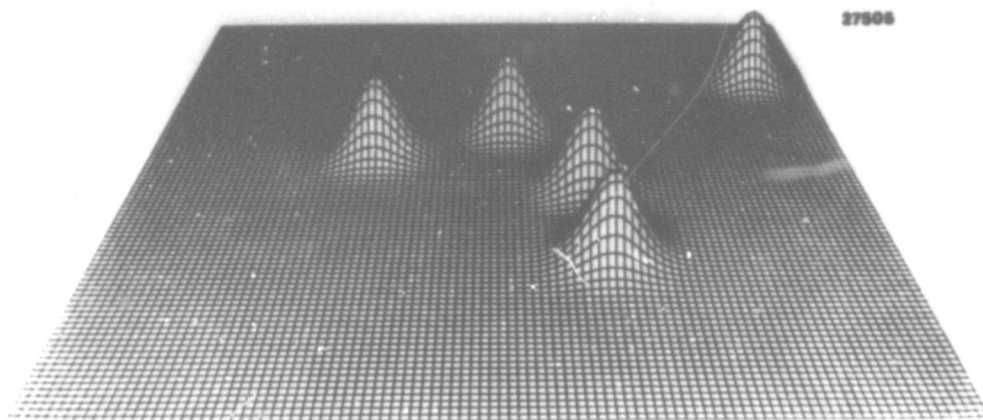
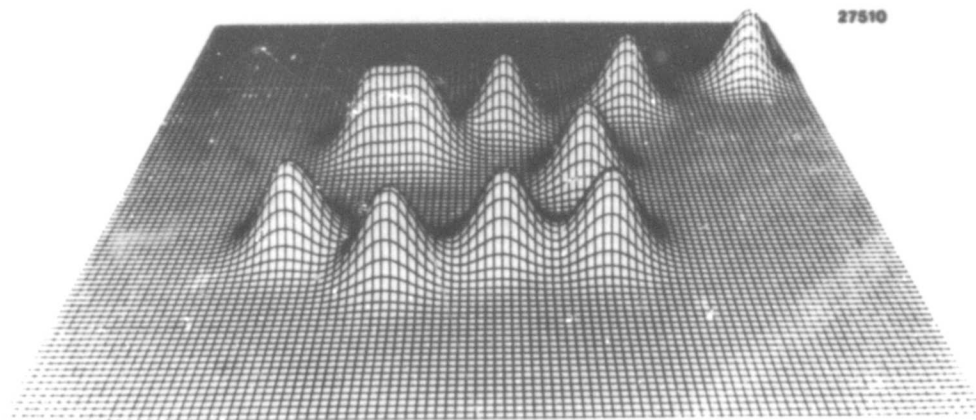


FIG 9



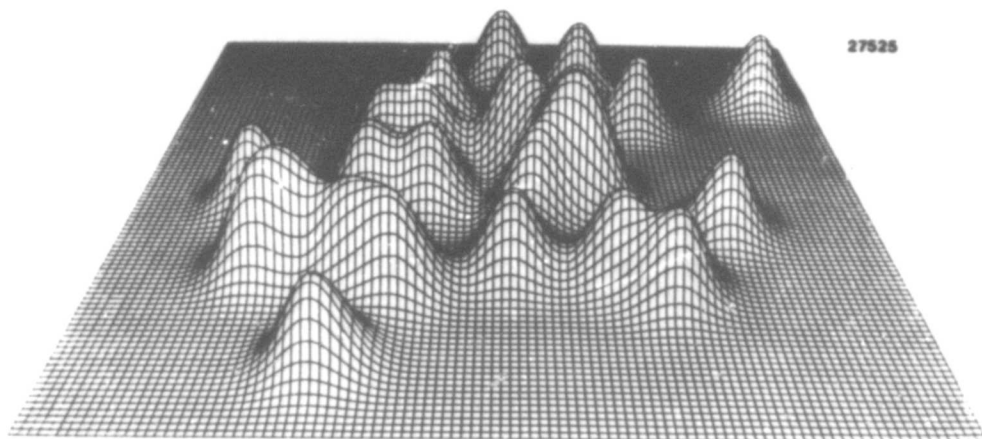
27506

FIG 10



27510

FIG 11



27525

FIG 12

27606

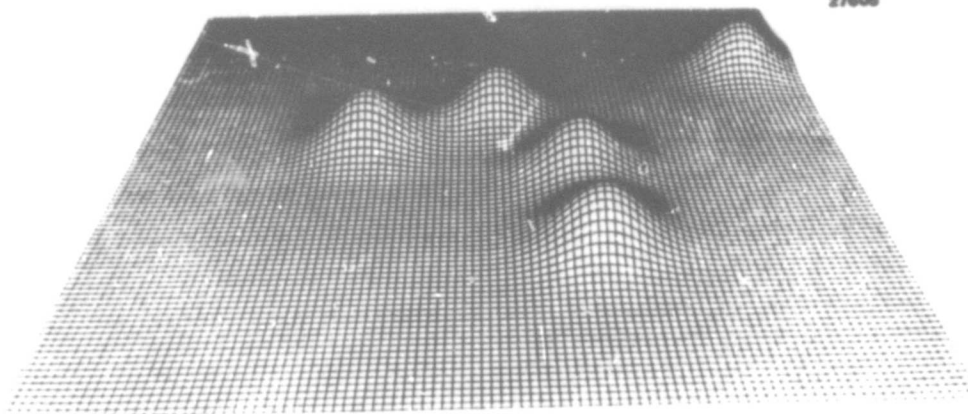


FIG 13

27610

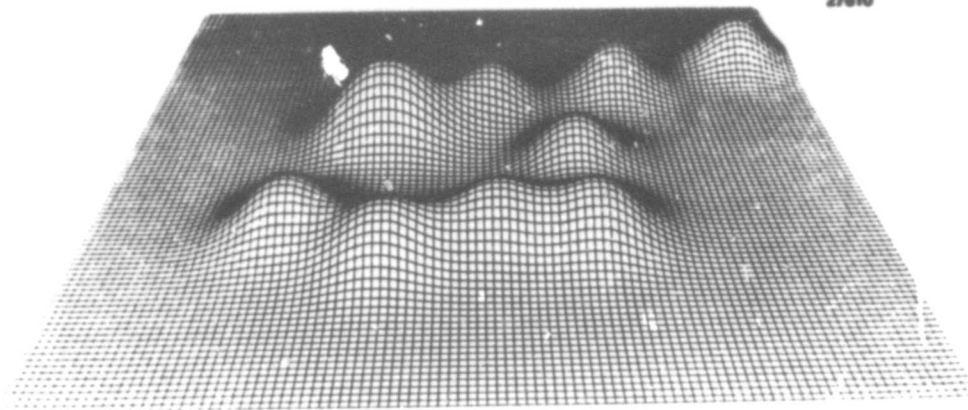


FIG 14

27625

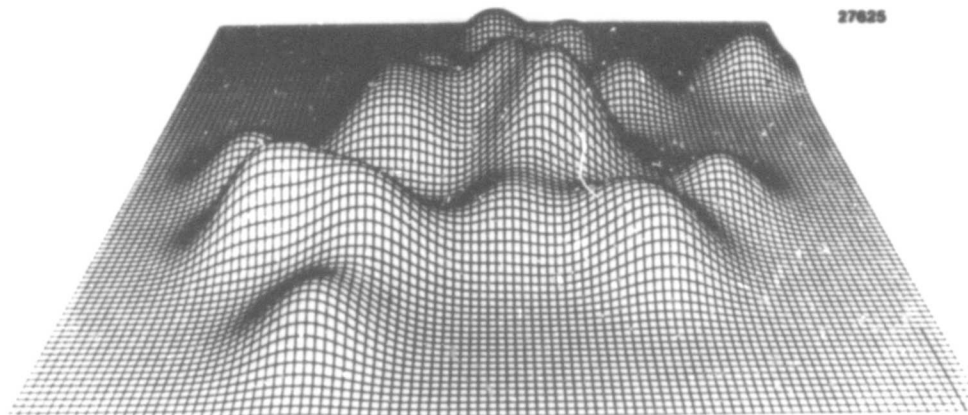


FIG 15

DISCUSSION - PAPER 20

Mr Glassman: Have you looked at the effects of rain or bad weather on system effectiveness?

Mr Andrenucci: Up till now we have only approached the problem from the standpoint of rocket performance and the ground support system. We have not yet selected or studied extinguishing systems.

Mr Jackson: What is the effect of severe thermal current turbulence from the fire on the parachute?

Mr Andrenucci: We have two parachute devices, one to decelerate the motor, which caused substantial deceleration. The head parachute is a small one for minor adjustments so the powder-head falls directly on the fire. Errors involved would be of the same order of magnitude as those in the rest of the positioning system.

Mr Monti: One drawback seems to be the decision point to use the system; it seems possible that it might be activated and inundate people unnecessarily. The natural competitor is the helicopter; would you care to comment on the relative advantages?

Mr Andrenucci: Both helicopters and a guided missile type system would probably give better performance but would involve the use of highly skilled and highly trained, consequently highly paid personnel on duty full time ready to arrive on the fire site in two minutes. We have not done a full cost study, but two minutes is a very short time for helicopter response and would pose some severe operating problems and costs.

Regarding decision making, it is a practical problem. The system should be organized so that all preliminary preparation for launch is done automatically; the system should be such that the operator only has to push a button for final go-ahead.

Mr Hayward: With reference to the query regarding the use of Dry Powder during rainfall, its use does not present serious problems. Whilst I have some reservations about the viability of a project of this nature, I would not discourage research into this, but would prefer efforts to improve conventional facilities. Could the system be used to attack and locate a crash fire during conditions of low visibility, i.e. when ground forces would have difficulty in location of the incident and were forces (by the visibility conditions) to travel at reduced speeds?

Mr Andrenucci: Our basic approach was to study the feasibility of this type of approach, i.e. how many rockets would be needed to make it practical to cover a sufficient area around an airport. The possibility of operating in limited visibility is certainly important since many landings can now occur under very limited visibility conditions. If the system proves feasible, it could be possible to tie it in to the airport locating system.

FIRE FIGHTING AGENTS FOR LARGE AIRCRAFT FUEL FIRES**R. FIALA, K. DUSSA****DEUTSCHE FORSCHUNGS- UND VERSUCHSANSTALT
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Most important demands in aircraft fuel fire fighting are minimum extinguishing time and consumption of agent, suppression of heat radiation as far as possible and prevention of re-ignition. No extinguishing agent is able to fulfill these four demands equally well; therefore a combined application of different agents seems to be necessary, if maximum efficiency is to be achieved. According to the nature of the fire, combinations of foam and halon, or foam and powder, or combination of all three types are under consideration.

For a critical evaluation of the properties of the different types of agents experiments were carried out by DFVLR under contract of the Fed.Min. of Def., using standardized small and large fuel fires (4 m² and 200 m²). The time until extinguishment occurred and the amount of agent needed, were measured. Additionally, the time which, after a deliberate reignition, elapsed until the whole fuel surface was on fire again, was measured.

Among the powders, K₂SO₄ proved to be the most effective. Kryolithe, which, from a test on Laboratory scale seemed to be promising, failed in the large scale test, mostly due to buoyancy effects. Despite their good properties, the use of halons in large scale fires cannot be recommended, before a suitable procedure for expelling the agent from the storage tank is developed. Out of the investigated protein and synthetic foams, the first showed the best safety margin against reignition, whereas the latter exhibited the smallest extinguishing times.

INTRODUCTION

CRASHES OF AIRPLANES are mostly followed by fuel fires. These fires can be divided into two groups. The first comprises surface fires where the fuel has been spilled over a large area on the ground; hence, these fires have a quasi-two-dimensional character. In the second group the space around the airplane is involved, like for example with engine fires, or fuel mists; hence fires of this type have a quasi-three-dimensional character. For each of these types of fires special requirements for the extinguishment have to be fulfilled. In addition, after extinguishment the fuel has to be prevented from re-ignitions by still existing ignition sources like hot metal parts or residual flames.

In order to rescue passengers from the crashed airplane, only a short period of time is available in which the extinguishment has to be carried out. No single extinguishing agent is able to fulfill all demands for the extinguishment. Dry powders and halons are suited best to extinguish three-dimensional fires, because they can be distributed in the volume occupied by the flames. The extinguishing mechanism of these substances is based on the chain breaking efficiency of these compounds. Due to this chemical interference with the reaction mechanism of the combustion the amount of agent needed to achieve extinguishment is very low and the whole process takes place in short time. But dry powders and halons do not prevent reignition, or do so only for a short period. This demand is better fulfilled by foams. Foams also are known as proper agents to extinguish two-dimensional fires in the presence of ignition sources, because they separate the combustible fuel from the oxidant.

For fighting airplane fuel fires a combination of at least two agents is needed, one agent to extinguish the flames rapidly in order to stop the heat flux to the fuselage and the other to prevent reignition and to cool the hot parts.

In order to find combinations which offer optimum properties with respect to the demands mentioned, experiments were carried out by DFVLR under contract of the Federal Ministry of Defence. In these tests the extinguishing efficiency of several agents belonging to each of the three groups has been examined separately. From the results combinations with optimum properties can be deduced.

TEST FACILITY AND EXTINGUISHING EQUIPMENT

One of the great difficulties associated with experiments on the efficiency of an extinguishing agent is the question how to carry over to large-scale fires results obtained in a laboratory apparatus. Owing to the fact that many properties of a large-scale fire vary from one case to the other, distinct scaling rules are not known presently. Therefore, two sizes of fires have been selected for the planned experiments, one on a pan with 4 m²-fuel-surface, the other on circular pools with a fuel surface of 200 m². The fire with the smaller size comes closer to laboratory experiments, whereas the larger fire is not very far away from actual crash fires. One of the large pools had a water base, the other was filled with soil.

The extinguishment of the fire on the 4 m²-pan was always carried out with two hand-extinguishers. For dry powders standard 12 kg-handextinguishers, for halons 2.4 l-cabin-extinguishers were used. Foam was discharged with 10 l-pyrene-handextinguishers. For the extinguishment of the fires on the 200 m²-pools, the standard fire-fighting vehicles of the German Air Force were used; in particular, for dry powders a TROLF 750 and for foams a TLF 3 800/400.

For halons no suitable fire fighting equipment was available on the market. So two 750 kg dry-powder equipments had to be modified, using the powder-container as the vessel for the halon and expelling the halon as usual with nitrogen.

TEST PROCEDURE

In a number of tests the best way to extinguish the fuel fire in the 200 m²-pool was evaluated first. This was achieved by carrying out the extinguishment with four hand-lines in the following way: At the beginning of the extinguishment all four handlines stood close together with a distance of approximately 3 m between each handline. When an area of approximately 30 % was extinguished the outer two handlines moved around the pool. The inner two hand-lines prevented the already extinguished fuel surface from re-ignition.

For each test 5 000 l of fuel were used and a preburn time of 60 s was chosen. The time needed for extinguishment, the consumptions of agent necessary for extinguishment, furthermore wind-velocity, fuel- and ambient air-temperature and, in case of foams, solution-ratio and expansion ratio were measured. After extinguishment with foams an area of 1 m² was cleared from the foam and after approximately 5 min reignited. The time elapsing until the whole fuel surface was on fire again, was measured.

From all tests carried out on the 200 m²-pools movie pictures were taken, which allow reexamination of all extinguishment processes. A short film showing examples of the tests is available.

TEST RESULTS

In all tests the total mass of the extinguishing agent needed to completely put out the fire was chosen as a measure for the extinguishing efficiency. For the extinguishment of the 4 m²-fire, 15 tests were performed with each extinguishing agent. The results of these tests scattered by approximately ± 10 %, on the average. In order to keep the total costs within reasonable limits only five tests with each agent have been performed with the large-scale fire (200 m²). The scatter of the result was again in the order of $\pm 10 - 15$ %.

Fig.1 shows the test results with halons and dry powders on the 4 m²-pan with water base. The best results were obtained with halon 1202, 2402 and 1211. The quantity needed was nearly the same for the first three halons. This result deviates from measurements of the reduction of flame speed by these halons, carried out on a Bunsen-burner [1] where an influence of the constitution of the compounds was found. The reason for this deviation must be sought mainly in differences between the halon distributions in a real pool fire and in a homogeneous Bunsen burner-flame.

The tested dry-powders show a wide range of efficiency. The one with the best extinguishing efficiency, Sodium cryolite is nearly as effective as the halons. This finding does not correspond to measurements, reported in [2], where in a laboratory apparatus the sodium-cryolite was found to be roughly twice as effective as halons. Then powders on potassium base and Monnex follow. In this group potassium sulfate has the best efficiency. Sodium bicarbonate with an amount of 2.70 kg/m² for extinguishment is nearly 4 times less effective than the halons and twice less effective than potassium sulfate. Furthermore, there exists a marked difference in efficiency of dry powders of the same base substance delivered by different manufactures as can be seen in the case of potassium-sulfate and potassium bicarbonate. A possible explanation can be sought in different particle size distributions.

Among the foams (Fig.2) Aqueous Film Forming Foams (AFFF) exhibit the best extinguishing efficiencies. Less effective were synthetic foams and fluoroprotein foams. It can be seen, that there is little difference in the extinguishing efficiency of these foams. The poorest results were obtained with protein foams.

Fig.3 gives the results for halons and dry-powders on the 200 m²-pool with water base. Also under these fire conditions, halon 1211 has the best extinguishing efficiency. These tests have been carried out very carefully, ensuring that the application of the halon to the fire took place no later than approx. 10 minutes after pressurizing the halon vessel with nitrogen. In the preliminary tests it had been found, that if halon is stored under nitrogen pressure for approximately 15 min or longer, the efficiency decreases due to dilution of nitrogen in the halon. After a storage time of 3 hours the efficiency was only nearly half that at the storage time zero.

For the discharge of halon 2402 no suitable nozzle was available. Therefore, a nozzle normally used for water was applied. As the tests proved, the range of the nozzle was insufficient and the droplet size too large. This caused the high amount of halon 2402 needed for extinguishment compared to the halon 1211.

Under the dry powders tested on the 200 m²-pool potassium sulfate was most effective. Its effectiveness is nearly equal to that of halon 1211. Sodium cryolite failed mostly due to its low density. In such large fires, the buoyancy forces acting on the jet carrying the low density dry-powder, are so large, that the cryolite particles are prevented from reaching the zones in which the flames are anchored near the fuel surface. As a consequence the light particles are carried away by the quickly ascending combustion gases. It may be possible to overcome this effect by carefully adjusting either the particle size or the equipment to such large fires however, this was beyond the scope of these tests.

The extinguishing efficiency of dry powders against fires on soil depends on its wetness. The attempt to extinguish the fuel fire on dry soil was without success, independent on the nature of the powder used. The reason for this lies mostly in the formation of cracks in the soil, in which residual flames can withstand the extinguishing procedure. When the soil is very wet, nearly the same amount of agent was needed for extinguishment as on the water base.

As on the 4 m²-pan, among the foams AFFF exhibits the best extinguishing properties (Fig.4). The sequence in efficiency is the same as found on the 4 m²-pan: AFFF, fluoroprotein foams, synthetic foams and protein foams. Compared to the other foams, the backburn time of the synthetic foam is not sufficient. Also the foam blanket is sensitive against wind and tends to break up for higher wind velocities.

The superiority of AFFF-foam is also retained for 200 m²-fires on soil (Fig.5). For this case, the extinguishing efficiencies of fluoroprotein- and synthetic foam are nearly equal. Less effective was protein foam. A marked difference exists in the backburn resistance. On soil synthetic foams have nearly no thermal resistance.

Furthermore, the extinguishing efficiency of a Water/Light-Water/Halon mixture was examined. While all other solutions have to be foamed prior to its application, this mixture produces foam under the influence of heat. That means, the mixture can be discharged in the same way as water. The foam is produced, when it comes into contact with the flames or hot parts. Despite the low efficiency of the halons used this mixture proved to be highly efficient. Only 560 kg were required for extinguishment, half of the amount necessary with Light-Water. The reason for this increase in efficiency is not clear, at present, however further experiments are planned on this subject, in order to

optimize mixtures of water, foam solution and halons.

Considering a comparison of the mass of extinguishing agent per unit area for the small-scale and the large-scale fires, the present results are not yet sufficient to make firm statements. It seems however, that when using foams the larger fire needs a considerably larger mass per unit area, whereas for halons and dry powders the observed differences are rather small. Further investigation into this subject is necessary.

CONCLUSIONS

Among the various substances suitable for fighting quasi-three-dimensional-fires halon 1211, potassium sulfate and Monnex fulfill best the demands for rapid extinguishment of fuel fires. Considering the three above mentioned agents, the halon 1211 has another advantage; on contrary to the dry powders it does not obscure the visibility. However, besides the problem of expelling the agent from the storage tank for which a solution still has to be found, there is one main restriction. Halon 1211 is slightly toxic and under certain conditions not negligible amounts of halogen acids can be formed during extinguishment.

Taking these two points into consideration, the use of halon in large scale fires can not be recommended until a suitable procedure of expelling the agent is found and more experience in view of the formation of acids under various fire conditions is available.

Despite its good extinguishing properties, the use of Monnex is somewhat restricted by ambient temperature, on contrary to potassium sulfate. Under high ambient temperature Monnex inclines to form clumps.

The demand for high extinguishing efficiency against quasi-two-dimensional fuel fires is fulfilled best by Light-Water, fluoroprotein foam and synthetic foam. Taking in account also the demand for a high backburn resistance and good blanketing properties for a longer period of time, only fluoroprotein foam and Light-Water can be considered suitable agents.

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Agent	Amount	Agent	Amount
CF_2Br_2	0.75 kg/m ²	$NaHCO_3$	2.70 kg/m ²
$C_2F_4Br_2$	0.73 kg/m ²	Na_3AlF_6	1.03 kg/m ²
CF_2BrCl	0.73 kg/m ²	K_2SO_4 Manufacturer A	1.4 kg/m ²
CCl_4	2.35 kg/m ²	K_2SO_4 Manufacturer B	2.05 kg/m ²
$KHCO_3$ Manufacturer A	1.5 kg/m ²	Monnex	1.6 kg/m ²
$KHCO_3$ Manufacturer B	2.15 kg/m ²	KCl-Base	1.2 kg/m ²
$KHCO_3$ Manufacturer C	2.05 kg/m ²		

Figure 1 Amount of agent needed to extinguish a fire on a 4 m² pan (water base).

Agent	Amount kg/m ²	Discharge Rate kg/m ² .min	Time for Extinguishment sec
AFFF Manufacturer A	1.4	7.32	11.5
AFFF Manufacturer B	1.7	6.50	12.1
Synthetic Foam Manufacturer A	2.3	5.52	25.0
Synthetic Foam Manufacturer B	2.4	5.33	27.0
Fluoroprotein Foam	2.5	6.76	22.0
Protein Foam Manufacturer A	2.7	6.22	26.0
Protein Foam Manufacturer B	more than 4	6.0	more than 40
AFFF-Water- Halon mixture	2.35	7.41	19

Figure 2 Amount of agent needed to extinguish a fire on a 4 m² pan (water base).

Agent	Amount kg/m ²	Discharge Rate kg/m ² .min	Time for Extinguishment sec
Halon 1211	1.3	4.27	18.3
Halon 2402	2.3	3.88	35.3
NaHCO ₃	3.3	6.0	33
KHCO ₃	2.1	5.7	21.7
K ₂ SO ₄	1.4	5.2	16.5
Na ₃ AlF ₆	no extinguishment		
Monnex	1.7	8.5	12.0
ABC-Dry Powder	2.8	5.5	30.0

Figure 3 Amount of agent needed to extinguish a fire on a 200 m²-pool (water base).

Agent	Amount kg/m ²	Discharge Rate kg/m ² .min	Time for Extinguishment sec	Backburn Time sec
APFF	5.2	12.4	11.8	571.
Fluoroprotein Foam Manufacturer A	6.3	11.7	32.2	278.
Fluoroprotein Foam Manufacturer B	6.2	12.4	30	477.
Synthetic Foam Manufacturer A	6.4	10.9	35.2	126.
Protein Foam	8.1	7.55	64.5	278.
APF-Water-Halon Mixture	2.8	3.1	54.3	189.

Figure 4 Amount of agent needed to extinguish a fire on a 200 m²-pool (water base).

Agent	Amount kg/m ²	Discharge Rate kg/m ² .min	Time for Extinguishment sec	Backburn Time sec
AFFF	5.5	13.0	25.2	795
Fluoroprotein Foam Manufacturer A	7.1	12.5	34	695
Fluoroprotein Foam Manufacturer B	7.0	16.5	25.7	660
Synthetic Foam	7.7	10.9	42.2	67
Protein Foam	16.8	9.7	104	164

Figure 5 Amount of agent needed to extinguish a fire on a 200 m²-pool (soil base).

DISCUSSION - PAPER 21

Mr Glassman: There are some aspects of your testing that present some problems for me. It appears there are some inconsistencies. For example, you stated you have tried certain of your extinguishing agents in a Bunsen Burner flame. I assume that there you had a pre-mixed condition. I think that the number of radicals created in a pre-mixed flame are much too great for one to kill the chain branching steps in a flame by the addition of a compound which will trap out H radicals that initiate the propagating mechanism. My own opinion is that these compounds act more as an inert to absorb heat in the actual system. Also I think that generally in fighting a fire you are fighting a diffusion flame, and therefore it is questionable that compounds found in a pre-mixed flame would really be applicable. Of course diffusion flames generally burn as if they were stoichiometric, so around the flame zone there must be many radicals. If my reasoning is correct the HALON's with the higher specific heat and higher molecular weight would seem to be the most effective contrary to the results you have obtained, where the lighter compounds are most effective. I can only come to the conclusion that when you apply the lighter weight halogen it reaches the flame more easily because of its greater diffusivity within the system, that is its effectiveness is not greater because of its extinguishing characteristics, but due to its diffusivity.

Mr Fiala: We have done measurements on the change in radical concentration in the flame when halons are applied. We found that small amounts of halogen ethers (because these halons are cracked) reduce the OH radical concentration substantially at stoichiometric mixture. This is in a region ranging from 300 to 700 degrees. If you stretch the reaction zone, you get an increase in OH radicals.

Mr Glassman: A basic question though is whether the halogen is extracting the OH or just lowering the temperature sufficiently for the steady state concentration of the OH to decrease.

In a chain branching reaction with the flame continuously propagating you usually have a large excess of OH radicals so removing a certain percentage really should not affect things too much. I think the temperature variation is a much stronger effect because it is an exponential effect.

Mr Fiala: We measured the temperature in the reaction zone and we found the temperatures higher with halon than without. The inhibition reaction takes place in the early reaction zone where the starting reactions occur. We think this will also occur in a diffusion flame.

Mr Hayward: You mentioned that "Monnex" was more liable to caking than other dry powders when stored in tropical temperatures. How did you conduct your tests which caused you to arrive at this conclusion?

Mr Fiala: We heated samples to 80° Centigrade. I believe the majority of tests are run at 60° C, but we believe that actually temperatures up to 90° are realistic.

Mr Hayward: In your description of the extinguisher used to contain Halons you told us that you used a modified dry powder appliance. For the purpose of your tests did you use optimized nozzle sizes?

Mr Fiala: This was really not a part of the effort; we had to make some adjustments in nozzle sizes to achieve operation.

Mr Pinkel: I would like to relate our (NACA) experience in dealing with one of the halon fire extinguishants, monochlorobromomethane, CH_2ClBr . We used a few pounds of this agent in the air induction system of a reciprocating engine to prevent flames from appearing at the air intake and the exhaust pipe during an experimental full-scale airplane crash. During the crash we observed brown flames issuing from the tail pipe which ignited the spilling fuel. Subsequently, in the laboratory, we established that CH_2ClBr would burn upon contact with a surface heated to about 1400°F.

In further experiments with a spontaneous ignition apparatus we found that a small amount of CH_2ClBr stimulated the ignition of gasoline at a temperature 50°F below the established spontaneous ignition temperature. By test in the spontaneous ignition apparatus, which is a uniformly heated glass vessel with a small aperture, we established that the gasoline sample had a spontaneous ignition temperature of 850°F and CH_2ClBr did not ignite at this temperature. When gasoline and CH_2ClBr were introduced together into the spontaneous ignition apparatus at 800°F, ignition occurred.

We recognize that CH_2ClBr is an effective fire extinguishing agent that has been used successfully for many years. The manner of its application to an existing fire avoids these effects.

Mr Fiala: We have also experimented in this area. We found that combustion reactions can occur with Halon at temperatures of 800 to 1100°C. But in your case you have a hot plate; this is an unfortunate situation. In extinguishing a flame you are always coming from the cool side into the flame.

Mr Winterfeld: We did some experiments at DFVLR with ingestion of air and Halon mixtures into reciprocating engines. We found in spark engines we had a decrease in power, but with a diesel engine with the higher temperature we increased power.

Mr Glassman: There is a difference in the two halons; my question is has anyone investigated the change in the bond strength of the C-H in the halon. Does it decrease more than the C-H in normal methane. It could be that the addition of the two large molecules of chlorine and fluorine weakens the bond strength in the C-H. This is a fundamental question that should be checked and may explain some of the phenomena encountered.

THE EXTINCTION OF AIRCRAFT CRASH FIRES

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SUMMARY

In this paper, the author discusses the problems of the aircraft crash fire, including the difficulty of arrival of the fire-fighting services in time to save life. He appraises the different fire-fighting agents available and shows that fire-fighting foams are the only satisfactory primary fire-fighting agents for major crash fire use. He discusses the research and development of foam liquids and the means used to assess their performance, in terms of the physical properties of the foam liquid. He also examines the development of foam-making equipment and appliances in order to put the foam liquid to test use to meet the operational requirement.

LIST OF SYMBOLS

Heat radiation (H) in watts per centimetre² (W/cm²).
 Rate of application of foam solution (R) in litres per metre² per min (l/m²/min).
 Quantity of foam solution (Q) (eg to control fire) in litres per metre² (l/m²).
 Foam expansion (E) the ratio of the volume of the made foam to the solution from which it is made.
 Shear stress of made foam (S) in Newtons per metre² (N/m²).
 '25 per cent drainage time' (T) in minutes.
 Solution strength in volume percentage of foaming agent in foaming solution.
 Pressure expressed in bars.

1. INTRODUCTION

The modern aircraft is one of the strongest structures for its weight created by Man, as it needs to withstand a wide range of conditions of loading, vibration and temperature. The necessary strength factors to meet these conditions are closely specified by the international statutory bodies, and the designer has the task of providing, within the framework of these requirements, an aircraft with the competitive performance so essential for commercial success. It follows that there is little extraneous weight available for additional strengthening to withstand unusual or unexpected loads such as those likely to occur under the impact conditions of a crash. With the added problem of a large content of passengers and a highly volatile liquid fuel load, we have the ingredients for one of the severest fire situations of human experience, the aircraft crash fire. In this paper I hope to assess the reasons for the severity of this type of fire in comparison with other fires, and to give some account of the research which has led to the present and potential effectiveness of external fire-fighting.

2. THE PROBLEMS OF THE AIRCRAFT CRASH FIRE

The essential problems of the aircraft crash fire which make it more critical than other major fire situations are as follows.

- a) There is a very high life risk involved. Modern passenger aircraft carry up to 400 passengers.
- b) The crash itself is likely to render helpless a large proportion of the occupants, who must nevertheless be regarded as potential survivors unless shown to be otherwise.
- c) The discharge of large quantities of a volatile liquid fuel in the immediate surroundings usually produces a very rapidly-growing and often catastrophic fire situation which can involve intimately all the lives to be saved. The use of higher flash-point fuels has helped this situation somewhat in so far as ignition may sometimes - and providentially - be avoided, but once ignition occurs, a fire of severity equivalent to that of a high volatility fuel will develop. The only real answer to that problem is the development of the truly safe fuel.
- d) The strength of the aircraft structure can never be adequate to withstand the tremendous effects of impact damage. Nor can an adequate load factor be allowed to install fire-fighting systems capable of dealing with a major fire - even if they remained operative after the crash.
- e) The location of the crash cannot be known, at least with any precision, until the crash has occurred. This means in effect that the fire-fighting and rescue services cannot be sent on their way in advance of the crash, except in certain pre-planned cases where they may be stationed at strategic points, eg at landing or take-off points.
- f) The time-scale of the aircraft fire under the worst conditions, and the likely survival time of the occupants are both so short that the chances of the fire-fighting services arriving and taking effective action in time to save life are very low, except on the airfield itself, if land-borne appliances are used. In this respect, we are 'living off the statistics' in so far as we are dependent for success on a less than maximum rate of fire development (see Section 3 also).

3. THE TIME SCALE OF THE AIRCRAFT CRASH FIRE

Several workers have made model and full scale experiments on the rate of development and intensity of major aircraft crash fires (1)(2)(3) and their results are substantially in close agreement that where a serious but survivable crash fire has recurred, and has resulted in a major fuel spillage and fire around the fuselage, then the survival time of the occupants may be counted in a very few minutes - ranging from 1 to 5 minutes where the fuselage remained intact, but even less than 1 minute where the fuselage was ruptured, or where escape hatches had been opened. Such a short time scale reduces greatly the useful potential of the fire-fighting services and shows the enormous importance to be placed upon developments in safety fuels.

In terms of today's volatile liquid fuels, however, the problem is illustrated in Fig.1 where the effective range of appliances of various point-to-point speeds is shown in terms of survival times ranging from 2 to 20 minutes, according to crash conditions. It may be seen that a land-borne appliance with an average speed of 64 km/hr (40 m.p.h) has an effective range between 0.3 and 3.0 km (0.2 to 2.0 miles) for a survival time range of 2 to 5 minutes. These estimates are based upon a response delay of 1 minute after the crash before the appliance is rolling, and a further 1 minute for substantial fire control to be achieved - neither of these times being unduly long. In effect, this limits the use of land-borne appliances to the airport or its immediate environs. In order to extend the effective range of land-borne appliances to a radius of the 6.4 km (4 miles) from the airfield, within which 90 per cent of crashes occur, the survival time must be increased to at least 8 minutes by use of safer fuels or by other measures. Alternatively, air-borne appliances such as helicopters or STOL OR VTOL aircraft must be used with an effective average speed of some 320 km/hr (200 m.p.h) or more. A proposed helicopter-based foam-making appliance is shown in Fig.2. For greater ranges than 6.4 km (4 miles), airborne appliances are imperative, and even so, the survival time needs to be extended to at least 10 minutes to get a useful range of, say, 24 km (15 miles). The method of foam generation is shown in Fig.3.

4. AIRCRAFT CRASH FIRE STATISTICS IN UNITED KINGDOM

Aircraft crash fire statistics (4) in the United Kingdom have shown that approximately 83 per cent of all incidents (with and without fire) occurred on the airfield, 12 per cent off the airfield and 5 per cent during flight. Of the incidents involving fire (about one-third of the total), some 69 per cent occurred on the airfield, about 19 per cent off the airfield and nearly 12 per cent during flight. A working party set up to assess the effect of fuel on deaths by burning concluded that in major crash fires, some 8 to 20 per cent of the deaths occurred due to burns, and the remainder were due to impact injuries. On average, they concluded that about 10 per cent of deaths were due to fire alone, and the rest were largely due to impact. There was some indication of a tendency for the fatal casualty rate and the fire incidence rate to increase with size of aircraft, and fire was found to occur more frequently, pro rata, in crashes off the airfield than in those on the airfield - probably due to the more severe nature of the crash on unprepared ground.

The statistics therefore give some support for the continued use of land-borne appliances on the airfield and its environs, if the 31 per cent with fire in flight or off the airfield could safely be neglected. If they could not, a new form of airborne fire appliance would be needed.

5. DEVELOPMENT OF AIRCRAFT CRASH FIRE EXTINCTION AGENTS

5.1. The agents available

The fire-fighting agents available to the rescue services are as follows:

- a) Water jet or spray.
- b) Water-based foams.
- c) Dry powders.
- d) Inhibiting liquids or gases, eg halons.
- e) Other inerting gases such as carbon dioxide or nitrogen.

5.2. The role of the agents

These agents show the following advantages and disadvantages.

- a) Water. In the form of a jet, this is unsuitable for fires involving large quantities of flammable liquids. As a spray, its use is limited to the higher fire point liquids (fire point above 45°C), which effectively rules out its use on gasoline and wide-cut fuels, and leaves kerosene as a borderline case. Even with special applicators, it can readily be carried away in the updraught of flames and is therefore only likely to be of use as a secondary agent, eg for keeping cool the outside or inside of a fuselage while the major fire is handled by other agents, or for subduing a fire in an enclosed part of the structure, which could not otherwise be reached. Even so, its action can only be regarded as temporary, and it will not exclude toxic gases which may kill, although the temperature is subdued.
- b) Water-based foams. These are by far the most promising agents as they can seal a fire and give time for rescue to proceed, the fire area to cool, and complete extinction to be achieved. They are more economical in water usage than direct application of water spray, and likely to be far more successful in their effect. They are very good at dealing with large scale spill fires, but not effective with running fires, eg fuel falling from fuel tanks to the ground. The latter, however, do not constitute a major hazard once the main spillage fire has been covered with foam. Foam can readily penetrate under an aircraft fuselage or within semi-open compartments, eg baggage compartments, engine nacelles

etc, but is not suitable for penetrating well-enclosed areas, eg wing-roots and leading edges, where fire may persist. The use of foams is discussed in detail below, in relation to their physical properties.

- c) Dry powders. These are very effective agents for dealing with spill fires on open ground, or even in semi-enclosed or enclosed compartments. Weight for weight, they are probably the most efficient fire-fighting agents for this purpose, but they suffer from the fact that they are only effective while being applied, and leave the fire area unprotected when application ceases. In this respect, they resemble carbon dioxide, halons, and water sprays, to a greater or lesser degree according to circumstances. When applied in large bulk at high rates of flow, dry powders are capable of extinguishing very large fires, but they suffer from the disadvantages that they tend to obscure the fire zone, they are impermanent and may have severe choking effects on any survivors. Large-scale dry powder appliances have not tended to make headway for this reason, leaving the foams as the primary fire-fighting agents.
- d) Inhibiting and inerting gases. These all suffer from the disadvantage of being 'transient' agents, except in enclosed volumes such as wing-roots and leading edges, interior of nacelles etc, where an inerting atmosphere may linger for several minutes. On fires in the open, they are not as effective weight for weight as dry powders, and in the case of halons, they tend to be more expensive for a given effectiveness. Their role is therefore as secondary agents for specific duties in 'mopping up' a fire situation, or in dealing with difficult enclosed areas.

5.3. Characteristics of fire-fighting foams

Foams may be divided into three main classes, viz:

- a) Low expansion air foams. Foams made by aerating a solution of a foaming agent in water. Agents are based upon protein derivatives and stabilising agents such as fluorinated compounds (fluoroprotein foams), or upon synthetic fluorinated surfactants (aqueous film forming foams). Solution strength varies in the range 3 to 6 per cent, and expansion in the range 6 to 30. Suitable for surface application to large flammable liquid spill fires (non water miscible) from self-aspirating foam-making equipment such as branch-pipes and monitors. Can be projected under pressure up to a range of 200 feet approximately.
- b) Medium expansion air foams. Foams made by aerating a solution of a synthetic foaming agent in water. Agents based upon chemicals such as ammonium lauryl ether sulphate and stabilisers. Solution strength in the range $\frac{1}{2}$ to 2 per cent, and expansion in the range 30 to 200. Suitable for surface application to large flammable liquid spill fires, but difficult to project over more than moderate distances, eg about 20 feet, especially at the higher expansions.
- c) High expansion air foams. Made as for medium expansion air foams, but with a greater air supply to provide an expansion in the range 200 to 1000. This supply is usually provided by a suitable I.C., electric or water-driven motor. Foams not really suitable for application to external fires as they may be readily carried away by the updraught of flames, wind etc. May have some application within cabins, luggage compartments, wind roots etc, but it is difficult to see how its usage could provide compensating advantages to offset the need for further specialised equipment on the site of the fire.

5.4. The performance of fire-fighting foams

The performance of low-expansion fire-fighting foams can best be described in terms of their physical properties, and the rate and quantity of foaming solution per unit fire area necessary to control the fire. By 'control' is meant the reduction of heat radiation from the fire zone to a selected fraction of its free-burning value. Thus '9/10 control' means reduction of the intensity of emergent heat radiation to 1/10th of the initial free-burning value. This concept is used because it gives less variable results than the equivalent values for extinction, and in reality, rescue can often proceed before complete extinction of the fire.

The performance of foams on flammable liquid fires may best be described and compared by use of two graphs, viz:

- a) Rate of application per unit area (R) against time to control (t) (see Fig.4).
 b) Quantity of foaming solution to control (Q) against rate of application (R) (see Fig.5).

The second curve is derived from the first by multiplying, viz $R \times t = Q$.

Both these curves exhibit a minimum rate of application, below which the fire cannot be controlled (or extinguished). This rate is called the 'critical rate of application'. At rates above the critical, the time to control - and hence the quantity to control - fall rapidly with increasing rate. The time to control reduces progressively, but proportionately less rapidly, as the application rate is further increased. The quantity to control falls at first, but may pass through a minimum and then begin to rise again at higher rates. The rate of application at which the minimum occurs is called the 'optimum' or 'most economical' rate. The critical rate of application of low-expansion foams to fires in non-water miscible flammable liquids varies with the type of foam used, the flammable liquid to which it is applied, the concentration of foaming agent in the solution and the method of application. For gentle application to the surface, it lies in the range 1 to 2 l/m²/min. The most economical rate is usually some 2 to 5 times the critical rate, depending again on the same factors. As the quantity to control does not rise very rapidly above the optimum rate, it is often desirable, for safety reasons, to operate at a 'preferred rate' somewhat above the optimum. The possibility of doing this is, however, dependent upon the size of the fire in relation to the equipment available.

At the Fire Research Station, research on the performance of foams has been carried out for a number of years, on fires ranging in size from 0.25 m^2 (2.7 ft^2) to 325 m^2 (3500 ft^2). A systematic study of foam performance on flammable liquids was recently put in hand to fill in some of the unknown 'areas' of knowledge, and some of the results are shown in Figs 6, 7, 8. These experiments were made on a 0.25 m^2 (2.7 ft^2) circular fire tray in which the aviation fuel (AVTUR, AVTAG or AVGAS) was burnt for a period of 60 seconds before commencing foam application. The foam was then applied for a total time of 3 minutes to the centre of the circular tray by means of a 'model' branch-pipe, at a rate equivalent to $3 \text{ l/m}^2/\text{min}$. This branch-pipe was specially designed to give a 'good' foam in which the foaming liquid available had been processed to give a foam of expansion about 8 to 10 units, and a shear stress of between 4.5 and 26.5 N/m^2 , dependent upon the foaming agent used. In the test, the 90 per cent control time and the time to extinction were both measured. At the cessation of application, a small pot containing burning AVGAS was lowered into the centre of the foam layer, and as a result, the fuel was reignited and burnt back the foam. The time from lowering the pot into the foam, to the complete destruction of the foam layer was measured and termed the 'burn-back time'.

The value of this method of test is that the control of an actual aircraft fire has two significant and separable factors which are

- c) the time to control the fire and thereby reduce the high level of radiant intensity, which is the immediate reason for the spread of fire and loss of life, and
- d) the ability of the foam to keep a fire under control, when it has been reduced to a small residual fire and is trying to reassert itself, governs the necessity to bring in further appliances to back up the initial attack, so that rescue operations can safely proceed.

Thus the 9/10 control time and the burn-back time are good measures of these two factors, and hence of the overall performance of a foam in relation to a fire.

The results show (Figs 6 and 7) that at the rate of application selected, AVTUR, AVTAG and AVGAS fires are increasingly difficult to control and extinguish, in that order, for protein, fluoroprotein and fluorochemical (A.F.F.F.) foams, but for synthetic foams using the agent developed for high expansion air foams, the AVTAG fires were the most difficult, with the AVTUR and AVGAS about the same at a much lower level. This would suggest another reason for using kerosene fuels in addition to their difficulty of ignition. In general order of ability to control a fire on an aviation fuel, the fluorochemical agents (A.F.F.F.) were best, the fluoroproteins next best, the proteins were third best and the synthetic agents last, as far as the turbine fuels AVTUR and AVTAG were concerned. These results are largely explained by the differing shear stresses of the foams produced, rather than by differences in their chemical constitution. A fluid foam can sweep readily over a flammable liquid surface and provided it is not destroyed too rapidly, it can produce a low control time by its rapidity of coverage and hence rapid reduction of incident heat radiation. If the shear stress is too low and the foam too unstable, however, it will be destroyed even more rapidly than it can cover a fuel surface, and a poor control time will result. The synthetic foam fell into this category, even though the agent was being used at 3 per cent concentration. The protein and fluoroprotein foaming agents were used at 4 per cent and the fluorochemical agents at 6 per cent (Belgium and U.S.A.) and 4 per cent (France). These concentrations were generally in accordance with the makers' recommendations.

The burn-back results for the same range of foaming agents are shown in Fig. 8. Here again the synthetic foam showed the poorest performance, the fluorochemical foams were the next best, and the protein and fluoroprotein foams were best. The overall ratio of best to worst performance was about 6 to 1. In general, the foams performed best on AVTUR, next best on AVTAG and worst on AVGAS, although the overall ratio of best:worst varied between 1:1 and 3:1, being greatest for the protein and fluoroprotein foams.

In all the above results, expansion may be shown to have a negligible effect, provided it is not so low that the foam cannot be fully developed, and its other properties suffer thereby. This is a matter of vital importance in the design and development of equipment for the making and projecting of foams, since it permits simple self-aspirating equipment to be used and avoids the need for complicated vane-type foam-making pumps and compressor systems in which an unduly large proportion of the energy available is used in giving the foam an unnecessarily high expansion, to the detriment of the power available to project the foam.

5.5. Medium expansion airfoam

Medium expansion airfoam made from a synthetic foaming liquid to an expansion in the range up to 200 units has been shown to be a very effective fire-fighting agent for flammable liquid spill fires. Thus a hand-held medium expansion foam generator with a throughput of 230 l/min of foaming solution and an output of 35 kl/min of expanded foam, can control a 11.2 m^2 (120 ft^2) in about 4 seconds. This type of foam, has, however, to be poured onto the fire from close range, and this factor would put a very severe limitation on the manoeuvrability of an aircraft fire appliance, since it would need to approach very close to the fire and be handled with considerable care under conditions of intense heat radiation to achieve success. An alternative would appear to be an appliance with an extending boom and generator. If applied from a helicopter, this type of foam would probably be equally difficult to 'place' owing to the likelihood that foam at this expansion would be carried away in the down-draught or cross-winds. It therefore seems improbable that this agent will be used successfully in this application, but it is worthy of trial to find out its possibilities and limitations.

RESEARCH ON AIRCRAFT FIRES

Much large-scale research on simulated aircraft crash fires has been carried out (5)(6)(7) in Europe and the United States over the last 25 years. This work has been either with pool-type fires in banded areas, with or without a simulated aircraft crash in the area, or an actual aircraft placed in the centre of an area over which a substantial fuel spill fire has been ignited. The results have generally supported the findings of small-scale research, that is, that the most significant factors in rapid fire control have been the rate of application of the foaming solution per unit fire area, coupled with a careful selection of foam properties to ensure a fluid yet stable foam. In this respect, the actual value of shear stress necessary to ensure fluidity with stability is a characteristic of the particular foaming agent and its concentration in solution. A.F.F.F. foaming agents have been shown to retain their stability to lower values of shear stress than fluoroprotein agents, and they in turn to lower values than protein agents, a fact which explains their order of superiority in control performance. After fire control, post-control stability becomes the salient performance factor, and this is greater for the proteins and fluoroprotein agents than for the A.F.F.F. agents. In the aircraft crash fire, the fire control factor is clearly of very great importance, but the burn-back factor must not be ignored as it is also highly important.

In deciding whether small-scale tests may safely be used to predict results for large-scale tests and actual practice, it is necessary to know how the heat flux from the fire varies with fire size, for distances close to the fire, since it is the intensity of heat radiation which will largely determine the ultimate life of the foam blanket on the fire. Figure 9 shows several measurements of heat flux adjacent to pool fires, in the region between the edge of the fire and 2 diameters from it, using AVTUR, J.P.5 and crude oil fires with a size range 2.7 m² to 28 m². The results suggest that close to the fire, the foam will not receive harsher treatment on the large fire than on the small fire by heat radiation effects. Its endurance time on the larger surface may however, need to be longer, if, for example, it needs to traverse a greater path in forming a foam layer.

Very few series of experiments have been designed with the primary objective of determining the scaling factors of fire extinction, and when it is remembered that the area bounded by a Boeing 747, ie wing span x length overall is some 4220 m², while the largest experimental fires have been of the order of 500 m² - a factor of 8:1 - it will be seen how important this knowledge is. Experimentation on truly full scale is just not practicable. G B Geyer (8), however, has carried out many experiments, the results of which are summarised in Fig. 10. The results suggest that for each size of fire, there is a most economical size of branch-pipe, and larger or smaller branch-pipes will be less efficient. As the fire size increases, so does the 'most economical' size of branch-pipe - an extension of the concept of 'optimum' rate in laboratory fires. This point was also illustrated by some Fire Research Station results of 1969. The Fire Research Station is developing a series of branch-pipes each capable of producing a well-developed foam at its selected rate of flow. So far, the 5 l/min, 50 l/min and 200 l/min sizes have been designed and made. The other characteristics of branch-pipes and monitors which can have a significant effect on fire control are throw and dispersion pattern, and these are both being studied over the range of sizes.

7. DESIGN AND DEVELOPMENT OF AIRCRAFT CRASH FIRE APPLIANCES

The freedom of the appliance designer from the need to consider the expansion of the foam produced by his monitor has simplified and improved this type of foam-making equipment tremendously. The most recent appliance, manufactured in the United Kingdom for use with jumbo-sized aircraft, has a roof-mounted monitor capable of delivering over 60,000 l/min of made foam at a maximum range of 90 m (300 ft) in addition to a further 9000 l/min through any 2 or 4 available side-lines. On the basis of an expansion of 10 units, and an application rate of 5 l/m²/min, this is equivalent to controlling a fire size of 1200 m². The foam output is available for 2 minutes, so that an average depth of foam of 20 cm (9.5 in) would be available over the whole area. As this is about 4 times as much as necessary for fire extinction, the application could be shifted to other areas, giving adequate foam coverage for a 'maximum' size of fire in a Boeing 747 aircraft. These modern monitors, freed from the need to produce expansions of values above 10 units, are self-aspirated, and all the power available in the water supply is used in making a good foam and in throwing it to a good range (Figs 11, 12 and 13).

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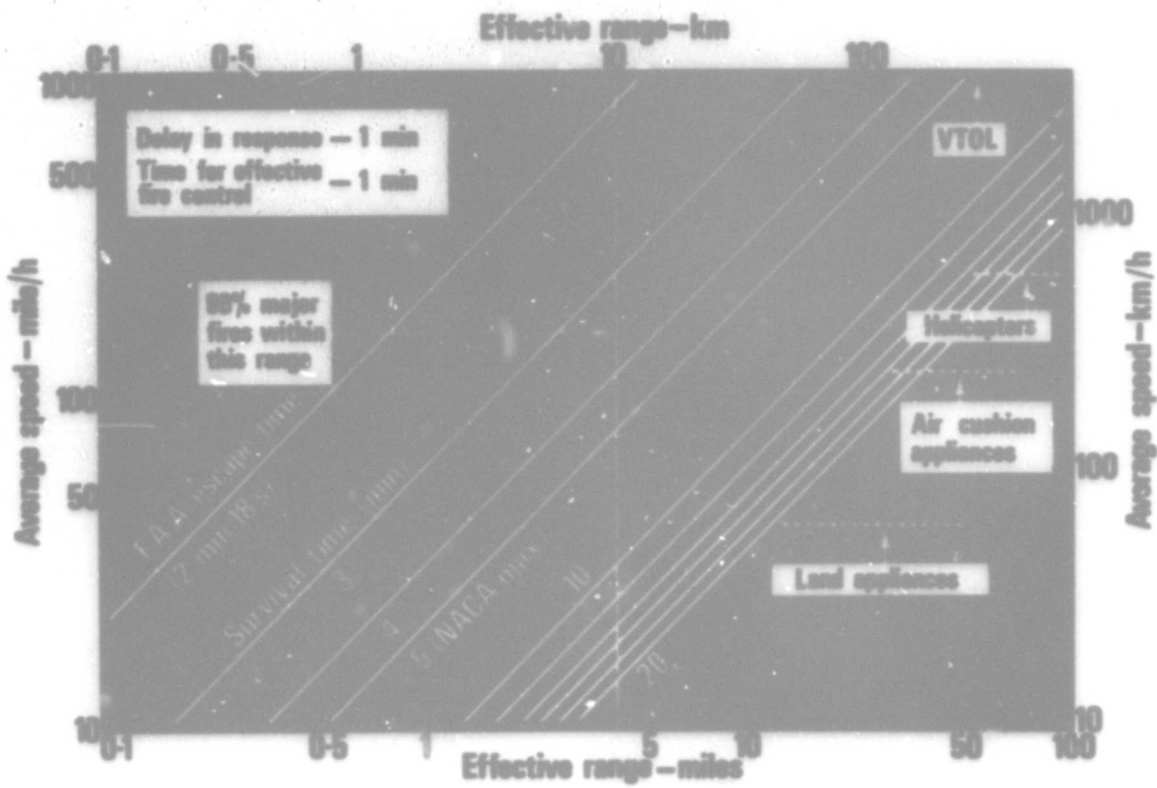


Fig.1 Effect of appliance speed on effective range

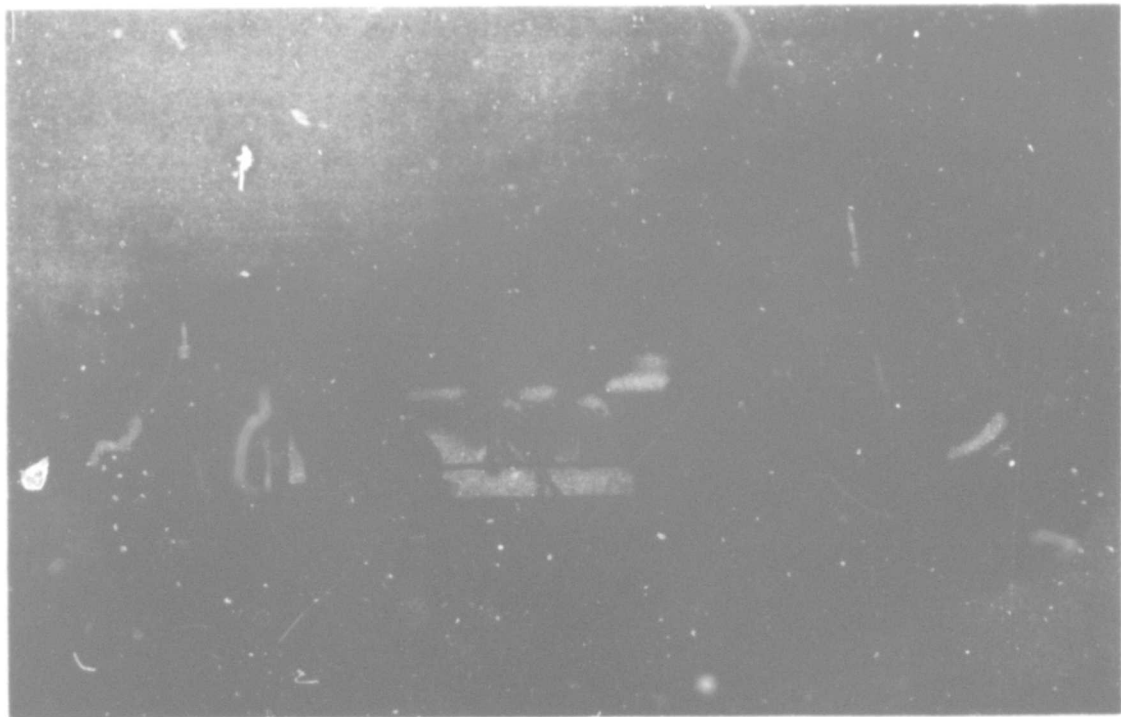


Fig.2 Proposed helicopter crash tender

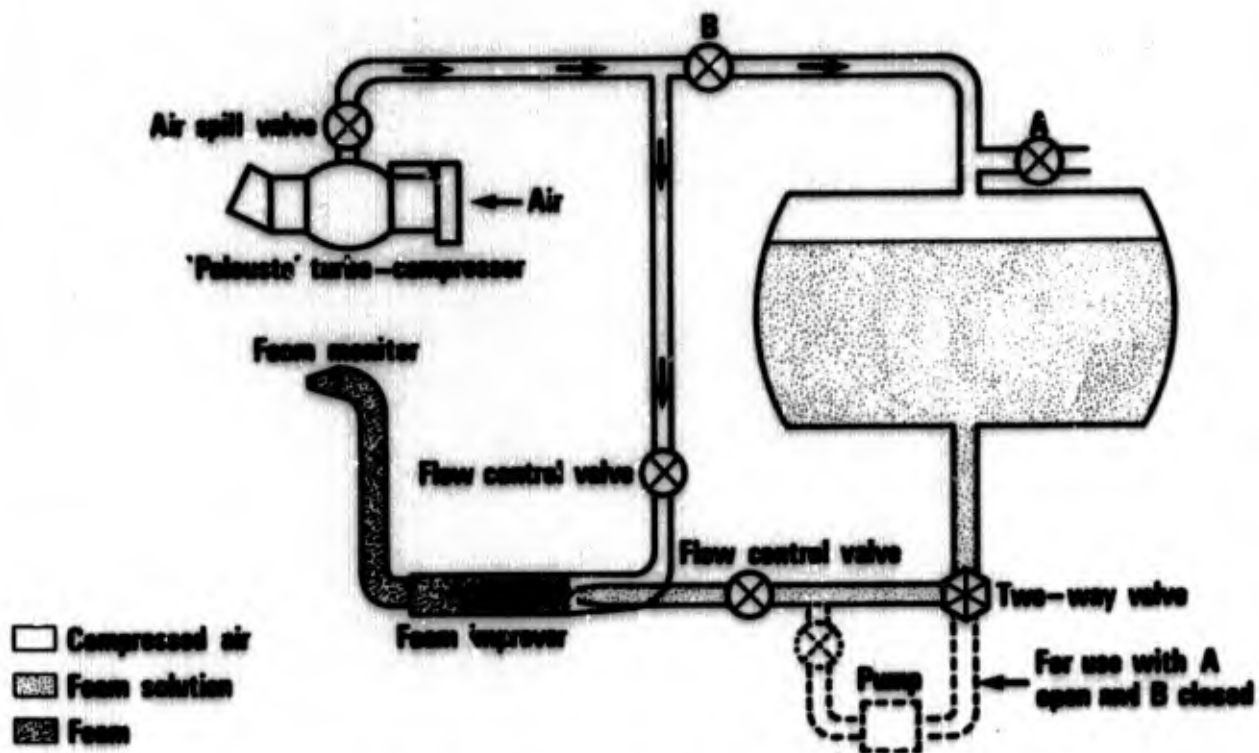


Fig.3 Method of foam generation - helicopter crash tender

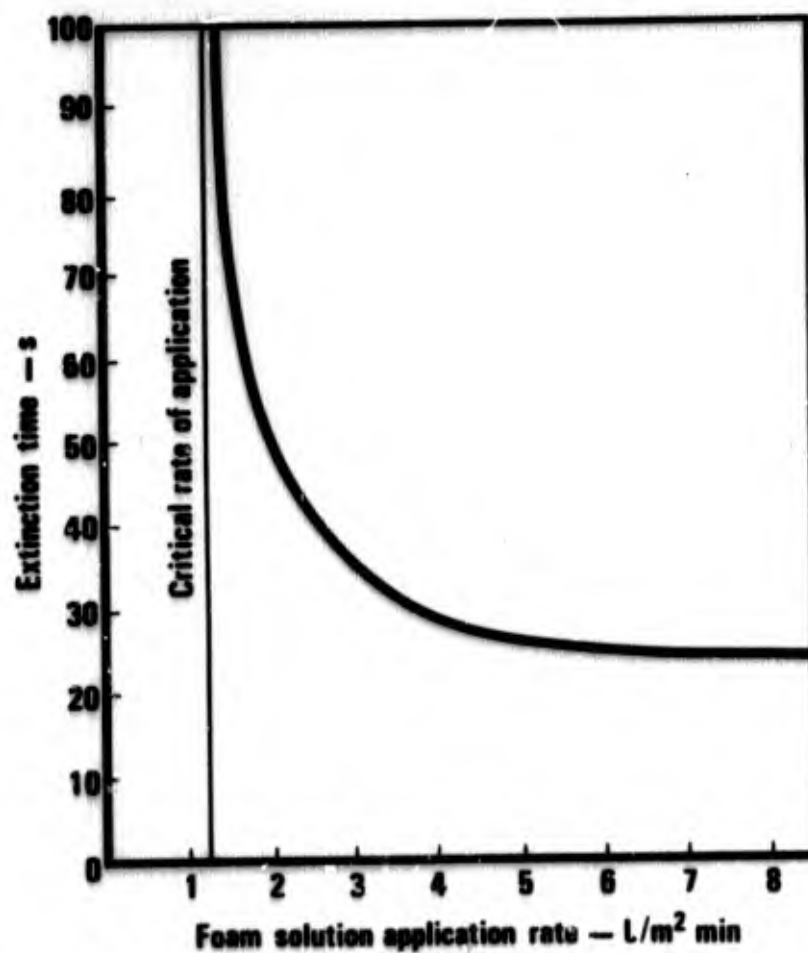


Fig.4 Extinction of Avtur fire with fluoroprotein foam - time - rate curve

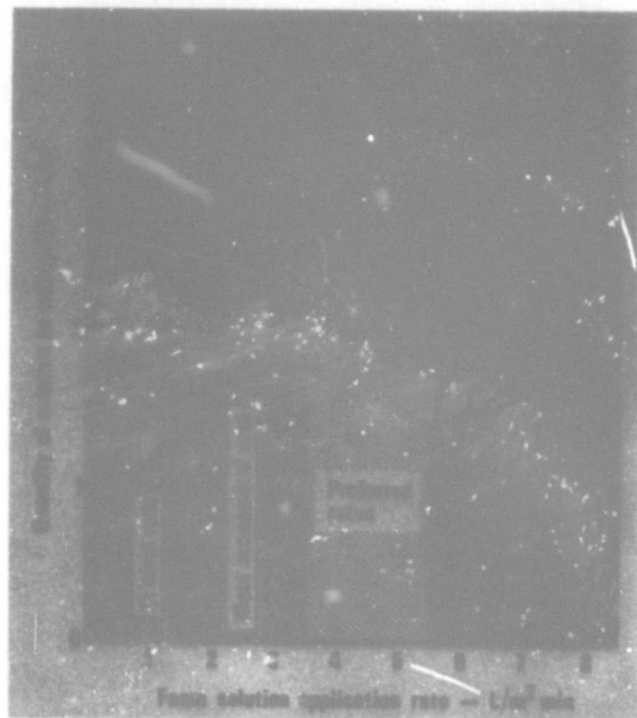


Fig.5 Extinction of Avtur fire with fluoroprotein foam - quantity - rate curve

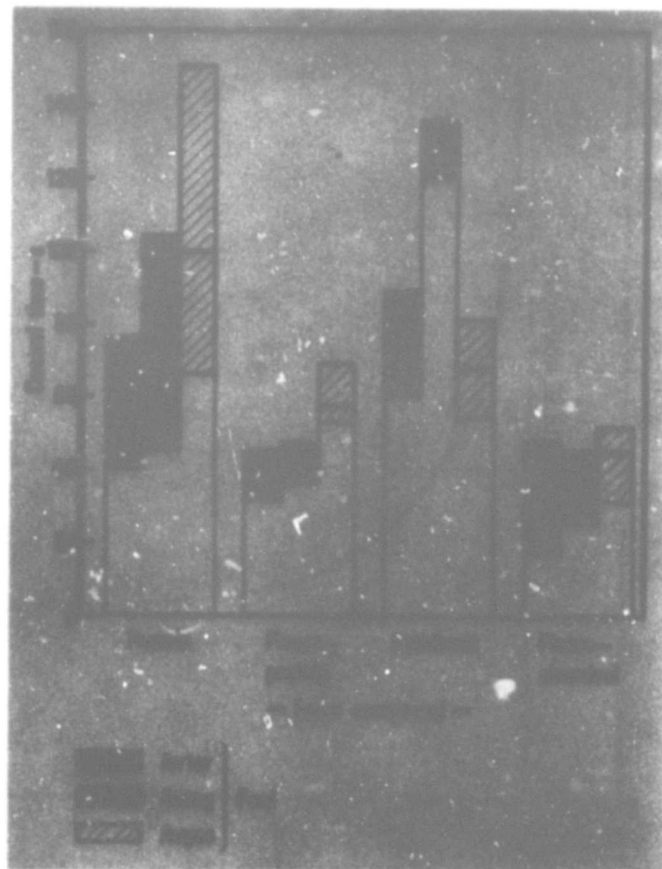
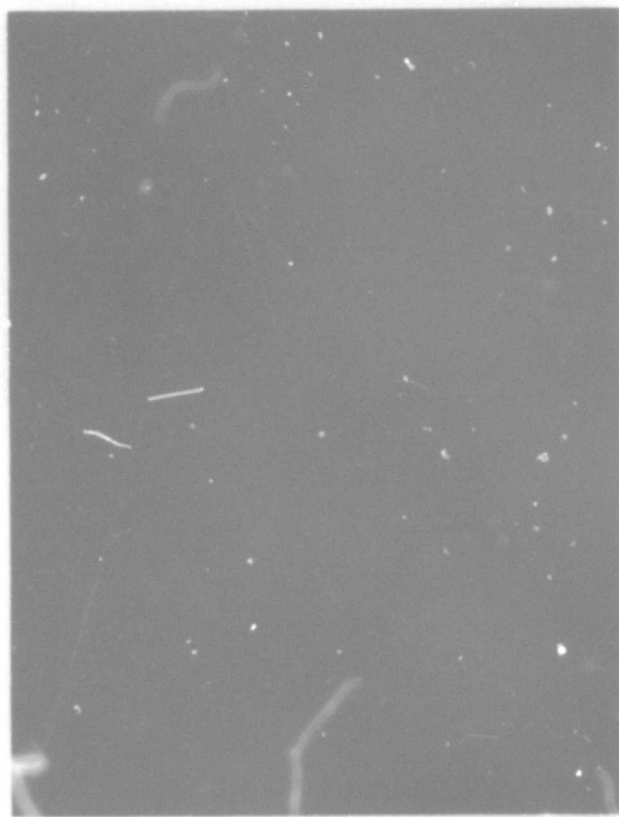


Fig.6 Comparison of different foams controlling aviation fires



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Fig.7 Comparison of different foams extinguishing aviation fires

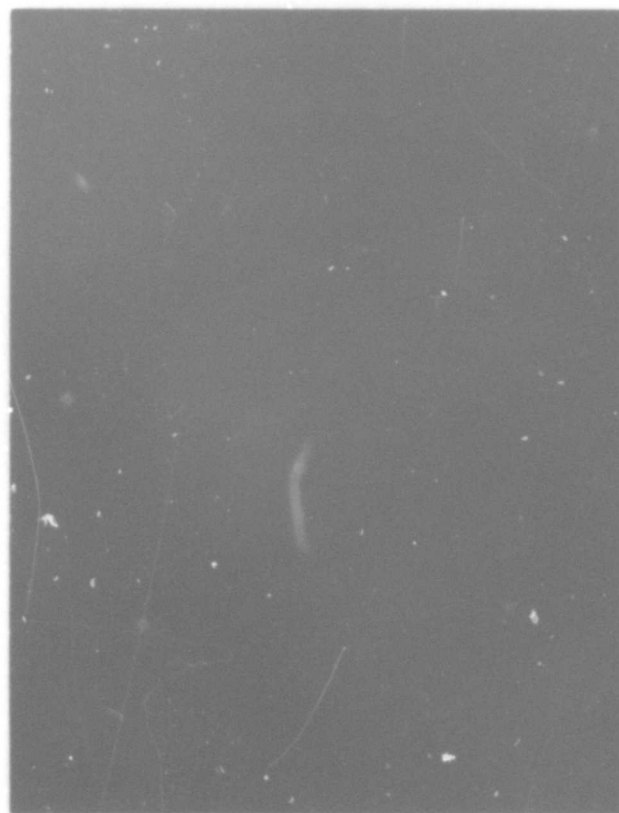


Fig.8 Comparison of burn-back of different foams on aviation fires

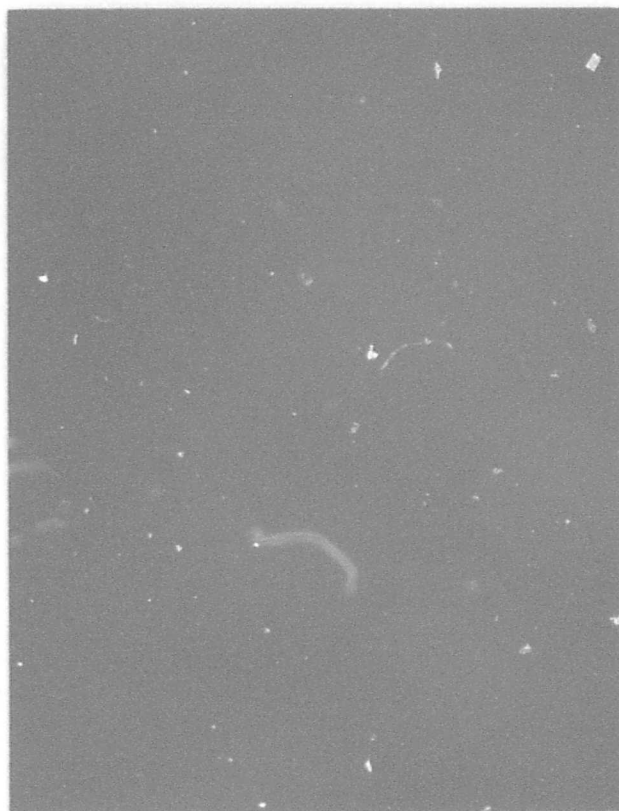


Fig.9 Radiation up-wind of petroleum fires

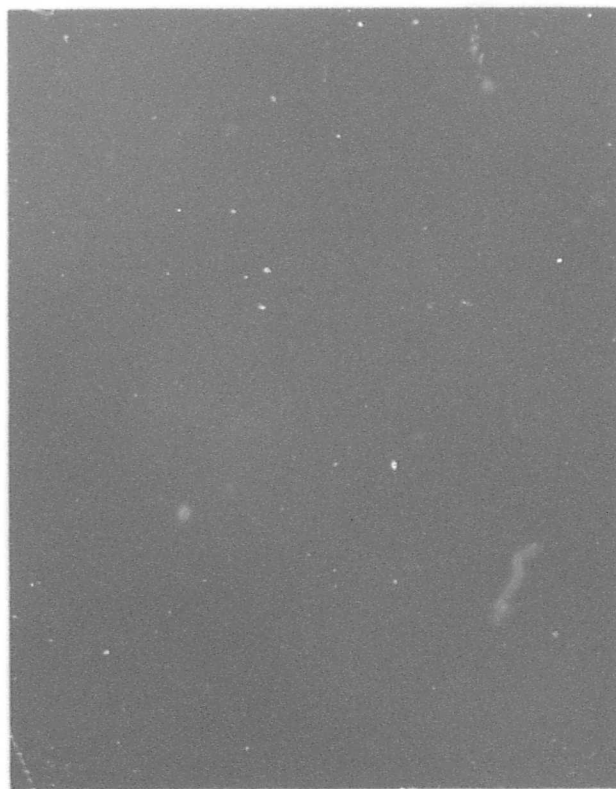


Fig.10 Control of jet A fires with protein foam using four different branchpipes

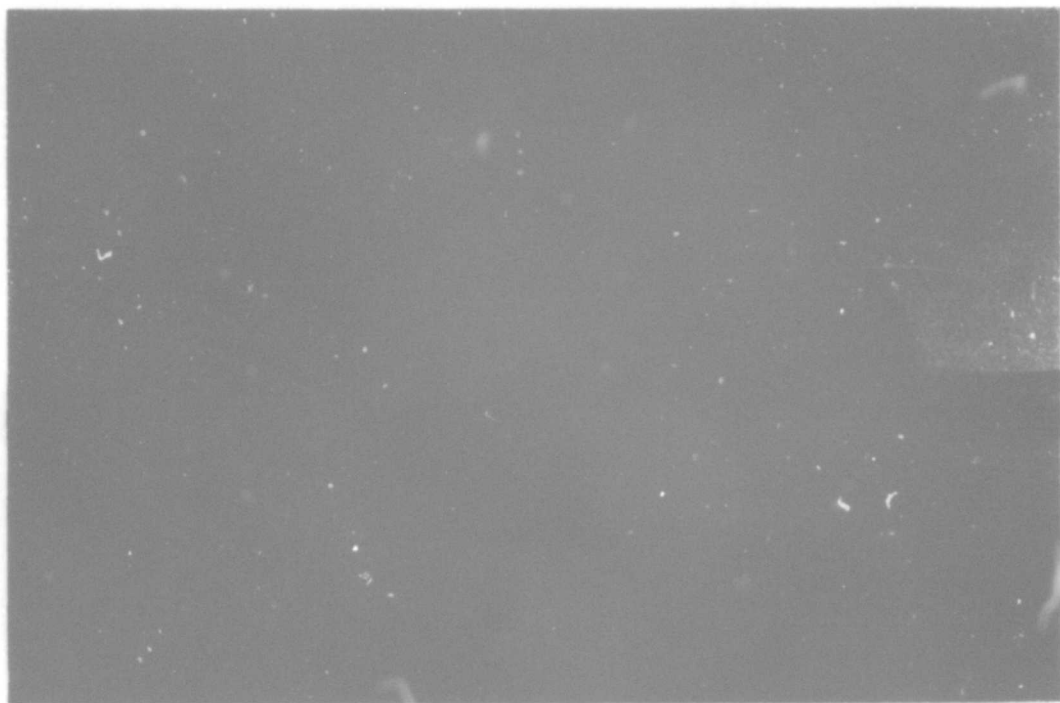


Fig.11 Chubb "Pathfinder" aircraft crash tender

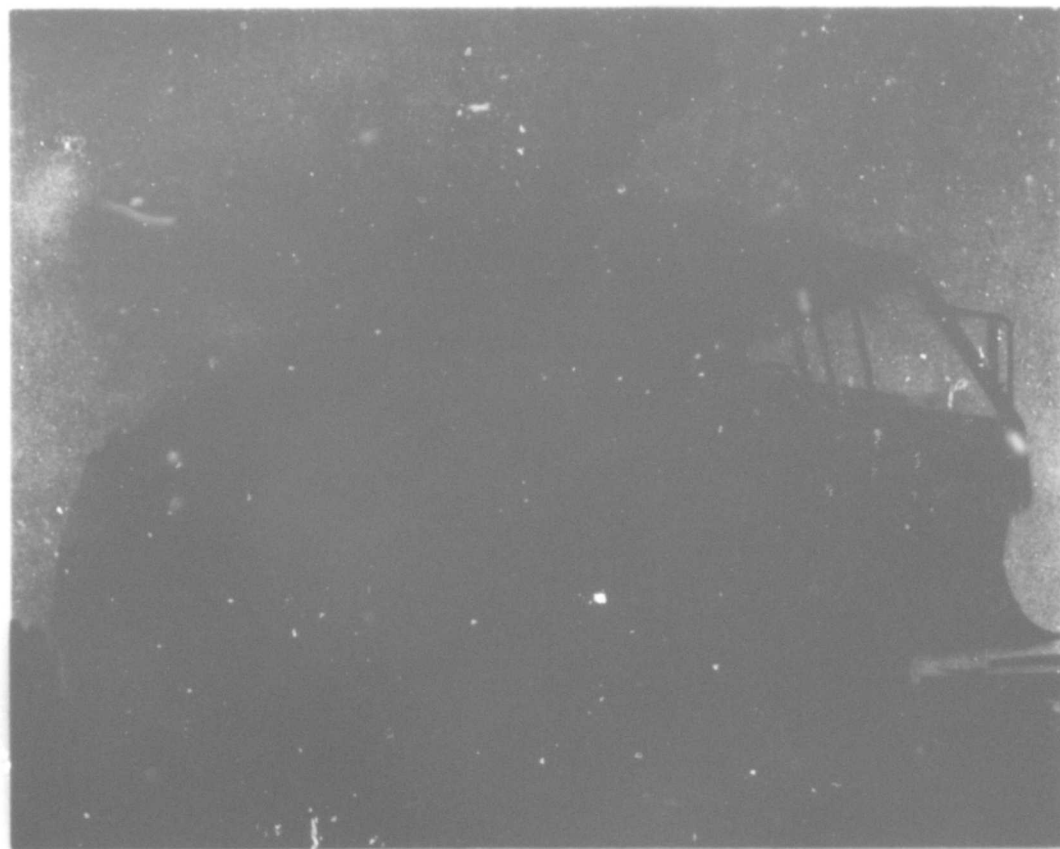


Fig.12 Close-up view of "Pathfinder".

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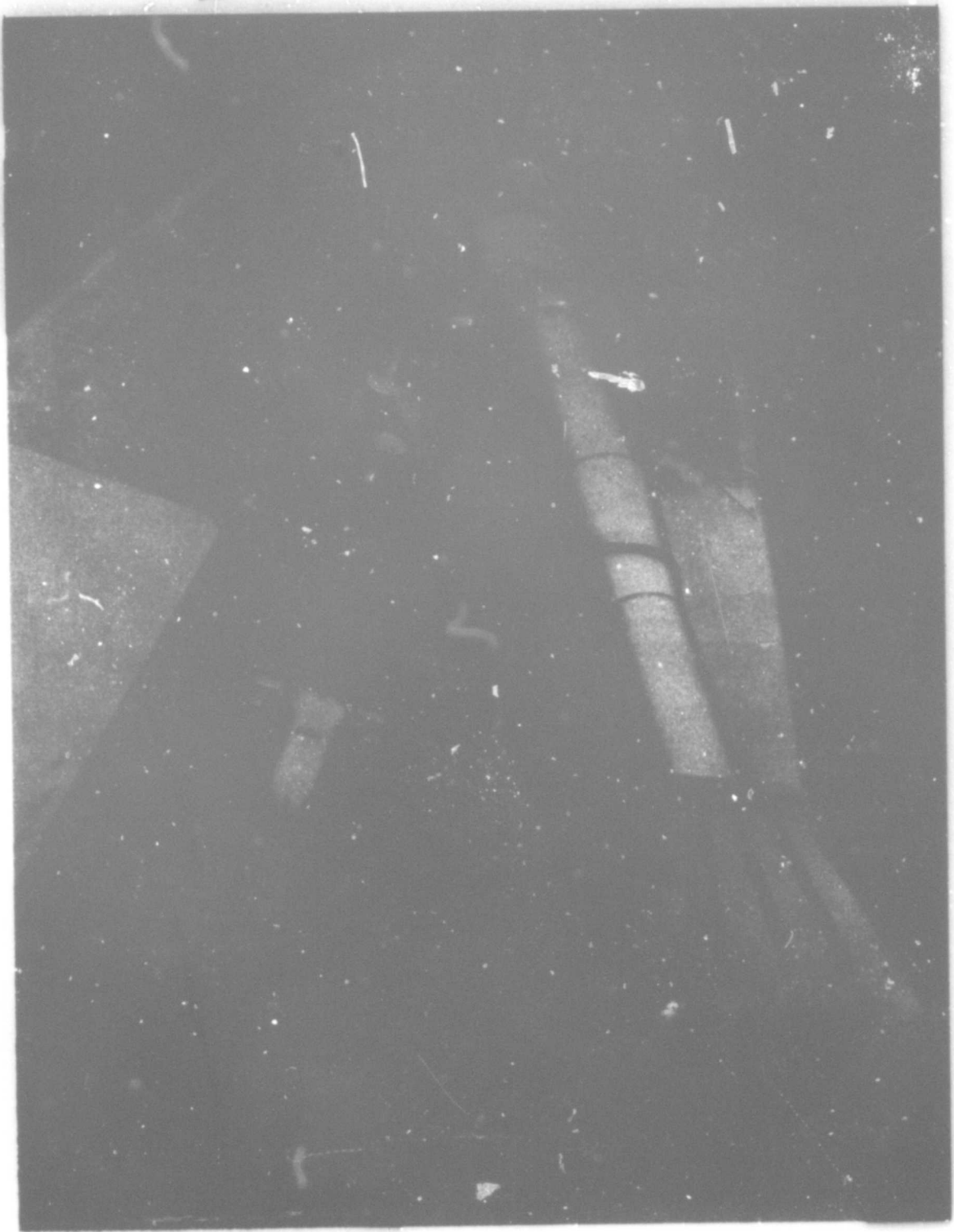


Fig.13 Close-up view of monitor showing variable flaps to orifice.

DISCUSSION – PAPER 22

Mr Hewes: Should more use be made of the air cushion vehicle for an airport crash fire? Helicopters have not proved to be of much advantage and are very expensive to operate.

Mr Nash: My impression is that the air cushion vehicle would only show an advantage in situations where the airport was adjacent to swampy or tidal areas where the wheeled vehicle could not go. We all know of airports in this type of situation – Boston, Mass. or Thorney Island, UK. Where the airport is entirely land-based, particularly in built-up areas, the wheeled vehicle would be likely to be much more manageable for fires off the airport. For fires on the airport I doubt whether the cushion vehicle would show a material advantage over the wheeled vehicle, and might well suffer greater wear and tear to the skirts which would render it more costly to maintain – but I have no figures to support this view.

Mr Hewes: The critical area for fire apparatus would seem to be in the airport area; in other regions you are much more likely to have severe structural failures.

Mr Ansart: L'utilisation des aéroglisseurs a été envisagée en France mais nous nous sommes rapidement heurtés au problème du coût. En effet, à prix égal la charge utile de ces engins est de 10 à 15 fois inférieure à celle des véhicules conventionnels.

Mr Nash: Thank you. It is interesting to know of an actual cost assessment which has been carried out. This bears out my impression that the application of air cushion vehicles is likely to be restricted to special cases as described in the previous answer.

Mr Hayward: Whilst I am full of praise for the work that scientists are performing in their endeavours to evaluate fire extinguishing agents, I am most concerned to find serious conflicts in their respective findings.

Mr Nash: The performance of fire-fighting agents is dependent upon many factors including, above all, the effect of rate of application and the type of fuel being considered. Unless all these factors are clearly expressed, there is likely to be an apparent discrepancy in the results produced. For example, dry powders are sensitive to the particle size and particle size distribution. The foaming agents are sensitive to the nature of the flammable liquid being extinguished, and particularly whether it contains any water-miscible admixtures. The foams, as permanent sealing agents, are capable of sealing fires with potential re-ignition sources whereas the dry powders and vaporising liquids (halons) do not do so. The performance of an agent must therefore be read in terms of the test method used.

We prefer (J.F.R.O.) to make our comparisons of foaming liquids at the most economical rate of application to free-surface fires without distractions, on the appropriate fuel. We have also used this method for dry powders, as well as using a laboratory method in which powder is fed into a gaseous fuel (propane) which is burning continuously at a downward facing jet with a diffusion flame. The laboratory method gives results which are broadly in line with practical fire results, but tends to reduce the scale of performance differences.

In short, the method of performance measurement must bear a known relation to actual fire usage conditions.

CHARACTERISTICS OF HALON 1301 DISPENSING SYSTEMS FOR AIRCRAFT CABIN FIRE PROTECTION

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SUMMARY

The Federal Aviation Administration is conducting a multifaceted experimental program at its National Aviation Facilities Experimental Center directed toward increasing passenger survivability in air transport cabin fire. One approach being investigated is a cabin fire protection system using Halon 1301, an extinguishing agent previously tested and shown to be effective in suppressing and controlling fires in a simulated transport cabin section and a cargo compartment.

Tests were conducted in an obsolete but completely furnished DC-7 passenger cabin equipped with two candidate Halon 1301 dispensing systems; modular nozzle and perforated tube. Under no-fire conditions, continuous measurements were made of the Halon 1301 concentration at approximately 20 locations; measurements were also made of temperature, noise, pressure, and visibility.

The modular nozzle system was judged to be best by virtue of its producing more rapid and effective agent distribution resulting in greater potential fire protection capability. Installation of the agent dispensers for both systems along the ceiling minimized the known possible transient adverse effects upon passengers from agent concentration overshoot, discharge noise and overpressure, and reduced temperature. Halon 1301 was found to rapidly permeate all cabin airspaces, including those shielded from the discharge streamlines.

The effect of agent leakage through opened emergency exits was investigated. It was determined that even under such unfavorable conditions of operation a high-rate discharge system would provide a significant degree of inerting protection over the normal evacuation period of several minutes.

INTRODUCTION

Cabin Fire Scenarios

The incidence of cabin fires in commercial transport aircraft can be divided into three general categories: (1) postcrash, (2) in-flight, and (3) ramp.

The large majority of occupant fatalities or injuries related to the hazards arising from a cabin fire occur in the postcrash category. An analysis of 16 impact-survivable postcrash fires by the Aerospace Industries Association of America (AIA) in 1968 indicated that for most cases the cabin was set afire by flames originating from a large external fuel fire entering the cabin through a rupture or open doors, while the remainder of the fuselage was otherwise intact (reference 1). More recent examples of impact-survivable cabin-fire accidents of U. S. air carriers are as follows: (1) United Airlines 737 at Chicago on December 8, 1972, (2) North Central DC-9 at Chicago on December 20, 1972, (3) Trans World Airlines 707 at Los Angeles on January 16, 1974, (4) Pan American Airlines 707 at Pago Pago on January 30, 1974, and (5) Eastern DC-9 at Charlotte on September 11, 1974. These five accidents have in common the fire destruction of the cabin interior, although the fuselage impact damage ranged from minimal, for the North Central DC-9 and TWA 707, to complete multiple separation for the Pan Am 707 and Eastern DC-9. Thus, the former accidents are those in which additional fire protection measures would have been of most benefit. Impact-survivable postcrash cabin fires involving U. S. air carriers appear to occur at the rate of about one or two per year.

The majority of in-flight fires occurring in the occupied sections of commercial transports have originated in either the galley or lavatory areas and have been detected early and extinguished with minimal hazard. The occupants of an airplane provide excellent early fire detection and, until the Varig 707 accident near Paris on July 11, 1973, (reference 2) the known occurrence of an uncontrollable in-flight fire originating in an occupied area was practically nonexistent. This fine record on the control of small fires can be at least partially attributed to Federal Aviation Administration (FAA) flammability

regulations for cabin interior furnishings and materials that were made more effective on May 1, 1972, by requiring that cabin materials be "self-extinguishing" in a vertical orientation after ignition by a small fire (reference 3) such as exists in most in-flight or ramp fires. However, experience shows that flame retardant materials alone cannot prevent flame spread under high energy in-flight, ramp, or postcrash ignition sources.

The third category of cabin fires is the ramp fire. This fire occurs when the aircraft is parked at an airport ramp and is being serviced or left unattended. Recently, ramp fires have either originated from faulty electrical circuits or devices, ignition of organic deposits in oxygen systems during emergency oxygen recharging operations, or have been of unknown cause (reference 4). An example of the latter was the TWA L-1011 cabin fire at Boston on April 20, 1974, (reference 5). Although furnished and lined with improved materials, the passenger cabin of this airplane was destroyed by a fire of unknown origin (no aviation fuel involvement) and vividly demonstrated that even flame retardant polymeric materials will indeed burn completely when exposed to a sufficiently intense ignition source. During the past 5 years U. S. commercial transport cabins have been destroyed by ramp fires at the rate of about one per year. Some improvement in this type of fire experience may be expected from the use now of safer cabin interior materials.

Current FAA Cabin Fire Programs

The FAA is conducting both in-house and contractual efforts directed toward the objective of increasing occupant survivability in an accidental cabin fire. These efforts are in direct support of proposed FAA regulations or consist of evaluations of fire protection systems or concepts. Two contractual efforts are presently active: (1) the Bureau of Standards is investigating the flash fire propensity of cabin interior materials, and (2) a mathematical modeling of cabin fires is under development at the University of Dayton. In-house studies are conducted at the National Aviation Facilities Experimental Center (NAFEC) and presently consist of (1) developing procedures for assessing the toxic gas and smoke hazards from burning cabin interior materials (the FAA has recently announced its consideration of the establishment of toxic gas and smoke emissions regulations (references 6 and 7)), (2) investigating compartmentation concepts to confine and control the spread of fire, and (3) determining the characteristics of Halon 1301 systems for passenger cabin fire protection - the subject of this paper.

DISCUSSION

Halon 1301

Halon 1301 chemically is bromotrifluoromethane, CBrF_3 . Under normal atmospheric conditions, Halon 1301 is a colorless, odorless, electrically nonconductive gas with a density approximately five times that of air. Halon 1301 liquifies upon compression and is stored and shipped in this condition. A list of some important properties of Halon 1301 is given in table 1.

TABLE 1. PROPERTIES OF HALON 1301 (reference 8)

Chemical Name	Bromotrifluoromethane
Chemical Formula	CBrF_3
Molecular Weight	148.9
Boiling Point at Atmospheric Pressure	-72°F
Vapor Pressure at 70°F	199 psig
Liquid Density at 70°F	97.8 lb/ft ³
Superheated Vapor Density at 70°	0.391 lb/ft ³
Heat of Vaporization at Boiling Point	51.08 Btu/lb

Halon 1301 is an effective fire-extinguishing agent against surface flaming on solid materials in contrast to deep seated smouldering, as well as fires involving flammable liquids or gases. It is particularly attractive for use in total flooding extinguishing systems which consist of the release of a predetermined amount of agent into an enclosure to develop a "uniform" extinguishing concentration with air throughout the enclosure. The advantages of total flooding Halon 1301 systems are: (1) compact storage volumes, (2) low vision obscuration, (3) lack of particulate residue, (4) rapid mixing with air, (5) accessibility to blocked or remote spaces, and (6) low toxicity of the extinguishing (undecomposed) atmosphere (reference 9). For extinguishment of surface flaming from cellulosic and plastic materials, a Halon 1301 concentration of 5 percent is recommended (reference 10), although extinguishment is attained with concentrations as low as 3 percent (reference 9).

It appears that Halon 1301 extinguishes by a chemical action. The halogen compound reacts with the transient products of the combustion process. This action is in contrast to the usual mechanisms of either cooling, oxygen exclusion, or separation of fuel and oxidant for the common extinguishants. As such, Halon 1301 is much more effective than carbon dioxide (CO₂), nitrogen, or water vapor in quenching the flames of hydrocarbons and other gaseous fuels (reference 11). In total flooding, Halon 1301 is three times as effective as CO₂ on a unit weight basis (reference 12).

When used properly under the guidelines established by the National Fire Protection Association (NFPA), it appears Halon 1301 can be safely used in occupied areas (reference 10). However, some toxicity studies have indicated a danger "under the worse conceivable circumstances" (reference 13). Utilization of Halon 1301 to extinguish a fire may create a hazard to occupants from either the virgin agent or the decomposition products of agent exposed directly to the fire. Usually, exposure to the virgin agent is of less concern than is exposure to the decomposition products. Based on medical research involving both humans and test animals, NFPA recommends that occupant exposures to Halon 1301 concentration levels of 7 percent or less not exceed 5 minutes (reference 10). For the majority of postcrash fire accidents, the evacuation of passengers from a commercial transport is completed well before the recommended Halon 1301 exposure time limit.

Absolute quantification of the hazard associated with Halon 1301 decomposition on exposure to a flame is impossible because of the infinite number of possible fire descriptions. It is known, however, that the primary decomposition products are hydrogen fluoride (HF) and hydrogen bromide (HBr), and that their levels will depend on the area of the flame, the concentration of Halon 1301, and the time during which the agent is exposed to flame. Obviously, in order to minimize decomposition, rapid detection and rapid agent discharge is highly desirable.

FAA Experience with Halon 1301

The selection of Halon 1301 as a candidate extinguishant for cabin fire control was based in part on the favorable results of earlier NAFEC fire test programs. Marcy conducted Halon 1301 fire extinguishing tests in a cabin mockup (reference 14). Using a Halon 1301 design concentration of 5.8 percent, a urethane seat cushion fire, which in a previous test had produced a flashover condition in only 2.6 minutes, was quickly extinguished by a high-rate discharge of agent when a recurrent flashover condition appeared imminent, and various attempts to reignite the foam were unsuccessful. In another test, it was demonstrated that a cabin galley curtain could not be ignited with a propane burner in a 3.9-percent Halon 1301/air mixture. An identical curtain tested in air was completely consumed by flames when ignited with the burner. Gassmann and Hill demonstrated the effectiveness of Halon 1301 in combating cargo compartment fires by conducting tests in a 5000-ft³ C-130 fuselage section (reference 15). Halon 1301 design concentrations as low as 3 percent were shown capable of extinguishing the flames from an excellent fire, preventing flashover, and controlling the continuing smoldering condition for a 2-hour period. Even earlier, as far back as 20 years ago, FAA had gained considerable experience in the development of equipment and specialized techniques for evaluating high-rate discharge systems utilizing Halon 1301 for protecting air transports against in-flight engine fires (reference 16). The derivation of present regulations requiring such fire protection has established a precedent facilitating consideration of similar solutions to the problem of cabin fires.

General Description and Purpose of Subject Study

The subject study was undertaken to answer some fundamental questions about the distribution of Halon 1301 in the main cabin of a transport aircraft from an overhead dispensing system. Utilizing unique continuous and highly responsive gas analysis equipment, extensive measurements were made of the rapidly changing concentrations of agent following discharge for a period of 10 minutes. The majority of tests was conducted in a closed cabin. The primary objective was to develop an agent dispensing system that would rapidly distribute Halon 1301 throughout an aircraft cabin in concentrations sufficient to extinguish fires, and without producing peak concentrations or other effects that would be intolerable to occupants. A secondary objective was to examine the effect of open emergency exits on the retention of agent in the cabin air space.

DC7 Test Article Description

The test article used for this investigation was an obsolete DC7 fuselage with a completely furnished passenger cabin (figure 1). The fuselage was housed inside a heated building. The length of the protected cabin was approximately 72 feet and the volume of air space was calculated to be 4,000 cubic feet. For an enclosure of this size, the weight of Halon 1301 required to produce a uniform volumetric concentration of 5 percent is 80 pounds. This value is based on an equation recommended by NFPA that compensates for agent loss through small openings during discharge overpressure by assuming that the agent was lost at the design concentration (reference 10).

Candidate Agent Dispensing Systems

Two basically different Halon 1301 dispensing systems were evaluated: (1) modular and (2) continuous perforated tube.

The modular system was designed so that only each discharge spreader head was visible from within the cabin. This feature could probably be configured to meet the aesthetic demands of a production installation. Agent discharges through a cylindrical spreader head which provides a radial horizontal pattern designed to minimize direct agent impingement upon passengers. A drawing of the agent discharge spreader head is shown in figure 1A, and the four module locations within the DC7 cabin are illustrated in figure 1B. The cabin was divided into four equivalent volumetric zones and one module was placed at the approximate center of each zone. In an operational system, the storage containers and actuating devices would be placed in the void space between the drop ceiling and fuselage skin.

In concept, the perforated discharge tube promised a more effective and safe "continuous" release of Halon 1301 along the entire fuselage length in contrast to the point discharge from the modular system. The perforated tube system is illustrated in figure 1C and consisted of two main elements: (1) 3/4-inch inner tube containing two 0.0468-inch-diameter through holes rotated 90° every 6 inches of tube length (four holes per foot) and (2) 1-inch outer tube containing two 0.187-inch-diameter through holes rotated 90° every 3 inches of tube length (eight holes per foot). The inner tube is designed to serve as a plenum chamber discharging agent from the relatively small 0.0468-inch-diameter orifices at critical flow conditions (reference 17). When discharge was initiated, equivalent quantities (40 pounds) of Halon 1301 were simultaneously supplied to each end of the inner tube from pneumatically-activated storage containers. The perforated discharge tube was about 70 feet long, extending from fuselage station (FS) 143 to 976 (figure 1B).

As recommended by NFPA (reference 10), each storage container was "super-pressurized" with nitrogen to a pressure of 360 pounds per square inch gage (psig) at 70° Fahrenheit (F). Additional pressurization above the agent vapor pressure (199 psig at 70°F) helped to maintain the agent in the liquid state during discharge.

Instrumentation

The concentration of Halon 1301 was measured with two similar analyzers, Statham Models GA-2 and GA-2A, each containing 12 channels for a total capability of 24 channels. Each channel provided a continuous concentration measurement at a relatively fast response rate; 95-percent full-scale was attained in 0.10 second (reference 16). The Halon 1301 concentration in air was determined by measuring the differential pressure across a porous plug maintained at constant flow by a downstream critical orifice (reference 18). This instrument had also been used to measure the concentration of CO₂, methyl bromide, and bromochloromethane, each separately in air, and in principle, can be used to measure the concentration of any binary gas mixture. A least-squares power law curve fit was generated for each channel in the Halon 1301 concentration range of zero to 20 percent, using five certified Halon 1301-air calibration mixtures. Sampling lines were made of identical 10-foot lengths of 1/4-inch tubing in order to equalize the sampling lag time for each channel.

The cabin air temperature was continuously measured with 30 American wire gage (AWG) iron-constantan thermocouples.

Two pressure transducers, zero to 0.10 psig and zero to 5.0 psig, continually monitored the cabin air pressure. The pressure in the Halon 1301 storage container was also measured, using a zero to 500 psig transducer, to provide an indication of the time required to expel the agent into the cabin.

The noise created by the rapid discharge of 80 pounds of Halon 1301 into the cabin was measured with a Bruel and Kjaer precision sound level meter, type 2203 using a condenser microphone, type 4131 and windscreen, type UA 0082. This is an internationally standardized instrument, fulfilling the requirements of the International Electrotechnical Commission.

TEST RESULTS AND ANALYSIS

A total of 17 tests were conducted and are reported in detail in reference 19. The following is a discussion of the most important results.

Discharge Time

When designing a fire suppression system, an important criteria is the time it takes to discharge the agent and achieve a desired concentration in the protected volume. This important parameter has been defined and measured a number of different ways. For the total flooding discharge into an enclosure, an appropriate definition of an "effective discharge time" is "the time required to complete the desired mixing of agent with air in all spaces in the enclosure." As defined herein "effective discharge time" can be determined by measuring the agent concentration histories at a number of representative cabin locations and observing when all the profiles become invariant with time. In this study "effective discharge time" was determined by examining the vertical Halon 1301 distribution near the center of the cabin. Eight sampling probes were arranged on a vertical line at the fuselage symmetry plane at FS 540.

A plot of the vertical Halon 1301 concentration profile in the closed cabin at selected times immediately following activation of discharge of the modular suppression system is shown in figure 2. From the profile at 1 second, it appears as if the agent fills the cabin in a manner like a curtain dropping

from the ceiling. By 2 seconds, the agent has covered the symmetry plane from ceiling to floor and the shape of the profile is established. From 2 to 4 seconds, the concentration decreases slightly as the agent permeates the remaining cabin spaces, but the shape of the profile remains unchanged. After 4 seconds, the concentration also becomes invariant, indicating that the "effective discharge time" was 3 to 4 seconds. Once the cabin is completely flooded with agent and mixing is completed, it is evident that there is stratification with the concentration at the ceiling roughly 2 percent less than at the floor and that the concentration of Halon 1301 exceeded the required extinguishing level throughout the cabin.

In contrast, the "effective discharge time" for the perforated tube system was significantly longer (figure 3). After 20 seconds the shape and magnitude of the agent profile becomes invariant, indicating that the "effective discharge time" was 20 to 25 seconds, compared to 3 to 4 seconds for the modular system (figure 2). In addition, it is apparent from a comparison of the profiles after completion of mixing in figures 2 and 3, that the degree of agent stratification was greater for the perforated tube system. Although the average agent concentration in the cabin produced by both systems was about the same, the modular system provided a higher ceiling concentration and lower floor concentration than did the perforated tube. This relative behavior prevailed for the entire 10-minute test, in spite of the progressive increase in stratification during the test as agent leaked from the cabin. Thus, the modular system distributed the agent more efficiently (faster) and effectively (uniformly) than did the perforated tube system.

The superior performance of the modular system is attributed to its high discharge rate of agent. An indication of the discharge rate for each system was obtained by measuring the drop off in pressure inside the storage containers as the agent was being expelled into the cabin. The storage pressure decreased to an ambient level in 2.5 and 19 seconds after activation of discharge for the modular and perforated tube systems, respectively. Thus, the average discharge rate of agent from the modular system was seven to eight times faster than from the perforated tube, and this value also corresponded approximately to the ratio of "effective discharge times" for the two systems. As previously mentioned, the discharge rate of agent from the perforated tube system is controlled by the choked flow condition through the orifices of the inner tube.

System Effectiveness

In order to further compare the extinguishing effectiveness of the two systems, gas sampling lines were relocated from the symmetry plane to peripheral cabin locations. These locations were at symmetrically opposite sides of the cabin at the ceiling-sidewall juncture, inside the hatrack and adjacent to the sidewall, underneath the hatrack and adjacent to the sidewall, and at the floor-sidewall juncture. For both systems, Halon 1301 concentration histories over the entire duration of the test were identical at locations symmetrically opposite to the fuselage symmetry plane. Furthermore, once the initial mixing of Halon 1301 was completed, it was determined that the concentration remained only a function of elevation and time and was essentially independent of either cabin longitudinal (fuselage station) or lateral location.

A comparison of the Halon 1301 concentration histories produced by the perforated tube system at a number of symmetry plane and peripheral cabin locations at FS 540 is shown in figure 4. A fairly significant overshoot in agent concentration above the design level was experienced during the initial mixing process. This behavior probably indicated the creation of a stagnation region in the inner discharge tube at the center of the cabin (near FS 540), resulting from the convergence of Halon 1301 to this area supplied by storage containers located at each end of the cabin. At these particular measurement locations, Halon 1301 was first detected in 1.5 to 4.8 seconds and achieved a 5-percent concentration in 3.5 to 6.5 seconds. However, at fuselage stations away from the center of the cabin, the increase in agent concentration was generally more gradual and the design level was attained in an asymptotic manner by about 20 - 25 seconds; i. e., consistent with the determination of an "effective discharge time." An exception to this latter trend was experienced at measurement locations in the direct path of discharge streamlines, where brief overshoots in agent concentration similar to those at FS 540 were also experienced.

Figure 5 shows a comparison of the Halon 1301 concentration-time profiles produced by the modular system at a number of sampling locations at FS 540. These curves can be contrasted with figure 4, which is a similar comparison at FS 540 for the perforated tube system. For the modular system, Halon 1301 was first detected in zero to 0.6 seconds and achieved a 5-percent concentration in 0.5 to 1.2 seconds (versus 1.5 to 4.8 and 3.5 to 6.5 seconds, respectively, for the perforated tube system). Even at FS 540 where the maximum discharge rate of agent from the perforated tube was realized, the modular system still dispersed agent and achieved an extinguishing level at peripheral cabin locations more rapidly than did the perforated tube system. Other favorable performance characteristics of the modular system noted by comparing figures 4 and 5 are the more uniform distribution of agent at peripheral cabin locations, evidenced by the close grouping of concentration histories in figure 5, and the less pronounced overshoot in concentration.

Between the modular and perforated tube systems, the greatest difference in the time to build up agent concentration was found to exist at cabin locations shielded from the discharge streamlines; e. g., along the sidewall, immediately beneath the hatrack or near the floor. Figure 6 shows a comparison at these locations of the Halon 1301 concentration histories produced by both systems. A concentration of

5 percent is attained 7.6 and 12.2 seconds sooner for the modular system at sampling locations near the floor (FS 540) and underneath the hatrack (FS 432), respectively. However, once the mixing of agent was completed throughout the cabin in the perforated tube test, the concentration-time curves for the remainder of the test were very similar to those obtained with the modular system.

Adverse Effects on Occupants From Agent Discharge

A cursory evaluation was made of the possible adverse effects on cabin occupants from agent discharge. Those effects examined were high agent concentration, reduced temperature, discharge noise and overpressure, and obscuration of vision.

The Halon 1301 concentration history at the head level of a seated passenger at FS 540 is compared for the modular and perforated tube systems in figure 7. At this fuselage station, located at the approximate center of the discharge tube and also midway between the second and third agent dispersers of the modular system, the greatest overshoot in agent concentration was experienced by both systems. Because of the inferior mixing of agent with air provided by the perforated tube, the overshoot in agent concentration near seated passengers is higher and lasts longer for this system than for the modular system. In either case, the concentration surpassed the "safe" 7 percent level for only an exceedingly short time (see figure 7) compared to the allowable 5-minute period, so that the danger from inhalation of agent in concentrations in excess of 7 percent was probably nonexistent for both systems, although surely less for the modular. The more rapid buildup of fire extinguishing concentrations obtained with the modular system could, in addition, reduce the level of toxic gases produced by burning interior materials and decomposed agent.

Thermocouple measurements were made primarily to determine if occupants might be exposed to drastic reductions in air temperature associated with the rapid vaporization of agent during discharge. A comparison is made in figure 8 of the air temperature at the head level of a seated passenger at FS 540 after initiation of discharge for each of the two systems evaluated. Since a minimal temperature change is desirable, the modular system is clearly more suitable from this respect. The temperature drop from the modular system can be likened to the cooling effect associated with walking into an air-conditioned room on a hot, summer day; whereas, for the perforated tube system, the temperature would be reduced to near or below the freezing point of water. In either case, the temperature change is not very profound, demonstrating that this effect is not an important consideration.

The noise level associated with the rapid delivery of 80 pounds of Halon 1301 into the protected cabin is compared for both discharge systems in figure 9. Discharge from the modular system, which was much faster than from the perforated tube, produced a peak noise level of 120 dB(A), but the noise only lasted about 2 seconds. In contrast, the discharge noise from the perforated tube was much lower (difference in peak levels over 25 dB(A)), but did continue significantly longer. The sound inside the cabin from the discharged perforated tube was likened to a leaking automobile tire, while the 120 dB(A) peak noise level from the modular system corresponds approximately to the sound from a loud automobile horn (reference 20), which might startle an individual, but not affect the hearing threshold (reference 21).

A harmless increase in cabin pressure was measured for several seconds during agent discharge from either system. The peak overpressure from the perforated tube, however, was small (0.0025 psig) compared to that from the modular system (0.033 psig). The net small pressure increase is a consequence of the pressure rise from mass addition which overcompensates for the pressure drop from air cooling.

A rapid, substantial reduction in cabin temperature, as shown in figure 8, can create a fog cloud in the cabin from condensation of water vapor in the air. Visual obscuration can result if the cloud is sufficiently dense. During the course of testing, the ambient relative humidity ranged from 28 to 88 percent. It was observed that the occurrence of visual obscuration was strongly dependent upon the ambient relative humidity. Substantial obscuration inside the cabin followed the discharge of agent when the ambient relative humidity exceeded 70 percent; however, no fog or resulting obscuration occurred at relative humidities of about 50 percent or less.

Effect of Exit Openings on Inerting Protection

If a fire should erupt in the cabin of an airplane following a crash landing or when parked at the loading ramp, the natural instinct of the reacting occupants is to escape from the confined danger through the nearest emergency exit. The extinguishing effectiveness and, more important, inerting capability of Halon 1301 when passengers are departing through the available exits will depend upon the agent leakage rate through these same exits. Conceivably, fire-induced (automatic) agent discharge could occur before or after the opening of the emergency exit(s). These situations were examined by measuring the vertical degradation of agent concentration at five sampling trees (each containing four levels of sampling lines) distributed throughout the cabin.

In one test, the galley door (75 inches by 35 inches) was opened at a time 10 seconds after activation of discharge from the modular system when it was known from prior tests that Halon 1301 total dispersion was completed. Figure 10 contains the concentration histories measured by the symmetry plane sampling

tree at fuselage station 265, located 38 feet forward of the 18.3-square-foot galley door opening. The depletion of Halon 1301 concentration behaved similarly to that measured previously in the closed cabin, but occurred at a significantly accelerated rate. A major reduction in agent concentration was first measured at the sampling location positioned nearest to the ceiling; similar reductions occurred progressively later in the test the nearer the sampling probe location was to the floor. At distances of 72, 52, 32, and 12 inches above the floor, a 3-percent agent concentration was maintained for 28, 50, 90, and 193 seconds, respectively.

The reduction in inerting protection throughout the cabin, as a function of time, resulting from the opening of the galley door is shown in figure 11. The time duration that the Halon 1301 concentration exceeded 3 percent, for each sampling tree, is plotted against the sampling line elevation from the floor. Within the measurement accuracy, the vertical agent profiles at the symmetry plane are identical and thus are independent of relative location to the galley door opening. The Halon 1301 profile adjacent to the galley door has a shape similar to, but slightly lower concentration level than, the symmetry plane profiles. A resemblance of an interface with air above and Halon 1301/air below can be interpreted from the data. The receding movement of the interface is essentially independent of location relative to the leakage opening and is analogous to the top surface of water draining out of a tub. From figure 11, the agent concentration near the floor exceeded 3 percent for about 2.5 minutes longer than it did at the ceiling. (This extended protection at the floor relative to the ceiling may be an asset in cabin protection by retarding fire entry from an external fuel fire burning on the ground).

The reduction in inerting protection resulting from the opening of the four left-hand emergency windows, in addition to the galley door, at 10 seconds after activation of the modular system was also determined. This configuration included all emergency exits on the left-hand side of the cabin. Current FAA regulations require that the evacuation from a completely occupied cabin be effected within 90 seconds using the exits on one side of the airplane. Figure 12 compares the average duration of concentrations in excess of 3 percent at four levels above the floor for the two exit configurations tested. Two important trends are evident. First, the expected increased loss of Halon 1301 through the door and four windows as compared to the door only did not correspond to the increased (79 percent) area. Because of stratification causing a lower agent concentration at the upper cabin levels, less agent was found to have leaked out of the windows than at the galley door lower level. Second, the reduction in inerting time due to the additional four-window area increased progressively toward the floor where, fortunately, the loss tends to be compensated by longer inerting times in this direction. Opening the emergency windows in addition to the door only reduced the inerted level of the cabin by about 10 inches.

Additional tests demonstrated that the loss in inerting protection was minor when the cabin exits were opened before discharge, as compared to after discharge for both types of agent-dispensing systems.

CONCLUSIONS

Based upon the data obtained from the test program, it is concluded that:

1. A Halon 1301 dispensing system similar to the modular system tested and utilizing air turbulence created by rapid agent discharge to insure effective mixing will provide excellent distribution of agent without exceeding the limits of human tolerance for the agent or for the noise, reduced temperature or cabin overpressure resulting from agent discharge.
2. As may be expected, open exits result in a more rapid loss of agent. However, under such adverse conditions, a significant degree of inerting protection will still result for a normal evacuation period of several minutes.
3. A perforated tube type of dispensing system provides a slow discharge and poor distribution of agent in the cabin compared to a modular system.

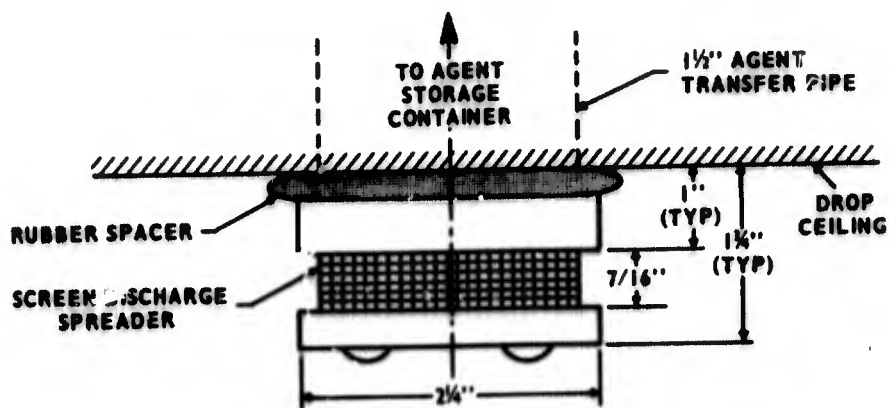
FUTURE WORK

The information provided herein demonstrates the potential fire protection capability of Halon 1301 systems in aircraft cabins and the superior performance of the modular agent dispenser. Future work outlined in reference 22 consists of an assessment under typical full-scale cabin fire conditions of all problems associated with the use of Halon 1301, with emphasis on the decomposition aspects, relative to the hazards of an uncontrolled cabin fire. The degree of cabin protection provided by Halon 1301 against entry of an external fuel fire through a fuselage rupture or open exit will also be determined.

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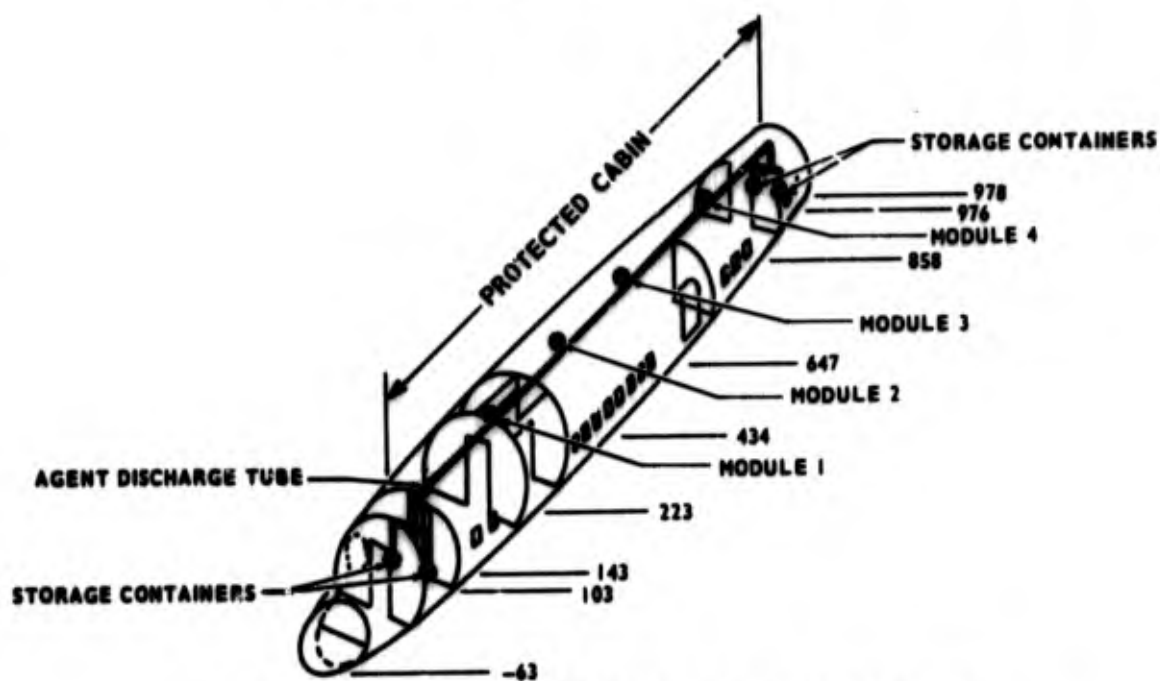
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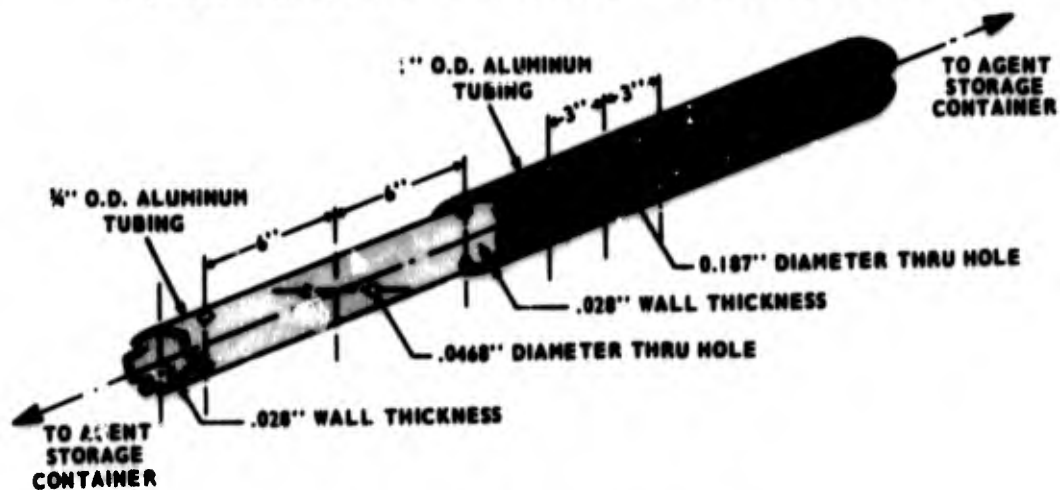


NOTE: 0.690-IN² ORIFICE AREA

A. MODULAR DISCHARGE SPREADER HEAD



B. LOCATION OF DISPENSING SYSTEMS IN PASSENGER CABIN



C. PERFORATED DISCHARGE TUBE

FIGURE 1. MODULAR AND PERFORATED TUBE HALON 1301 DISPENSING SYSTEMS EVALUATED IN DC7 PASSENGER CABIN

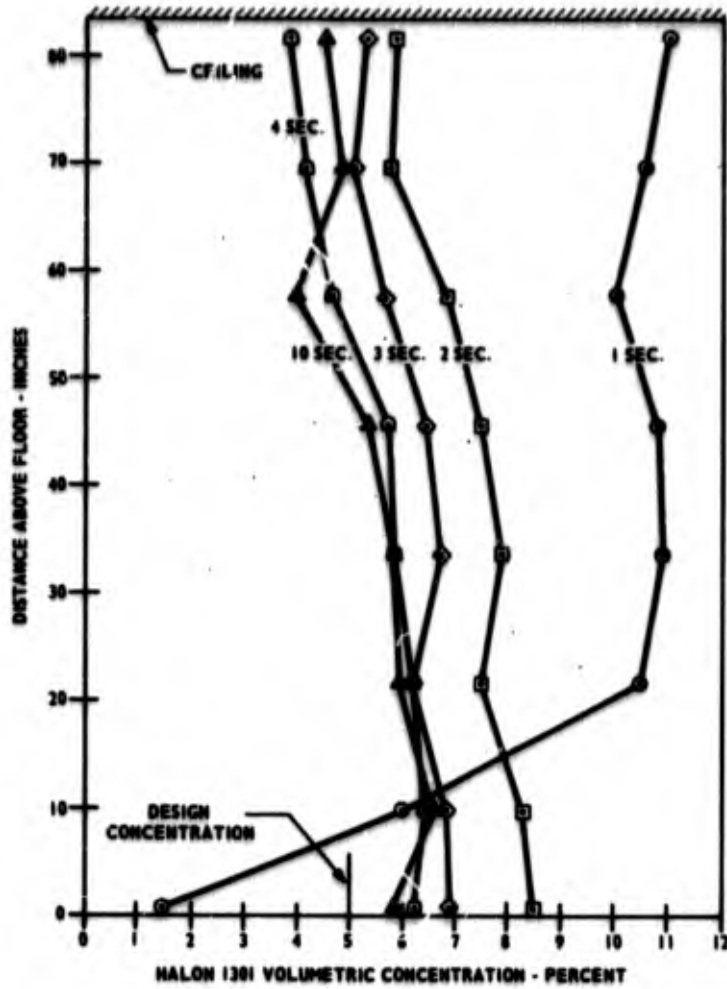


FIGURE 2. VERTICAL HALON 1301 PROFILES AT FUSELAGE STATION 540 AFTER DISCHARGE OF THE MODULAR DISPENSING SYSTEM

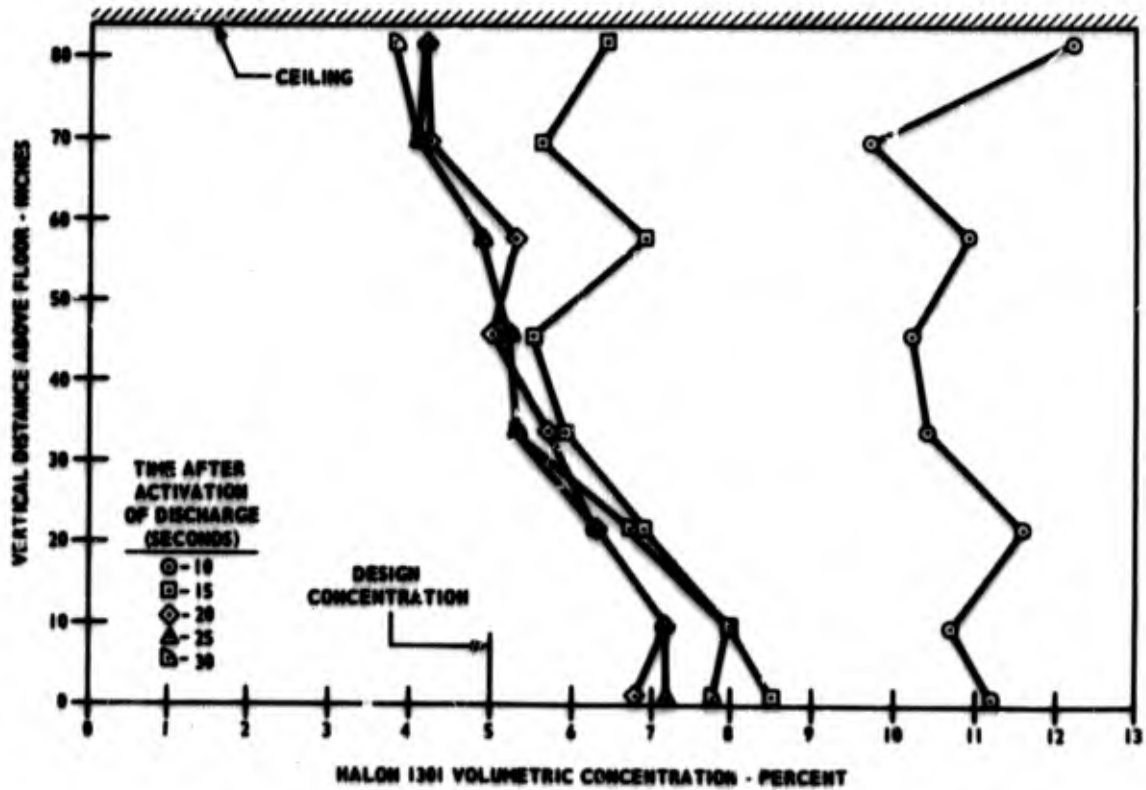


FIGURE 3. VERTICAL HALON 1301 PROFILES AT FUSELAGE STATION 540 AFTER DISCHARGE OF THE PERFORATED TUBE DISPENSING SYSTEM

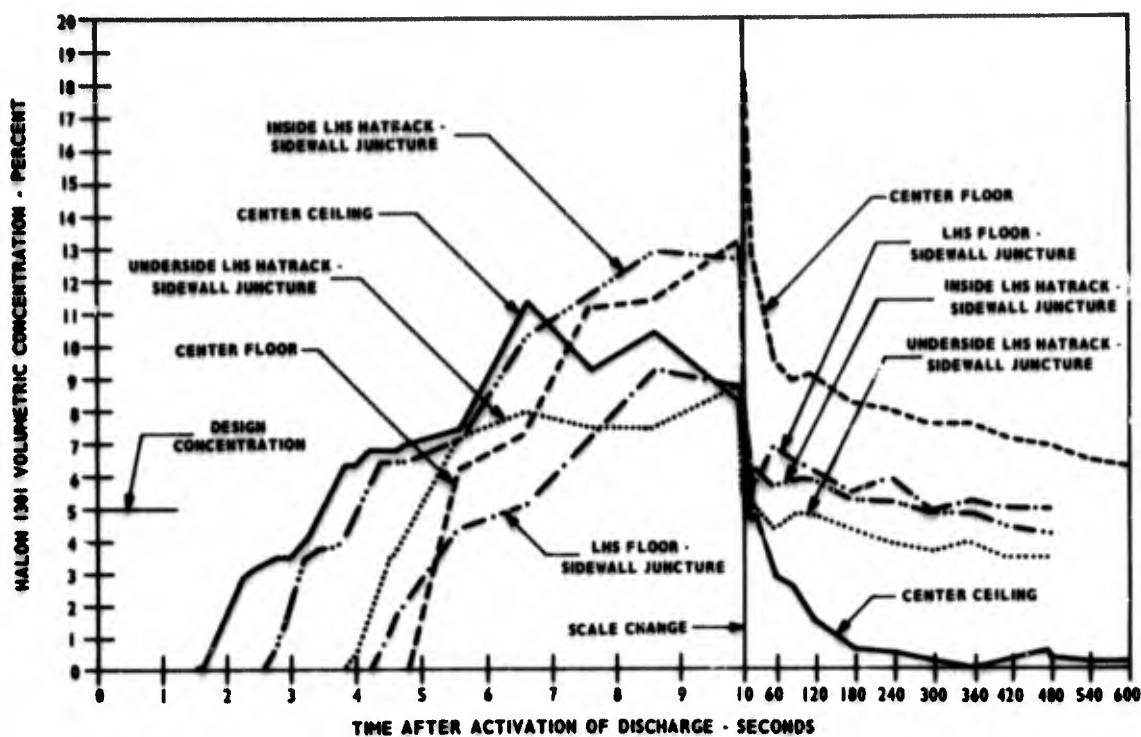


FIGURE 4. HALON 1301 CONCENTRATION HISTORY AT PERIPHERAL CABIN LOCATIONS AT FUSELAGE STATION 540 FOR THE PERFORATED TUBE DISPENSING SYSTEM

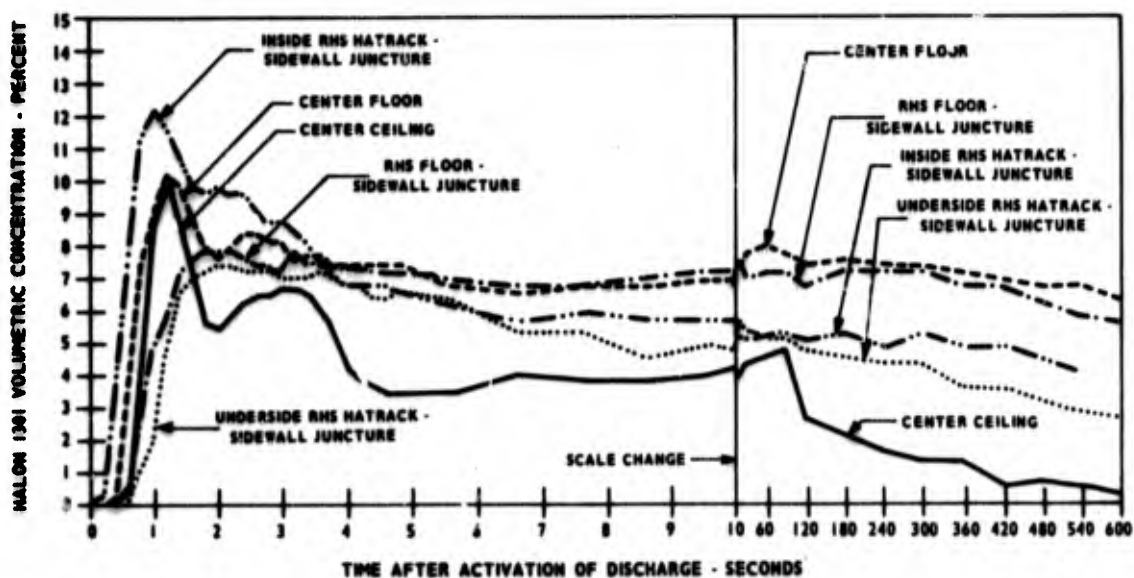


FIGURE 5. HALON 1301 CONCENTRATION HISTORY AT PERIPHERAL CABIN LOCATIONS AT FUSELAGE STATION 540 FOR THE MODULAR DISPENSING SYSTEM

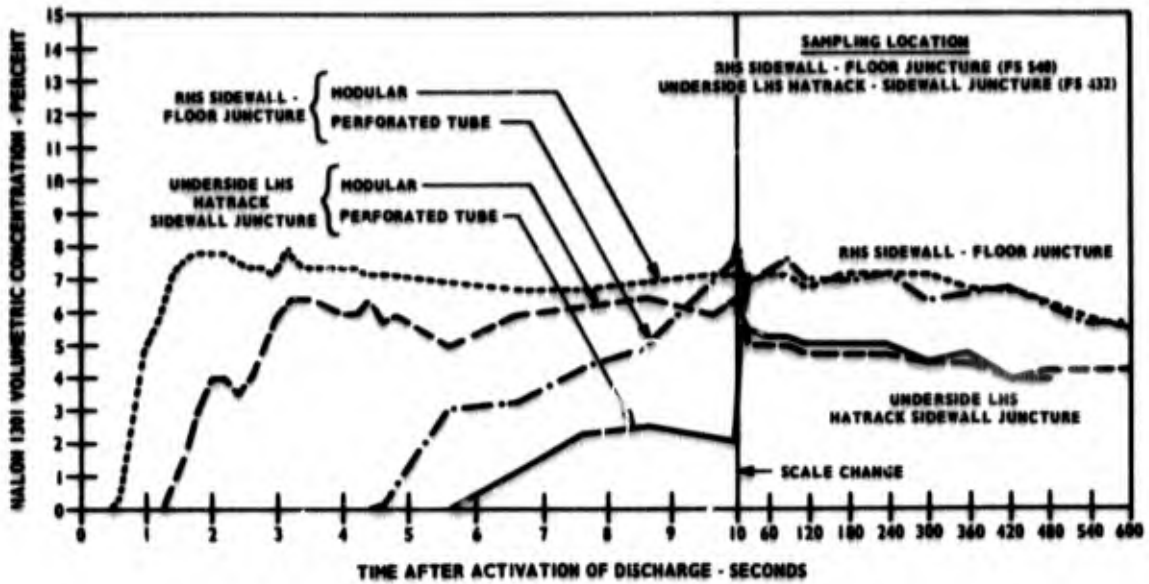


FIGURE 6. AGENT BUILDUP AT CABIN LOCATIONS SHIELDED FROM THE DIRECT DISCHARGE OF AGENT FOR THE MODULAR AND PERFORATED TUBE DISPENSING SYSTEMS

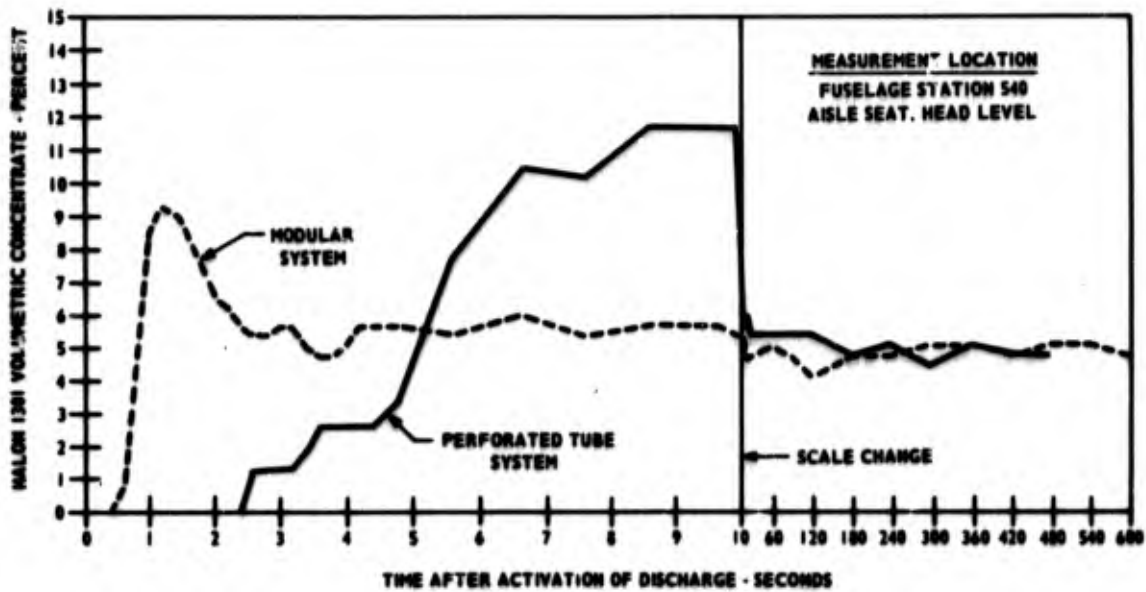


FIGURE 7. MAXIMUM HALON 1301 EXPOSURE LEVEL FOR A SEATED PASSENGER; MODULAR VERSUS PERFORATED TUBE DISPERSMENT

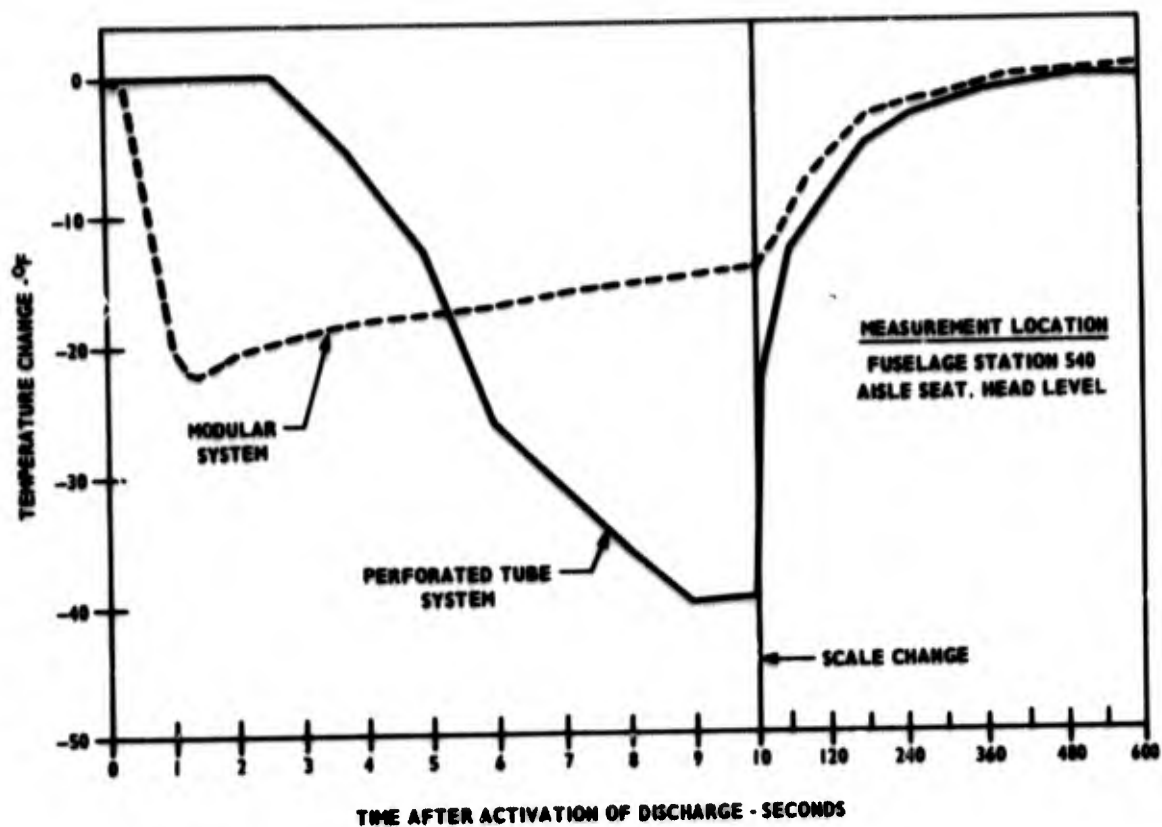


FIGURE 8. MAXIMUM REDUCTION IN AIR TEMPERATURE FOR A SEATED PASSENGER; MODULAR VERSUS PERFORATED TUBE DISPENSEMENT

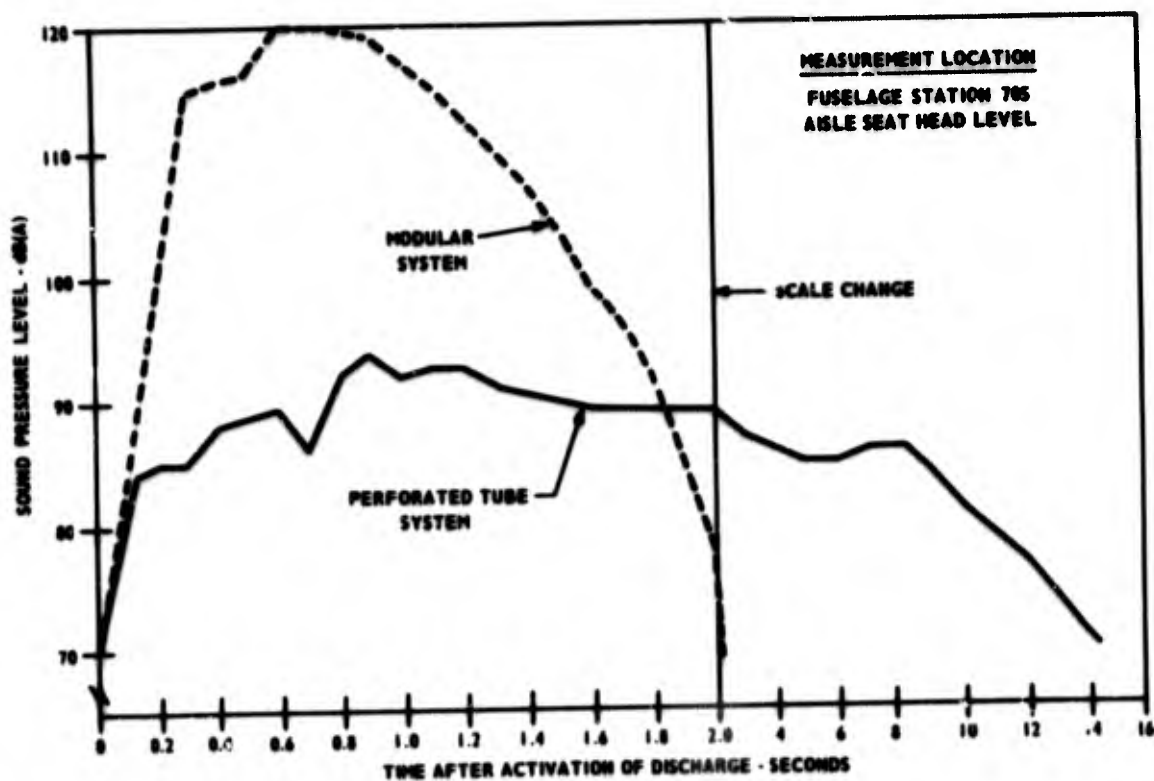


FIGURE 9. CABIN NOISE DURING HALON 1301 DISCHARGE FOR MODULAR AND PERFORATED TUBE DISPENSING SYSTEMS

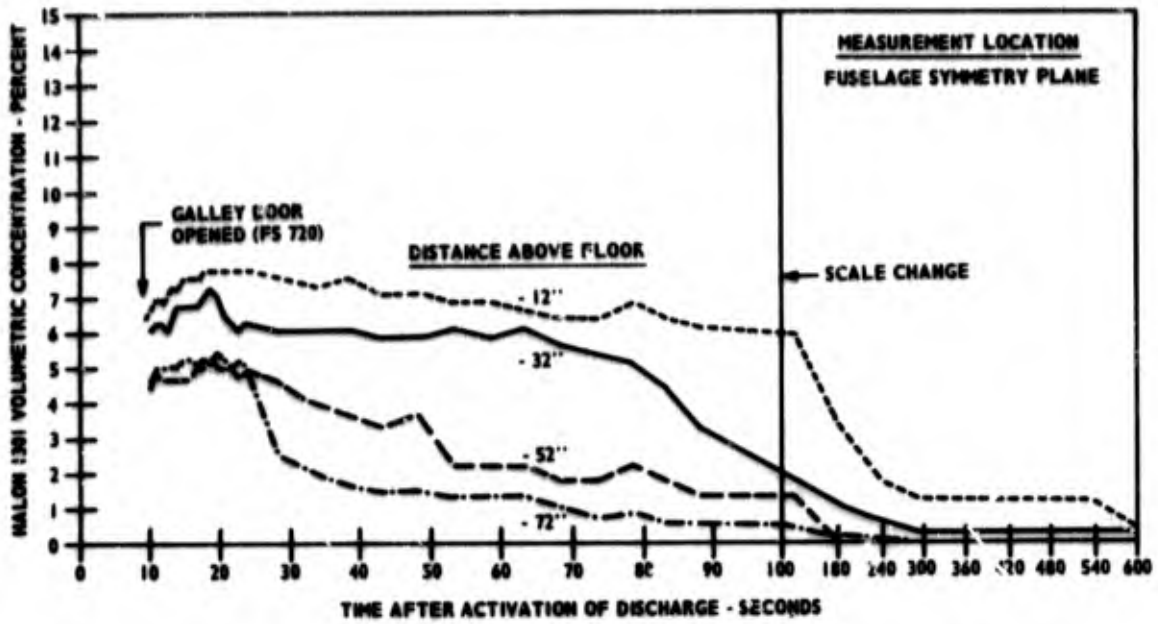


FIGURE 10. LEAKAGE OF HALON 1301 AT FUSELAGE STATION 265 WHEN GALLEY DOOR IS OPENED 10 SECONDS AFTER AGENT DISCHARGE

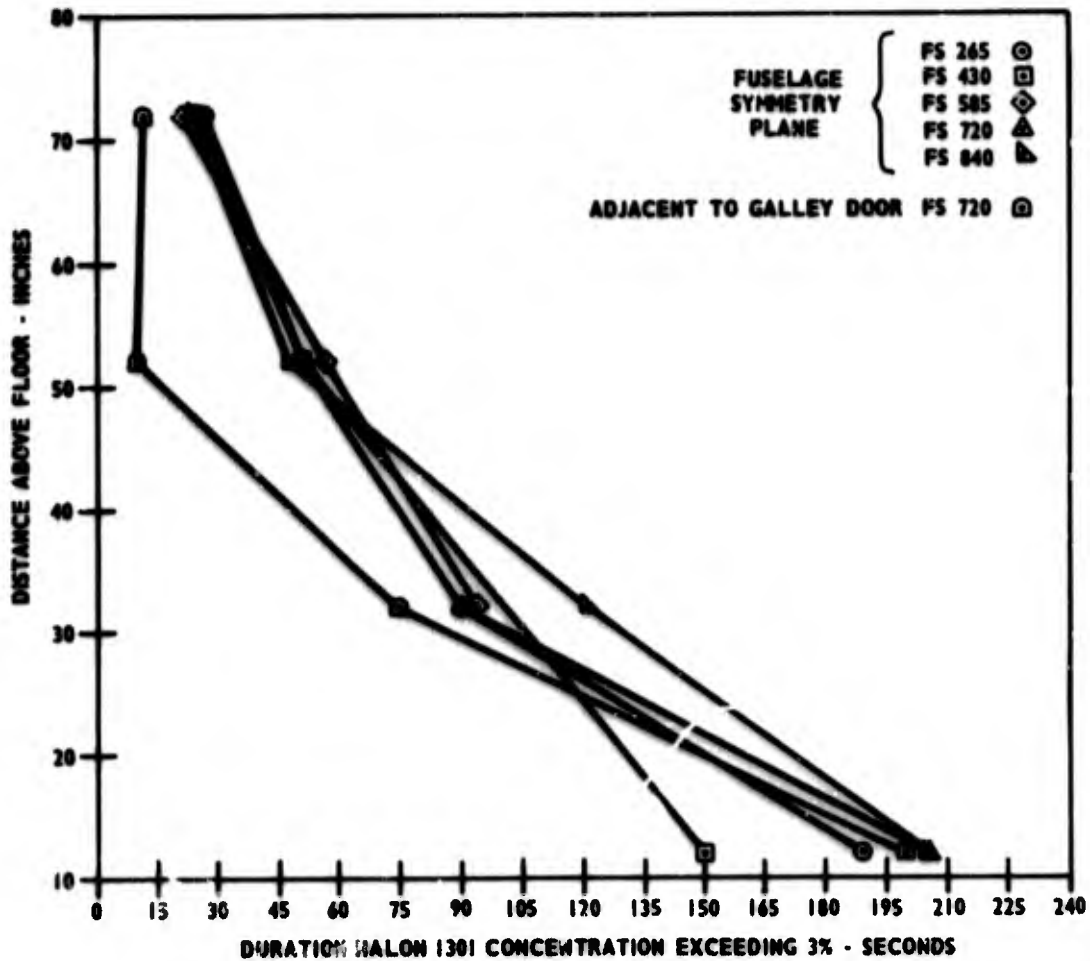


FIGURE 11. LEAKAGE OF HALON 1301 FROM CABIN WHEN GALLEY DOOR IS OPENED 10 SECONDS AFTER AGENT DISCHARGE

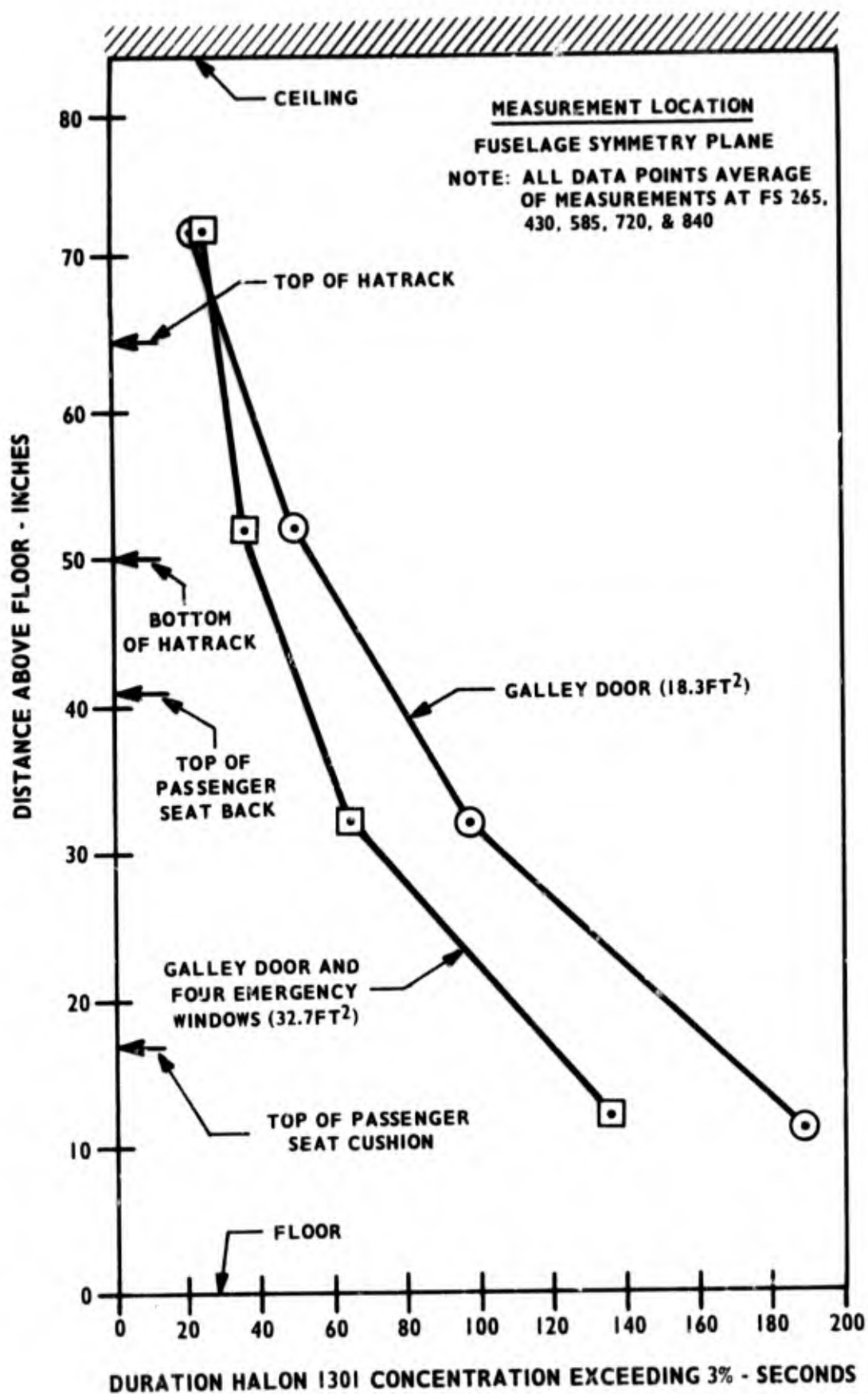


FIGURE 12. DEPENDENCY OF CABIN INERTING TIME ON LEAKAGE AREA

DISCUSSION – PAPER 23

Mr Kipke: Your tests did not appear to consider the high ventilation rate in modern aircraft which would influence results drastically beyond one minute.

Mr Sarkos: I don't believe that application of a total flooding system throughout the cabin is necessary at this time for inflight fire protection. Accident statistics do not bear out a need for this type of system. Inflight fire can be controlled in these areas by using hardening techniques, and detection and in inaccessible areas by detection and automatic suppression. I would not conceive of using this system in an inflight fire. If the environmental system is in operation, the agent would be depleted very rapidly.

A LABORATORY TEST METHOD OF EVALUATING THE EXTINGUISHING EFFICIENCY OF DRY POWDERS

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SUMMARY

The laboratory test method of evaluating the extinguishing efficiency of dry powders developed by the Forschungsstelle für Brandschutztechnik is based on the burning velocity of a laminar premixed methane-air flame. The dry powder being tested is fed into the premixed fuel gas-air flow by a vibrating chute. The powder particles reach the test flame and reduce the burning velocity more or less depending on their extinguishing efficiency. The burning velocity is determined by the nozzle method and by schlieren photography. The evaluation of the measurements shows that the square of the burning velocity is a linear function of the mass flow of the dry powder fed into the fuel gas-air flow. The theoretical minimum value of the mass flow of the dry powder being necessary to extinguish the test flame may be determined by the slope of the straight line. Apart from the fact, that the consistency of measuring values is very good, the main advantage of this method, contrary to the most other laboratory test methods, is that it allows to evaluate the extinguishing efficiency of dry powders only by a few measurements.

LIST OF SYMBOLS

c	Fuel concentration
c ₁ , c ₂	Corrective factors
G	Specific powder charge
u	Flow velocity of the fuel-air mixture
U	Mean flow velocity in the nozzle burner cross section
α	Slope angle of the cone side
A	Burning velocity

SUBSCRIPTS

min	Minimum value
n	Standard condition
O	With addition of dry powder
P	Without addition of dry powder

1. INTRODUCTION

There are two ways of evaluating the extinguishing efficiency of dry powders: large-scale tests using test pieces of nearly true size or laboratory test methods. Experience, however, has shown that in cases where larger burning objects were employed, certain values of the burning process - e.g. intensity and duration of the fire etc. - cannot be reproduced in an identical manner and that various environmental influences, as, for instance, wind, in tests conducted in the open, cannot be allowed for its full extent. In addition, the quenching operation depends on the discharge device of the fire extinguisher and the skill of the operator. Another handicap exists in that large-scale tests require a lot of money and time, so that in most cases it is not feasible to conduct the number of measurements required to guarantee the consistency of measuring values. In comparison, these disadvantages do not occur in laboratory tests, i.e., test conditions can be kept steady and consequently measuring results will be consistent. For this reason, laboratory test methods must be considered the safest way for detailed investigations of the characteristic of action which during the quenching operation becomes effective in dry powders and of the influences of physical and chemical properties of the specific extinguishing agent - as chemical composition, size and shape of particles, particle-size distribution etc. - on the extinguishing efficiency.

2. CHARACTERIZATION OF LABORATORY TEST METHODS

In the last years, a number of laboratory test methods of evaluating the extinguishing efficiency of dry powders have been developed [1]. These methods differ fundamentally from each other. On the one side the difference relates to the way of feeding dry powder into the test flame, on the other hand to the value which is the determining factor for rating the extinguishing efficiency, respectively is used to identify this efficiency. For example, in some testing methods where actual design models are used, the dry powder is added to the flame from outside by means of an adequate device whereas in other methods the powder is fed into the flow of the

fuel gas of the test flame. In order to assess the extinguishing efficiency, most of the testing methods normally applied will determine either the minimum quantity of dry powder required to put out the test flame or the number of quenching operations in proportion to a certain quantity of dry powder. In the other testing methods, physical properties of the test flame serve as basic values for evaluating the extinguishing efficiency of the specific type of dry powder under test. The testing method described in [2] uses the flow velocity of the fuel gas where a flame stabilized at a baffle carrier will be interrupted when a certain amount of dry powder has been applied as basis for evaluating the extinguishing efficiency. The testing method developed by Hoffmann at the Forschungsstelle für Brandschutztechnik [1,3,4,5] which is described later, is based on the change of the burning velocity of a premixed flame as a function of the dry powder quantity. To determine the extinguishing efficiency, other tests, discussed in [5,6], refer to the change of the radiation intensity of the OH-radical as a function of the dry powder quantity reflecting the extent of the concentration change of one of the radicals particularly affecting the burning process.

Testing methods where dry powder is added to the flame from outside offer no opportunity for determining the quantity of dry powder required for extinguishing since only a part of the dry powder, which cannot be determined exactly, will enter the flame whilst the rest gets lost around the flame and, consequently, does not contribute to the extinguishing of the flame. In addition, the spreading of the powder cloud also depends on the discharge device. For this reason and because accidental errors and erratic values of varying degrees must be taken into account, a great number of measurements on a specific quantity of dry powder are required to allow analysing of the measuring results by means of statistical methods, in order to obtain safe values for the extinguishing efficiency of dry powders. It seems, indeed, that the most appropriate testing methods for the evaluation of the extinguishing efficiency of dry powders are those where the burning velocity or the concentration change of radicals in the flame are used as basic values as in this case - contrary to all other known methods - the process observed is not a momentary but stationary one.

3. TESTING METHOD DEVELOPED BY THE "FORSCHUNGSSTELLE FÜR BRANDSCHUTZTECHNIK"

Based on afore-mentioned findings, a testing method of evaluating the extinguishing efficiency of dry powders has been developed by the Forschungsstelle für Brandschutztechnik which is based on the burning velocity of a laminar premixed flame. The basic principle of this method is the fact that the burning velocity decreases in accordance with the quantity and extinguishing efficiency of the dry powder added.

3.1. THEORETICAL BASIS

The burning velocity is the velocity with which a flame front moves through a fuel-air mixture. During this process, the state of the fuel-air mixture may be quiescent or flowing. If the fuel-air mixture is flowing, the velocity of the flow may be adjusted in such a manner that a steady-state flame develops which in a laminar flow produces a stationary flame front. In case of a turbulent flow, the flame front will not be stationary but subjected to temporal fluctuations. The burning velocity can be determined as well in quiescent as in flowing fuel-air mixtures. The testing method presented here, refers to a burner method which is based on a flowing mixture and a stationary flame front. Although all geometrical data of the flame cone could be used for determining the burning velocity, the observation of the side of the flame cone must be considered most suitable as this method eliminates all interference factors arising from anomalies occurring at the tip and the base of the flame. Since with a tube burner the side of the flame cone is curved due to the parabolic velocity profile of the flow pattern and therefore unsuitable for determining the burning velocity, it is necessary to use a nozzle burner which produces a straight-line cone side. As shown in Fig. 1, the burning velocity Λ is defined as

$$\Lambda = -u \sin \alpha \quad (1)$$

where u is the flow velocity of the fuel-air mixture and α the slope angle of the cone side. Since normal photographing of the flame cone does not reproduce a proper image of the cone side necessary to determine the slope angle of the side the schlieren photography should be applied to obtain a picture of the flame cone as required. The flow velocity u will be determined by means of the particle-track method.

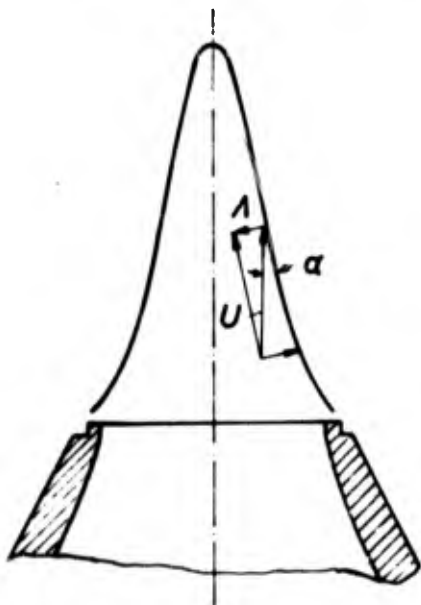


Fig. 1. Interrelation between the flow velocity and the burning velocity

This burner method, so far considered the most precise, which, essentially, has been developed by Lindow [7] was used as basis of the testing method for evaluating the extinguishing efficiency of dry powders presented here. According to Lindow [7], the flow velocity u can be determined by the following equation:

$$u = c_1 \bar{u} + c_2 \quad (2)$$

In this equation \bar{u} is the mean flow velocity in the nozzle burner cross section whilst c_1 and c_2 are representing corrective factors allowing for the influence of the nozzle boundary layer, respectively of the back pressure of the flame which depends on the fuel concentration. Since the testing method of the Forschungsstelle für Brandschutztechnik uses the same burner nozzle as employed by Lindow, values for c_1 and c_2 determined by him empirically, may be taken from his study [7].

3.2. MEASURING DEVICE AND TEST CONDITIONS

The essential elements of the measuring device used to determine the extinguishing efficiency of dry powders are as follows:

1. Nozzle burner with inlet pipe
2. Appliance for continuous feeding of dry powder into the fuel gas-air mixture
3. Mixing unit for producing the fuel gas-air mixture
4. Schlieren arrangement for photographing the flame cone
5. Device to determine the quantity of dry powder to be added.

The arrangement of one part of the measuring device consisting of nozzle burner, dosing apparatus and mixing unit for the production of the fuel gas-air mixture is shown in Fig. 2, the shape of the burner nozzle and the most essential dimensions are indicated in Fig. 3. As Fig. 2 shows, the dry powder will be discharged from the storage bunker *a*, travels over a vibrating chute *b* and from there is added continuously into the flow of the fuel gas-air mixture at the lower part of the inlet pipe *c*. The vibrating chute fixed to the storage bunker is thrown into vibration by the magnet *d*. The powder rate can be adjusted through the vibrational amplitude of the vibrating chute by varying the alternating voltage applied to the magnet. This latter will be effected by means of the variable-ratio transformer *e*. On the other hand, the powder rate can also be regulated by changing the cross-sectional area of the discharge outlet of the storage bunker. The chute including the storage bunker and the driving magnet are located in the non-oscillating box *f* which is attached to the inlet pipe *c* in such a way that insensibility for oscillations and impermeability to gas are guaranteed. Fuel gas and air for combustion are drawn from steel cylinders via pressure-reducing valves and precision-pressure regulators. The volumes of fuel gas and air will be regulated according to the chosen concentration of fuel gas over the two Rotameter flowmeters *g* by means of the controlling valves *h*. The calibration state of the flowmeters will be monitored by the mercury thermometers *i* and the U-tube manometers *j*. The fuel gas

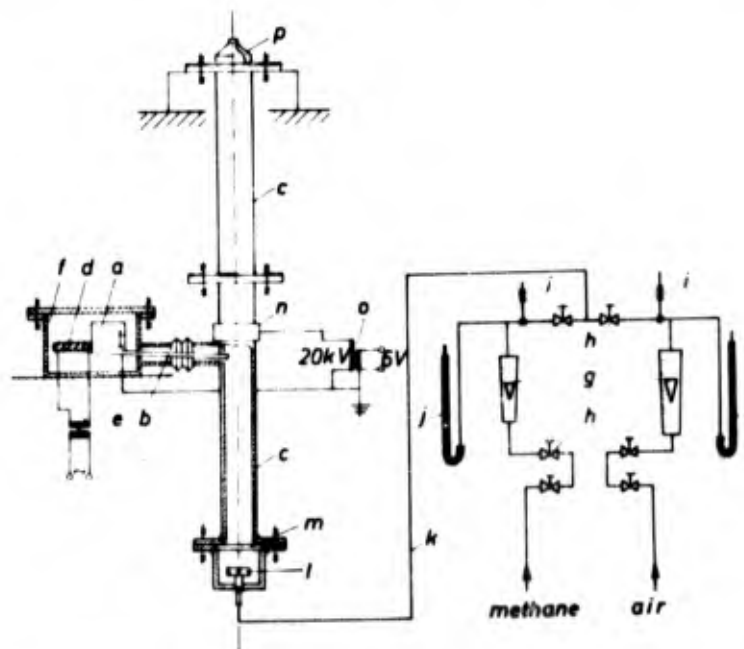


Fig. 2. Schematic diagram of the measuring device
a storage bunker, *b* vibrating chute, *c* inlet pipe, *d* driving magnet, *e* variable-ratio transformer, *f* box, *g* flowmeter, *h* controlling valve, *i* mercury thermometer, *j* U-tube manometer, *k* pipe line, *l* flow distributor, *m* sintered metal inlet, *n* annular electrode, *o* transformer, *p* nozzle burner

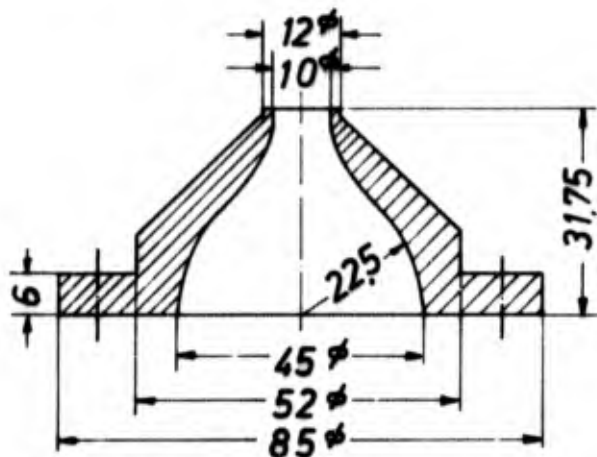


Fig. 3. Burner nozzle

is applied which will be generated by the transformer σ charged with 6 V interrupted direct voltage. The electric field originating from said high voltage ensures a uniform distribution of the powder particles discharging from the vibrating chute within the ascending fuel gas-air mixture flow. To avoid a premature decomposition of the dry powder and a condensation of water vapor produced during combustion, the rim of the nozzle burner p will be water-cooled and kept at a constant temperature of 40 °C.

As proposed by Lindow [7], the Toepler's schlieren arrangement will be used for depicting the flame cone. Fig. 4 indicates the schematic diagram of this arrangement. The beam of light emitted by the source of light a and focused by the condenser b , will be sharply dowsed to one side by the schlieren diaphragm c located in the focal point. The residual rays will be directed in parallel between the both achromats d . The schlieren zone e , i.e. the flame cone to be analysed will be arranged in the parallel path of rays in such a way that the plane of the cross section of the flame axis will be reproduced on the film surface in the camera g quite distinctly by means of the achromat f . The parallel light is focused by the second achromat and masked off by a second schlieren diaphragm adequately sited in the focal point. Consequently, light ray cannot pass the second schlieren diaphragm, unless, in travelling through the schlieren zone they will be deflected from their paraxial direction due to changes of the refractive index of the gases occurring during combustion. Since the point of impact of light rays on the film surface corresponds exactly to the point of their deflection, the schlieren image is representing a true reproduction of the flame cone. From the

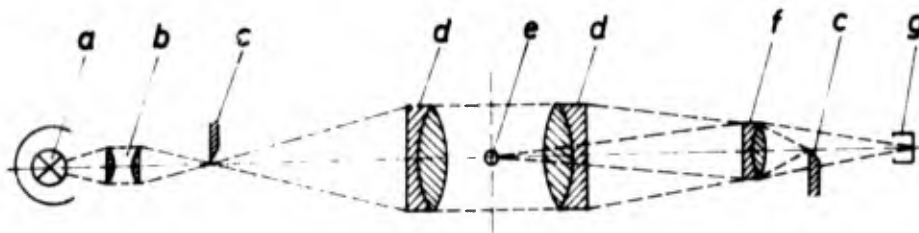


Fig. 4. Schematic diagram of the Toepler's schlieren arrangement
 a source of light, b condenser, c schlieren diaphragm, d achromat, e schlieren zone, f achromat, g camera

concentration in the fuel gas-air mixture adjusted by means of the flowmeters will, additionally, be checked prior to each test by an analysis in a infrared absorption spectrometer. From the flowmeters the fuel gas-air mixture will travel through the pipe line k where thorough mixing of both gas flows is accomplished and through the boreholes of the flow distributor l into the inlet pipe o . The uniform distribution of the mixture over the cross-sectional area of the inlet pipe is ensured by the sintered metal insert m which also serves as safety valve. Above the point where the vibrating chute enters the inlet pipe, the lower part of which consists of plexiglass, the annular electrode n embraces the inlet pipe. To this electrode and to the vibrating chute, high voltage of about 20 kV

photography of the schlieren image of the flame cone - provided that it has been enlarged sufficiently - the slope angle of the cone side can easily be determined.

In order to evaluate the mass flow of the dry powder, the powder loaded fuel gas-air mixture will be carried, for a predetermined period of time, through a filter mounted on the burner mouth, and the weight of the powder collected this way will be determined by means of an analytical balance. From the weight of this specific quantity of powder and the period of time the mass flow of the powder results which relative to the fuel gas-air-volume flow in standard condition will be specified in the following as specific powder charge G_n .

For the tests employing the above described testing method as performed by the Forschungsstelle für Brandschutztechnik, the fuel gas used was methane purified technically. To determine the interrelation between the burning velocity depending on the fuel gas concentration on the fuel gas-air mixture and the extinguishing efficiency of dry powders, fuel gas concentrations varying from 9.0 vol.-% to 12.0 vol.-% were applied. Dry powders tested were BC- and ABC-dry powders of commercial quality. To identify the influence of the particle size on the extinguishing efficiency, various ranges of particle sizes of the particular kinds of dry powders were prepared, the specific surface of which was determined by means of the Blaine's permeameter.

4. TEST RESULTS AND DISCUSSION

To compensate to some degree for fundamental errors and environmental influences inherent in this testing method, and in order to simplify the evaluation the burning velocities measured with the addition of dry powder will be related to the burning velocity of the fuel gas-air mixture without the addition of dry powder. Since in determining the burning velocities of the fuel gas-air mixtures with and without the addition of dry powder the fuel gas-air volume flows and also the pressure and the temperature within the nozzle burner are kept constant, it follows from Eq. (1) that the ratio of the burning velocity of a fuel gas-air mixture with the addition of dry powder Λ_p and that of a fuel gas-air mixture without the addition of dry powder Λ_0 may be defined by the following simple equation:

$$\frac{\Lambda_p}{\Lambda_0} = \frac{\sin \alpha_p}{\sin \alpha_0} \quad (3)$$

The development of the ratio of the burning velocities of fuel gas-air mixtures with and without the addition of dry powder as calculated by this equation is plotted in Fig. 5 (curve 1) as a function of the specific powder charge G_n . If the values for the ratio of the burning velocities are squared it shows that the square of the ratio of the burning velocities of fuel gas-air mixtures with and without dry powder being added is a linear function of the specific powder charge (curve 2).

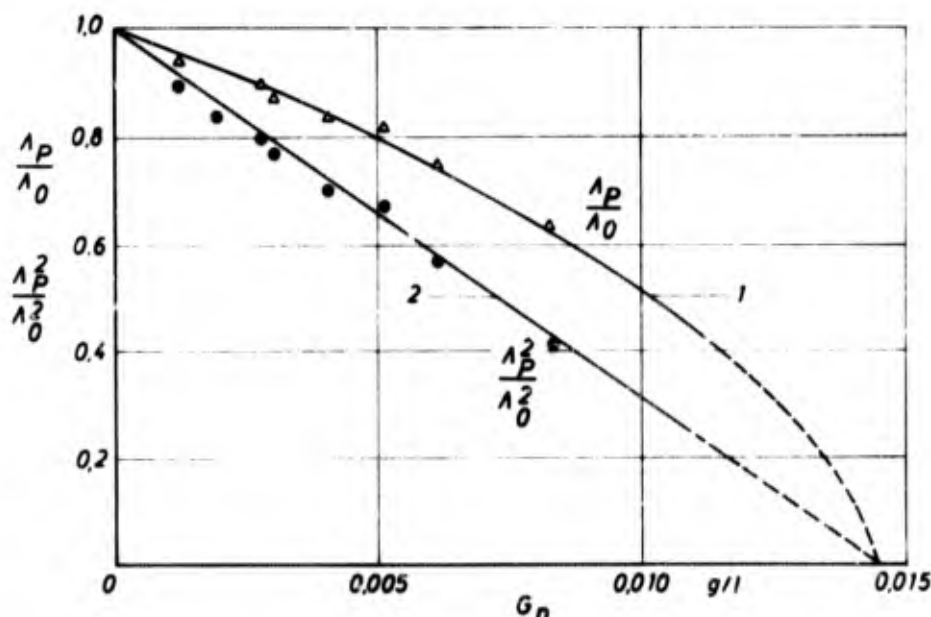


Fig. 5. Ratio and the square of the ratio of the burning velocities of fuel gas-air mixtures with and without dry powder added as a function of the specific powder charge

This interrelation between the square of the burning velocity and the added quantity of the inhibitor has already been proved by van Tiggelen and co-workers [5,8] in their theoretical and experimental investigations on the heterogeneous inhibition of flames by means of alkali metallic salts.

The defining quantity for the extinguishing efficiency of a dry powder may as well be based on the slope of the straight line as on the specific powder charge where the value of the square of the ratio of the burning velocities is 0. The better the extinguishing efficiency of a dry powder is the more the straight line will rise respectively the smaller the quantity of dry powder will be which is required to extinguish the test flame. Whereas the slope of the straight line may be calculated from the data by means of the Gauss's "method of least squares" an experimental determination of the minimum specific powder charge required to extinguish the test flame is not feasible. As shown by these tests, the burning velocity of a flame treated with dry powder cannot be determined exactly or in such a way that the results will be consistent if values for the ratio of the burning velocities A_p/A_0 are lower than 0.6. With increasing quantity of dry powder in the fuel gas-air mixture flow, the slope angle of the side of the flame cone will continuously decrease causing the flame to grow longer and longer until, in the end, it will loosen from the nozzle burner and, finally, lift up completely and go out if the slightest disturbances occur. Therefore, the minimum specific powder charge required to extinguish the test flame can only be determined theoretically with the aid of the point of intersection between the straight line, elongated accordingly, and the x-axis.

According to the extinguishing efficiency of a dry powder a certain amount of dry powder will reduce more or less the burning velocity of a fuel-air mixture. However, apart from the properties of the fuel and the general variables of state as pressure and temperature, the burning velocity also depends on the fuel concentration of the mixture. Consequently, the maximum burning velocity of a methane-air mixture at 20 °C will be reached when the concentration is 10.17 vol.-% methane [7]. Fig. 6 where the square of the ratio of the burning velocities of fuel gas-air mixtures with and without dry powder added, and with different fuel gas concentrations in the fuel gas-air mixture are shown for a BC-dry powder (potassium bicarbonate) indicates that in the same manner as with the burning velocity of the fuel gas-air mixture without the addition of dry powder also the reduction of the burning velocity caused by adding a certain amount of dry powder to the fuel gas-air mixture, depends on the fuel gas concentration of the mixture. With the same quantity of dry powder added, this means that the lower the burning velocity of an fuel gas-air mixture is, due to its fuel gas concentration, the greater is the reduction of the burning velocity of this mixture. The minimum specific powder charges, determined theoretically by elongating the straight lines up to the point of intersection with the x-axis, and the burning velocities of the corresponding fuel gas-air mixtures without the addition of dry powder can be taken from Table 1.

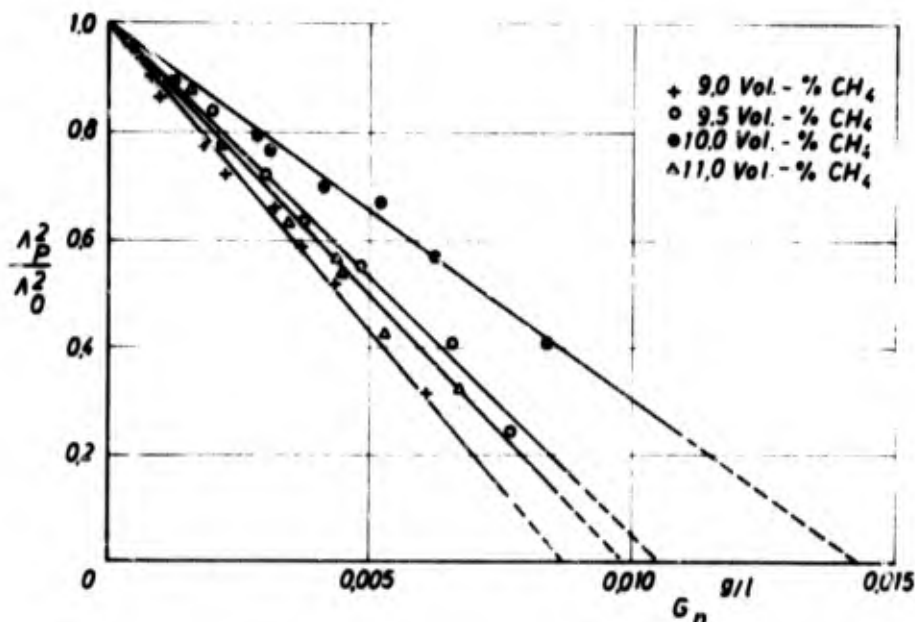


Fig. 6. Square of the ratio of the burning velocities of fuel gas-air mixtures with and without dry powder added as a function of the specific powder charge with different fuel gas concentrations for a BC-dry powder (potassium bicarbonate)

Table 1. Minimum specific powder charge as a function of the fuel gas concentration in methane-air mixtures for a BC-dry powder (potassium bicarbonate) according to [4]

Fuel gas concentration ϕ vol.-%	Burning velocity A_0 cm/s	Minimum specific powder charge G_n min g/l
9.0	38.5	0.0087
9.5	41.5	0.0106
10.0	43.0	0.0144
11.0	41.0	0.0099

As shown in the theoretical assumptions of van Tiggelen and co-worker [8] and Hoffmann [3,5], the extinguishing efficiency of a dry powder does not only depend on the powder added to a certain fuel gas-air mixture but, essentially, also on the chemical properties and the particle size respectively the specific surface of the dry powder. This can be seen in Fig. 7 where the square of the ratio of the burning velocities of fuel gas-air mixtures with and without the addition of dry powder, as a function of the specific powder charge has been plotted for different types of dry powders with a fuel-gas concentration of 10 vol.-% methane in the fuel gas-air mixture. The characteristic data of the dry powders tested are listed in Table 2. If one considers,

Table 2. Characteristic data of the dry powders tested

Dry powder tested	Dry powder type	Chief constituent	Specific surface cm^2/g
Powder A	BC-powder	Sodium bicarbonate	1390
Powder B	BC-powder	Sodium bicarbonate	2490
Powder C	BC-powder	Potassium bicarbonate	1370
Powder D	BC-powder	Potassium bicarbonate	2980
Powder E	ABC-powder	Ammonium phosphate + Ammonium sulfate	3690
Powder F	ABC-powder	Ammonium phosphate + Ammonium sulfate	4340

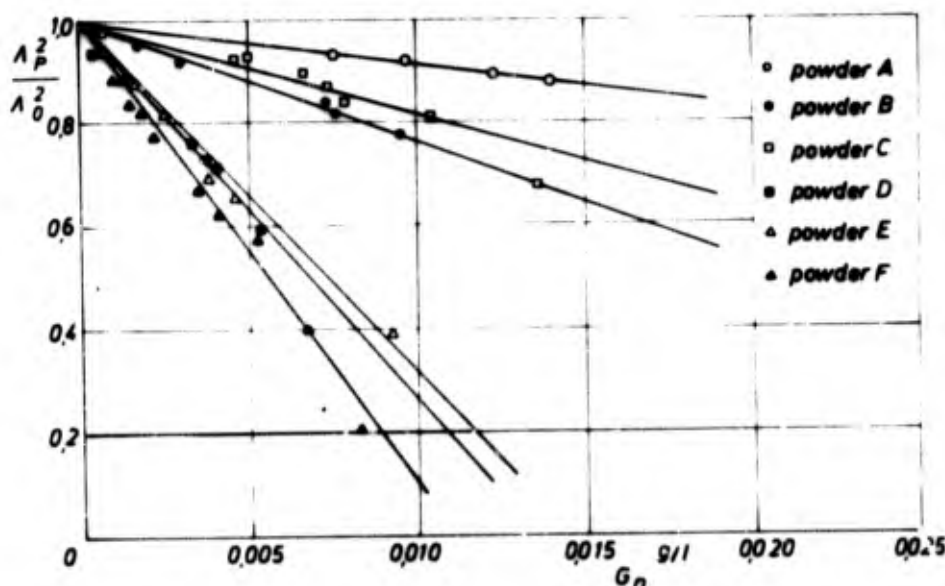


Fig. 7. Square of the ratio of the burning velocities of fuel gas-air mixtures with and without dry powder added as a function of the specific powder charge for different types of dry powder with a fuel gas concentration of 10 vol.-% methane

for instance, the dry powders A and C or B and D, it will be noted that - since both pairs of dry powder have about the same specific surface - the difference of the extinguishing efficiency is based on the heterogeneity of the chemical composition. The chief constituent of the dry powders A and B respectively is sodium bicarbonate, and that of C and D respectively is potassium bicarbonate. If, on the other hand, the dry powders A and B, C and D or E and F are examined, it will be realized that the differences regarding the extinguishing efficiency of the above-named pairs of dry powder are conditioned by the different specific surfaces of the dry powders. This effect of the specific surface which is bearing upon the extinguishing efficiency of a dry powder of a specific chemical composition, may be seen very clearly on Fig. 8 where the square of the ratio of the burning velocities of fuel gas-air mixtures with and without the addition of dry powders as a function of the specific powder charge has been illustrated for different ranges of particle sizes of potassium bicarbonate with a fuel gas concentration of 10 vol.-% methane in the fuel gas-air mixture.

As shown by the test results, this testing method allows the unambiguous and reproducible determination of the differences in the extinguishing efficiency of dry powders of varying chemical compositions and specific surfaces. Another important advantage which should be mentioned is that - contrary to the most other laboratory test methods - only a few number of individual measurements need to be taken in order to determine the extinguishing efficiency of a specific type of dry powder.

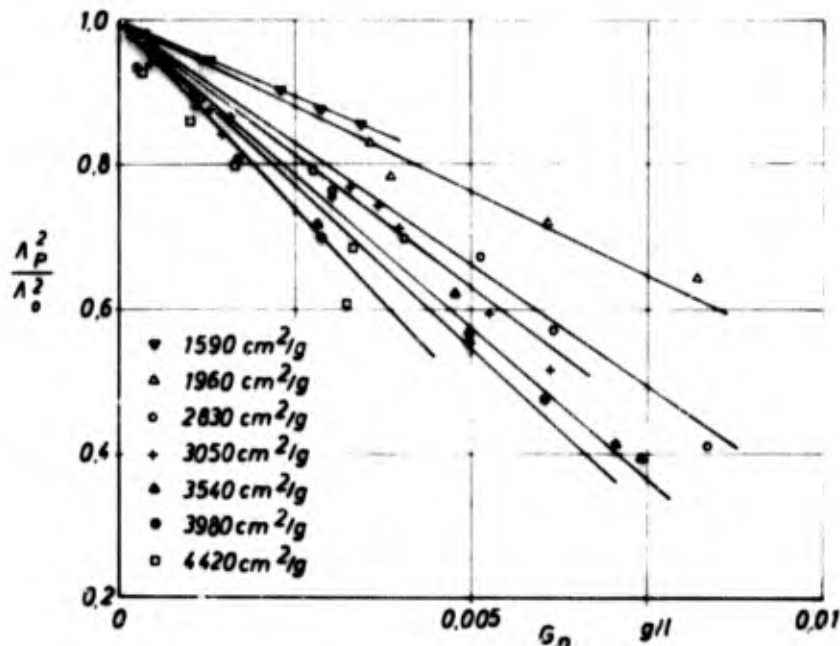


Fig. 8. Square of the ratio of the burning velocities of fuel gas-air mixtures with and without dry powder added as a function of the specific powder charge for different ranges of particle sizes of potassium bicarbonate with a fuel gas concentration of 10 vol.-% methane

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DISCUSSION - PAPER 24

Mr Glanman: We have done tests recently studying the oxidation processes of hydrocarbons which show that methane reacts entirely differently than all the other high order aliphatic hydrocarbons. I would like to suggest the use of a higher order aliphatic compound such as propane in your flame speed tests. Our results show that when one oxidizes ethane, propane, butane, and hexane, the first step is a conversion to the olefin a double-bonded compound, which is different than what is observed with methane. This would seem a simple modification and be more realistic to the actual hydrocarbons used. All the aliphatic compounds seem to go through a conversion step leading to the predominance of ethane or ethylene which is actually oxidized in the flame.

Mr Seeger: We have not performed tests with other aliphatic hydrocarbons.

Mr Fink: We have performed tests evaluating dry powders and found no significant qualitative difference in using propane rather than methane. Of course the results are different quantitatively.

Mr Glanman: This suggest that the dry powders and the sizes are affecting the thermal diffusivity of the mixture, rather than the reaction rate. The plot with the square of the flame speeds is appropriate because flame speeds are proportional to the square root of thermal diffusivity times the reaction rate term. If there is no difference between two vastly different reacting chemicals, then I would suggest that it is the thermal diffusivity which is being altered.

Mr Anart: Votre méthode d'essai assimile l'efficacité d'une poudre au rapport "carré des vitesses de combustion avec et sans poudre". Pour un G_n donné ce rapport est inversement proportionnel à la granulométrie. L'expérience à grande échelle montre que les poudres à très faible granulométrie ne parviennent pas toujours sur le foyer et ne peuvent donc l'éteindre. Comment pouvez-vous avec votre appareillage déterminer la limite de granulométrie efficace?

Mr Seeger: Our laboratory test method allows the clear determination of the effect of the particle size on the extinguishing efficiency of a dry powder. But it is not possible by this method to evaluate the minimum particle size which a specific dry powder must have, in order to reach the fire in case of a real fire. In order to find out the extinguishing efficiency of a dry powder in this case, it would be necessary to evaluate the minimum particle size in regard to its radius of action by extinguishing tests using test pieces of nearly true size and to determine the extinguishing efficiency of this particle size subsequently by our test method.

DYNAMIC EFFECTS IN THE SETTING OF AIRPLANE CRASH FIRES

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INTRODUCTION

Associated with the growing scarcity of liquid hydrocarbons and rising fuel prices is the anxiety that this will turn aircraft to fuels of high volatility that will increase the likelihood of fire when crash occurs. Attempts to assess the order of this increase in fire hazard through reduced scale and laboratory experiments has proved difficult because their relevance to actual crashes is uncertain. This difficulty arises largely from the fact that the dynamics, scale and geometry of airplane crashes are sometimes incorrectly simulated in the laboratory experiments and the potency of the ignition sources appearing in the crash are underestimated. Likewise, fuel spillage patterns and their relation to the position of these ignition sources are often improperly defined for the experiments.

It is the purpose of this paper to describe a few of the principal features of airplane crash dynamics that are reasonably typical of crashes involving the release of fuel. While crashes occur in many modes, so that a standard crash cannot be defined, it is safe to say that the crash fire is likely only when the fuel is spilled, regardless of the crash events. The movement of this spilled fuel to the main ignition sources during the time they are potent enough to start a fire is key to understanding the mechanics of the fire start. The knowledge of the several propagation modes of this fire to the main spillage and the fuel tank opening from which the fuel issues is basic to an understanding of the fire spread rate. Some of the main factors in the ignition and spread of fire are illustrated with slow motion pictures of full-scale airplane crashes conducted by the National Advisory Committee for Aeronautics (NACA) in the years 1950-1956 with piston and jet-powered aircraft.

FUEL SPILLAGE PATTERNS, FUEL VOLATILITY, AND THE IGNITION PROCESSFuel Mist

Since the energy for crash damage is provided by the kinetic energy of the airplane, fuel tank penetration or line rupture is most likely in a crash while the airplane is in motion. Fuel that spills to the open is atomized to a combustible mist that achieves a spanwise spread as it moves through the air around the airplane. For high crash deceleration, the fuel mist achieves a long extension ahead of the airplane and produces a broad spanwise wetting pattern where it is intercepted by the wing. This extensive fuel spread is illustrated in the first slow motion picture sequence of a crashing C-62. The crash simulates a take-off accident occurring at about 90 miles per hour. The airplane moves under its own power. The motion pictures show the forward and spanwise development of the fuel mist plume as the collapsing fuselage plows the ground to cause high airplane deceleration. Contact between the fuel and a wing-mounted engine is assured in this instance.

In contrast to this extensive fuel mist distribution one notices the limited fuel mist development of the next crash of a low-wing C-46. The slow-motion pictures show the airplane passing through a crash barrier where poles arranged in the path of each wing rip open the fuel tanks. Because the firm fuselage remains intact, the airplane slides along the ground without plowing and consequently has low deceleration. Only a slight forward extension of the fuel mist occurs, and the spanwise development is limited by the interception of the spilling fuel by the ground close by. Fuel contact with the engine nacelle does not occur.

The period of the most extensive fuel wetting of the airplane occurs during this dynamic phase of the crash as revealed by this crash of a small jet airplane. Moderate deceleration coupled with bouncing and turning of the airplane allows the fuel streaming to the rear to wet most of the airplane structure aft of the wing.

Likewise, most ignition sources are likely to appear during the same period. Chief among these ignition sources is the engine whose flames and hot metal parts, both internal and external, will ignite any fuel that reaches them regardless of volatility. The next two crashes will show ignition of the fuel spilling from the wings by flames issuing from a piston engine tail pipe. In the first crash the fuel is gasoline, in the second case a low volatility fuel equivalent in vapor pressure to kerosene. Notice that the ignition occurs in both instances when the tail pipe flame contacts the fuel mist. In the gasoline case the combustible envelope is defined by the extent of the visible fuel mist just as it is for the low volatility fuel. Gasoline vapors have

insufficient time to diffuse away from the mist droplets from which they were generated to enlarge the combustible envelope. While laboratory spark ignition tests show much higher spark energies are required to ignite a low volatility fuel mist than a gasoline mist, the flames torching from the engine have ignition energies many orders of magnitude above these spark ignition energies. The same would be true of the hot metal surfaces of the engine.

One crash circumstance in which the volatility of the fuel might make the difference is illustrated in the next slow motion picture sequence which shows the ignition of fuel spilled into the wake of a crashing airplane. A main wheel strut, separated from the airplane early in the crash event, accumulates electric charge as it tumbles through the dust and fuel mist raised in the wake of the crashing airplane. Discharge of this static electricity to ground from the metal of the strut ignites the fuel 60 feet behind the airplane. The resulting fire flashes through the fuel mist behind the airplane and ignites the fuel in the damaged tanks. Subsequent laboratory study of the mode of electrostatic ignition showed that the electrical capacitance of this strut and the electrical potential developed by passing through the dust were just sufficient to provide the necessary electrical energy to ignite a gasoline/air mixture. In this instance fuel volatility would have mattered because it is doubtful that this energy in the spark would have been enough to ignite low volatility fuel had it been involved in the same crash.

The role of the jet engine as an ignition source, and an aid in spreading spilling fuel, is illustrated in the next set of motion picture sequences. First, observe the ignition of a JP-4 fuel mist sprayed into the air entering the inlet of an operating jet engine on the test stand. In this experiment the normal fuel flow to the engine combustor is stopped just before fuel is sprayed into the intake air. Engine rotation is still high. The hot metal of the combustor and the turbine is the only ignition source. Notice that the pressure rise in the combustor produced by the ignition of the fuel ingested with the air stalls the compressor and flames appear at the inlet. Flames issue from the tail pipe as well.

The next full-scale crash of a C-82 airplane fitted with wing-mounted jet engines in place of the reciprocating engines shows the ignition of the fuel spilling from the damaged wing tanks by flames issuing from the jet engine. Notice that the fuel mist is sucked into the engine inlet from the broad zone covered by the approaching inlet air flow. In this crash the normal fuel flow to the engine combustor was shut off upon impact with the crash barrier. Ingestion of the fuel mist occurs several seconds later. A cross wind kept the mist away from the air streaming into the inlet of the engine on the right wing and no fire started there.

A view of the ignition of crash-spilled fuel for a jet fighter is shown next. In this instance the normal fuel flow to the combustor continues throughout the crash. Notice the continuing succession of flame bursts issuing from the tailpipe and the flame spread to the fuel spilled around the airplane.

JP-4 (Jet B) was involved in these fires. Based on the ignition and rate of spread of fire through mists of low volatility fuel shown previously, one doubts that the use of kerosene fuel such as Jet A would have prevented these fires, or reduced the rate of fire spread through fuel mist. The development of the fire after the fuel mist is enflamed would probably proceed a little more slowly with Jet A.

In one series of crashes with jet engines ignition of the ingested fuel was prevented in the following way. At the moment of crash impact the fuel flow to the engine combustor was stopped and a small amount of water was sprayed on those portions of the combustor where the ingested fuel/air mixture moves more slowly than the average. Ignition by hot surfaces requires a minimum residence time of the fuel air/mixture. Cooling of the metal at these locations of higher residence time, and the protection from ignition provided by the evolved steam while cooling occurs, prevents fire.

Here is one of the several crashes which evaluated this approach to reducing the crash-fire hazard. One observes that no fire occurs either at the engine on the left which is ripped from the wing intentionally, or the engine on the right. Post crash inspection showed that both engines ingested fuel mist. With modern engines which have a much higher combustor temperature, the water distribution system may have to be more elaborate.

Fuel Vapor; External Fuel Spills

Common experience with the extreme fire hazard raised by fuel vapors relates to indoor situations where vapors can accumulate to combustible concentrations readily. However, when fuel spills in the open such accumulation is far less likely because of the rapid dilution by the moving air, except in zones close to the liquid fuel pool which provides the vapors.

Fuel spilled in the slide path of a crashing airplane on a dry, bare, unfrozen ground sinks rapidly into the soil. During the several seconds required for the fuel to soak into the ground only a small volume of vapor is generated. A combustible atmosphere lies close to the ground if the fuel is volatile. Fuel vapors will spread away from the spill by gravity through channels in the ground, and ignition sources must exist at ground level to start a fire. Friction sparks, or hot metal parts shed by an engine disintegrating in the crash could be the ignition source. Such sources have a low ignition probability when exposed to fuel vapors in the open air where the residence time of the vapor in contact with the hot metal required for ignition is limited by the movement of the local atmosphere.

The next motion picture illustrates the short distance a combustible atmosphere extends down wind of a sizeable pool of gasoline in the open. The pool of gasoline is about five meters long and about one meter wide. The long dimension is aligned with the wind direction. A pilot flame moving toward the gasoline pool from down wind comes within ten centimeters of the pool before encountering a combustible concentration of vapor in a 15km. per hour wind.

To understand this result, one must remember that the heat of vaporization of hydrocarbons is appreciable. Therefore, the rate of vapor evolution is controlled by the heat transfer into the spilled fuel. If the ground on which the spill occurs is warmer than the fuel then there will be a rapid initial evolution of the more volatile constituents for a brief period of time, the heat of vaporization being provided by conduction from the warm ground. After this initial evolution of vapor, the heat for further vaporization comes largely from the atmosphere; the greater the wind the larger the heat transfer rate. However, the greater the wind, the more rapid is the dilution of the evolved vapors and so the zone of combustible concentration of vapor lies close to the pool of fuel in the open and is less of a fire hazard than is commonly supposed.

The combustible vapor atmosphere produced by spilled fuel may achieve dangerous dimensions if the spill occurs in wind-protected areas provided by vegetation or the collapsed structure of the crashed airplane. Under these conditions fuel volatility may be significant in the fire hazard that develops in the crash.

Fuel Vapor; Internal Fuel Spills

The vapor of fuel that spills into the interior channels and ducts of the airplane structure can achieve wide distribution within the airplane and reach damaged elements of the electrical system which have remained energized for many seconds after the impact. Long fuel lines from wing fuel tanks to engines mounted at the rear of the fuselage that might fail in the crash increase the probability of such internal fuel spillage. Fuels of high volatility would increase the internal distribution of combustible concentrations of vapor. If the airplane structure is warm when the crash occurs, the initial rate of vaporization of the fuel can be high and combustible concentration of vapors can achieve considerable spread within the structure. The vapors may reach the fuselage-ground interface through a break in the fuselage. Friction sparks, auxiliary power units and the electrical system would be the principal sources of ignition. Titanium and steel airplane parts scraping on the runway paving or stony ground produce sparks of sufficient size and temperature to ignite fuel vapors. Sparks from aluminium seldom do.

Ignition by systems within the airplane can be avoided by proper design. Auxiliary power units need not operate on take-off or landing and electrical wiring can be arranged to avoid exposed arcs if wires are severed in the crash.

Ignition of fuel by sources within the crashed airplane is illustrated in the next film sequence which shows the airplane at rest after sustaining crash damage. A small portion of the gasoline spilling from the damaged wing tanks is diverted into the wing leading edge duct used for hot-air wing de-icing. Gasoline as vapor or liquid, or both, flows toward the heat exchanger on the engine exhaust stack where ignition occurs. The flame flashes back through the hot air duct to ignite the fuel in the breached tank.

Fire Spread

If the crash damage is moderate or severe, the fire is most likely to occur while the airplane is in motion. The flame attaches to the airplane and ignites the spilling fuel as the airplane slides along the ground. The fuel spill rate and the airplane speed determine the rate of firespread. Fuel volatility is unimportant.

Wing tank explosions often occur which spread flaming fuel. With gasoline or JP-4 the atmosphere in the tank, sometimes initially too vapor-rich to burn, is brought into the combustible range by the air that enters the tank to replace the spilling fuel. Under these conditions explosions may occur early in the crash. The next film sequence shows such a wing explosion with gasoline.

When low volatility fuel is used, the tank atmosphere is too lean to burn initially, but explosions do occur a little later in the fire. The added time is required for warming the tank to vaporize the necessary fuel.

In some crashes fire spreads along a fuel-wetted path from one part of the fuel spillage to another. The next motion picture sequence shows the ignition of the fuel spilling from the right wing of a crashed airplane by a flame travelling along the fuel-wetted path on the ground from a fire burning on the left side. The rate of flame travel along horizontal fuel-wetted surfaces is much lower for kerosene than for JP-4. In the warmth of an existing fire the flame travel advantage for kerosene is not as great as one measures in tests at ambient temperature.

CONCLUDING REMARKS

While a standard airplane crash cannot be defined, some general remarks can be made about the probability of fire and its rate of spread. A few of these are:

- a. Fire is unlikely unless fuel spills in a crash.
- b. During the crash deceleration (dynamic period) fuel spreads as liquid droplet (mist) or liquid. Fuel vapors add only a little to the extent of the combustible environment.
- c. Ignition sources are most numerous and have their highest potency during the dynamic period.
- d. Fuel volatility plays only a minor role in enhancing the probability of fire during the dynamic period of the crash.
- e. For fuel spills within the airplane structure, fuel volatility is a principal factor in the spread of combustible concentrations of fuel.
- f. The risk of ignition of the external spillage is higher than for internal spillage since the engine is the principal ignition source for most airplanes. Ignition sources within the airplane can be limited by care in the electrical system design.

DISCUSSION - PAPER 25

Mr Botteri: Recalling 1955 NASA activities on development of A/C crash fire protection systems, to what extent is that technology applicable to current (modern) day jet aircraft?

Mr Pinkel: The technology still applies. However, since the hot zones of the engine are more extensive now and at higher temperatures, the water distribution system would have to be more elaborate and more water would be required.

Mr Macdonald: What objections have there been to using this system?

Mr Pinkel: The objection to the use of the crash-fire inerting system is the fear of inadvertent operation at a critical phase of flight. If the crash-fire inerting system were to come on during take-off, for example, all engine power is lost since the inerting system shuts off the engine fuel flow and a water spray in the combustor extinguishes any lingering flames.

Mr Feltham:

(1) Could you give the time/temperature profiles in the examples you have shown?

(2) Would you give your views on the hazards of hydraulic fluid spillage and consequent fire due to functional ignition in cases of wheels up landings.

Mr Pinkel:

(1) The crash fire flame is a diffusion flame whose temperature varies from 1800-2000°F, depending on the wind. A moderate wind produces the higher temperature. The flames endure as long as fuel spills from the tanks. However, the flames from the widespread fuel spillage produced during airplane deceleration endures for about a minute or two. If the ground is dry and porous, much of the fuel disappears into the ground and the fire duration is shortened accordingly.

(2) Because the quantity of hydraulic fluid is small compared to the airplane size, a crash fire involving the hydraulic system only is a small threat to survival of the nearby passengers. Generally the fire is located external to the fuselage in the area near the wheel well. As long as the wing tanks contain fuel, the hydraulic liquid fire is not likely to burn through the wing tank. The boiling fuel absorbs the heat and keeps the tank walls from melting.

Flames that reach into the wheel well may burn through some of the exposed components of the fuel system and ignite the fuel that spills. This fuel fire can be a serious threat to survival. Also, if fuel has been spilled during the crash, the hydraulic fluid fire might ignite this fuel to produce a major fire.

FIRE, FUEL AND SURVIVAL: A STUDY OF TRANSPORT
AIRCRAFT ACCIDENTS, 1955-1974

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SUMMARY

A study is being made, on a world wide basis, of accident summaries and reports together with existing papers on the various aspects of fire safety, the aim being to piece together a complete picture of the part fire has had in determining overall fatality rates in transport aircraft accidents. Note is taken of the sensitivity of the fire death ratio to the number of high impact accidents with no chance of survival and of how this sensitivity may have clouded some past comparisons between fuels of different volatility.

While the study is still far from complete it does seem that in post impact fires the higher volatility fuels, gasoline and wide-cut gasoline, have been responsible for proportionately more fire deaths than has low volatility kerosine, thus confirming predictions based on theory and experiment.

INTRODUCTION

From the ARB list of accidents to public transport type aeroplanes and executive jet aeroplanes of more than 5700 kg all up mass (reference 1) it has been deduced that within the period 1955-1974 there have been some 4000 accidents involving 84000 people of whom 21000 died. That is, of the occupants including both crew and passengers who were involved in an aircraft accident 25% died and the remaining 75% survived with or without some degree of injury.

Piston engined aircraft using gasoline involved 31000 people of whom 10000 died, that is 32%, whereas turbine engined aircraft, using with perhaps an occasional exception a kerosine and/or a wide cut fuel, involved 53000 people of whom 11000 or 21% died.

Such a simple comparison immediately shows there to be a significant difference between piston and turbine aircraft, a difference that may in part be due to the fuel used. However factors such as aircraft size, method of construction, speed, most common type of accident and many others will have some effect on survivability and might override any differences due to fuel properties.

The various turbine fuels on the other hand are used in a similar range of aircraft types under more or less similar operating conditions and there is far more likelihood that any differences that might appear between aircraft using the two principal turbine fuels will be due to the properties of the fuels and in particular to the difference in volatility.

The figures quoted in the opening paragraphs indicate that despite the very high level of safety achieved there should by now be ample evidence for such a study as this, particularly since the ICAO's 'Manual of Aircraft Accident Investigation' states that '... an equally important purpose (to determining the cause) is to determine the facts, conditions and circumstances pertaining to the survival or non survival of the occupants'. In fact very little information relevant to survival is available from accident reports so perhaps it should not surprise us if we find that whereas the overall safety record of air transport has improved considerably during the past two decades the average survival rate in those accidents that do occur has not improved at all. It should therefore be doubly helpful to establish what, if any, benefit has accrued from the use of low volatility fuels and thus to see whether the evidence of actual accidents does or does not confirm predictions based on theory and experiment, before attempting to assess the benefits that could accrue from the new fuels and safety measures currently being considered.

The first stage in this study has been to classify accidents according to whether or not the fire hazard has to be considered. In this context a 'non survivable accident' is defined as one where no one survived the impact and 'survivable accidents' include all accidents where at least one person did survive the impact and therefore might have been subject to the hazards of fire. Survivable accidents also include all those where fire was a cause of the accident rather than an effect of the impact, thus all 'in flight fires' are classified as 'survivable', even if the aircraft subsequently crashed killing all occupants by impact. Fires that occurred as a result of structural failure in the air are generally ignored, that is these accidents are in the 'non survivable' class along with nearly all those where none survived even if fire did occur after impact. Such a classification may not be suitable for a general study of accidents but is convenient for one dealing primarily with fire safety.

The second stage has been to try to establish three facts, (i) was there a fire?, (ii) what fuel was used?, (iii) how many deaths were due to fire rather than to impact? Although even fuller details have been sought it had been hoped that this basic information would be available for a sufficiently large number of accidents to draw statistically significant conclusions.

SOURCES OF INFORMATION

Given adequate time the best sources of information are the individual accident reports together with the people who know what was left out. In the meantime the original source has been the ARB 'world airline accident summary' (reference 1). This invaluable document lists chronologically all accidents (plus a few important incidents) with usually brief details including 'death' and 'aboard' it also classifies them according to cause or type of accident. Unfortunately it is not a reliable guide to post crash fires nor of course to fuel type, nor to whether fatalities were by fire or impact, all of which are essential pieces of information for this study.

The most convenient source of more detailed information is the set of ICAO aircraft accident digests (reference 2), these contain more or less full accident reports which are often improvements on the originals in that a standard layout is adopted. Thus in the last few issues each report has had the headings 'fire' and 'survival aspects' though all too frequently there has been little information thereunder. Also through no fault of ICAO one usually finds under 'aircraft information' the comment 'the type of fuel was not mentioned in the report' or else the fuel type uplifted immediately prior to the accident is recorded but not that remaining from preceding flights. Also on the debit side is the fact that only a very small proportion of accidents gets into the ICAO digests and those that do are not a random sample but naturally contain a much larger proportion of fatal accidents than does the complete list. However it seems reasonable to suppose that the sample of fatal accidents is, from the survival point of view, random even if the non fatal accidents include only the more severe ones or perhaps those with some clear lesson to be learned.

The next major source of information has been the NTSB Bureau of Safety in the form of accident reports, the ten year study of American accidents involving fire (reference 3) and recently the results of their search for data on American accidents involving post impact fire where fuel type was known and/or where the number of actual fire deaths was known. This valuable information is also not entirely representative of world wide operations because according to the very useful looking 'safety index' of reference 4 American operators are virtually the safest in the world. Nevertheless the accidents they do have should be reasonably typical.

The Easams report (reference 5) also seems to have used the ARB list and since it was produced for the British fire services much of the information presented is relevant to this study.

Other valuable information has been obtained from accident reports from manufacturers, airlines and aviation authorities, none of which can automatically be assumed to be entirely random in nature, nor should any of the information obtained and presented here be accepted without question.

The problem in trying to present a complete picture of the part fire has played in determining fatalities in aircraft accidents has been to piece together the evidence from these varied sources. The author's first attempt (reference 6) considered the period 1966-1973 but added wide cut figures for 1963 to 1965 to increase the sample size. Based on some knowledge and some assumptions turbine fuels were sub-divided into kerosine and wide cut, the latter including all mixtures of the two. The accidents were also divided into the two basic groups, 'probably impact' (non survivable) and 'survivable' (at least one person survived the impact) the latter being subdivided into those involving fire (in flight and post impact) and those where the ARB summaries gave no indication of fire.

Although this was a very hurried document and information received subsequently has modified the figures a little the principal conclusions stand. These were that in 'all accidents the fatality rate when using wide cut, 32%, was about half as high again as for kerosine, 21%, and that in survivable accidents known to have involved fire the ratio was increased to over two, 46% against 19%.

This preliminary study suggested that a more detailed analysis was required and the present paper sets out firstly to verify these conclusions for a longer period and then to explain them.

ANALYSIS AND DISCUSSION

The ARB summaries, together with the knowledge and assumptions concerning type of fuel already mentioned, allow a general comparison to be made of fatality rates for the three basic aviation fuels. These are shown in figure 1 as three year moving averages and may be compared with the combined 'all fuel' fatality rate running through the middle.

Several points arise from this, first of all the overall fatality rate has remained very nearly constant over the entire twenty year period. This result is disappointing especially as there is clearly a most significant difference between piston engined aircraft and those powered by turbines and since the period 1955-1974 has covered the almost complete change over from one type to the other. This is seen by the way the

'all fuel' line first clings closely to 'gasoline' but ends up close to 'kerosine'. Wide cut has always been the minority fuel and since 1966 has probably been involved in less than a tenth of all 'turbine' accidents, thus much greater scatter is found. It does appear however that for the first half of the period wide cut had the better record, probably because it was used mainly by a small number of large airlines, such as Pan American and TWA, that had very few serious accidents. During the second half, after these and some other airlines had practically stopped using wide cut, its record has been much worse.

At the same time both gasoline and the kerosine lines have drifted upwards a little and also have a certain similarity of shape that can have nothing to do with fuel properties. Note here and in the following figures that one particularly 'high' or 'low' year will affect the appropriate line for three years.

One factor that has a very marked effect on the fatality rate is the proportion of 'non survivable' accidents, that is those where all occupants are killed (almost invariably by impact). Since the presence of fire is of no significance in these accidents it is necessary to eliminate them so as to concentrate on 'survivable' accidents. Figure 2 shows how the proportion of those involved in survivable accidents has changed during the period.

Two points are immediately apparent, there is a clear difference between pistons and turbines, possible reasons for this include lower cruise altitude and greater likelihood of hitting high ground, and poorer engine out performance perhaps causing loss of control at low altitude. Also the lines are again of much the same shape. Furthermore there is a clear relationship between figure 1 and figure 2, as the proportion of survivable accidents goes down so, as expected, the fatality rate goes up. Figure 3 replots these results so that the space between each pair of lines shows those killed in survivable accidents. It should be noted that the complete elimination of fire would only bring the 'total' line part of the way down to the 'non survivable' line which represents the practical limit to our efforts to improve survivability.

Figure 4 shows that the fatality rates in these survivable accidents are still quite different, being roughly twice as high for gasoline as for kerosine. This difference is probably partly due to fuel differences but it is impossible to say to what extent. Note again the similarity in shape that may indicate some operating change or a change in qualification for entry into the list, that is the 'increase' in fatality rates could be due to a type of comparatively trivial non fatal accident no longer qualifying for entry.

The averages for the whole period show that wide cut at 15% is very close to gasoline, both being well above the 9% for kerosine. These figures are in line with those of 23%, 19% and 10% found in reference 6 for roughly the latter half of the period, bearing in mind the worsening record shown for all fuels in more recent years.

When this exercise was first carried out for reference 6 the results confirmed that there were many unreported post impact fires. However an attempt to fit a simple equation to the number of fatalities in each class of accident pointed fairly clearly to the fact that in survivable accidents about 47% of those at risk were also subject to a real fire risk regardless of fuel type. (This is almost the same as saying that 47% of survivable accidents involved fire but not necessarily quite the same). This same figure is quoted in reference 5 for all fuel types and a further check is obtained by comparing, for the accidents involving fire, the descriptions in the ICAO digests with the ARB summaries. Of 47 post impact fires involving kerosine fuelled aircraft between 1955 and 1964 only 28 were mentioned in the ARB summaries, thus one needs to increase the number already known to be at risk in post impact fire accidents by about 68% or, allowing for the fact that the summaries appear to correctly note all inflight fires, the overall survivable fire figures should be increased by about 49%. This adjustment while not quite making the various sources agree completely does more or less remove the discrepancy.

Furthermore the whole ICAO turbine sample has been studied for the period 1955-1964, it being found that 49% of all turbine accidents involved fire, and 42% of those people involved in survivable accidents also happened to be aboard aircraft involved with fire. It would therefore appear that whether one considers accidents or occupants at risk, all accidents or just the survivable accidents, all fuels or just one, then between 40% and 50% and probably about 47%, involve fire.

The ICAO accident digests include a considerable amount of valuable information in addition to the actual accident reports and two such summaries of fatal accidents covering the ten year period 1960-1969 are contained in numbers 15 II and 18 III of reference 2. This shows that of 11082 people at risk in fatal accidents to all types of aircraft 8276 or 75%, died. The point of interest however is that if one examines the comparably sized samples of jet, turboprop and piston engined aircraft one finds virtually no difference.

If one also examines the ICAO accident digests covering accidents during 1955 to 1964 one finds that in 13 fatal but survivable accidents involving fire, with turbine powered aircraft 50% of the occupants died. In 11 similar accidents with no fire 46% of the occupants died. Thus after considering fatal accidents alone and out of context, by ignoring all non fatal accidents, it might be deduced that not only does aircraft class make no difference but neither does fire!

It is therefore possible that undue emphasis on fatal accidents, of which non survivable high impact accidents are a considerable proportion, has helped to hide the significance of survival generally and post crash fires in particular. However any examination of both fatal and non fatal accidents immediately shows that the chances of survival are far greater if there is no post impact fire since there are far fewer fatal accidents in this category. For example if one adds the non fatal accidents to the ICAO figures shown above then the 50% who died in fatal but survivable accidents involving post impact fire still represent 26% of those aboard fatal and non fatal accidents involving fire, whereas the 46% who died in fatal accidents when there was no post impact fire, represent only 8% of the total aboard all such accidents.

Put simply there are far fewer non fatal accidents if fire occurs after impact, thus fire must be killing people in accidents where no one is killed by impact, some of these being relatively minor accidents. It is therefore probable that if any difference between fuels is apparent it will be seen as a different proportion of fatal to non fatal accidents since the idea that kerosine is the less hazardous fuel is based on the prediction that its lower rate of flame propagation and the usual lack of a ready made explosive mixture in the tanks will very often provide just sufficient time for the occupants to escape.

A convenient way of presenting this kind of information is the 'survival tree' and figure 5 shows a simple tree for all aircraft accidents involving passengers and crew. Note the convention adopted whereby those in the central area are 'at risk', those who move into the right hand area are dead and those who move into the left hand area are safe and no longer at risk. This convention is particularly useful then dealing with cause of death in post impact fires since any occupants killed by the impact itself are no longer at risk with respect to fire. It should however also be noted that no attempt has been made to make all numbers 'agree' exactly throughout the text and the figures lest the impression be given that only one interpretation of the results is possible.

ACCIDENTS INVOLVING FIRE

If one selects from the overall ARB list those survivable accidents to turbine powered aircraft where fire is known to have occurred, either before or after impact, one finds 256 accidents involving 14804 people of whom 3772, or 25% died. In fact these deaths occurred in the 99 fatal accidents involving 5965 people, thus in the fatal accidents 63% died. This is lower than the 75% previously quoted largely because the non-survivable accidents, where all occupants were killed, have been excluded.

The majority of these survivable accidents, 217, involving 12982 people most probably involved only kerosine, 2977 or 23% of these were killed in the 78 fatal accidents, 63% of the 4731 on board. There were nearly twice as many people involved in non fatal accidents as in fatal accidents.

In the remainder it is either known or is probable that a wide cut fuel was present. There were 39 such accidents of which 21 involving 1228 people were fatal and in which 795 or 65% died. Thus the fatality rate in fatal accidents is more or less the same regardless of the fuel used. However to balance these there were only 18 non fatal accidents involving 594 people, that is less than half those involved in fatal accidents. The overall survival rate for wide cut is therefore substantially worse with the 795 killed representing 44% of the 1822 aboard. Tables 1 and 2 for post impact fire and inflight fire respectively list all these accidents and include, when known, the number of deaths actually due to fire.

At this stage it is worth checking whether the apparent difference between kerosine and wide cut has any statistical significance since if it has not then it is likely that, for the time being, at least, more detailed studies of even smaller samples will provide no really convincing evidence.

Considering the total 256 accidents (or events) the probability of death is 0.255 whereas from the 217 kerosine accidents it is 0.229 and for the 39 wide cut it is 0.436, a difference of 0.207. The 'standard error' of the difference in proportions is equal to $\left[(0.255)(0.745) \left(\frac{1}{217} + \frac{1}{39} \right) \right]^{\frac{1}{2}}$ thus the standard error is 0.0758 and the difference, 0.207 represents 2.73 standard errors and is thus definitely significant.

The χ^2 method confirms this and suggests that such a difference would occur by chance only about once in fifty times. Note that a very similar result is obtained if one uses only 13 accidents where wide cut was certainly present, since in these accidents 55% of the 893 who were involved died. Statistical checks are of course not the whole answer and before believing that experience has actually confirmed prediction it must be shown that the additional fatalities were due to the effects of fire and not to impact in a series of unusually severe accidents.

Post impact fires

Of the 61 fatal 'post impact fire' and kerosine accidents the actual cause of death is known in 39 in which 1351 died, 57% of the 2376 aboard. Thus the sample is a reasonable cross section of survivable post crash fire accidents. It may therefore be assumed that

the proportion of impact deaths, 39%, holds for the whole sample. Thus it is probable that some 1530 or 19% of the whole 8044 at risk died by impact

Of the 18 fatal 'post impact fire wide cut' accidents details are known of 10 in which 62% died, again a reasonable cross section. In these only 18.8% of those at risk died by impact and if this figure is true for the whole sample then 190 died by impact or 13% of the whole 1520 at risk, rather less but of the same order as for the kerosine sample.

It is therefore reasonable to assume that not only are these small samples typical but the kerosine and wide cut samples represent a similar range of accidents at all stages in the comparison.

It is difficult to compare this sample of fire accidents with those in which no fire occurred since the ARB list is only of 'no known fire' and the ICAO list, though definitely of 'no fire', is probably short of non fatal accidents. However it is probable that somewhere between 2% and 8% of those involved die by impact in survivable accidents in which fire does not occur. Since this is lower than the 18% who die by impact in fire accidents it is confirmed that fire does not occur quite at random but is rather less often associated with the more trivial accidents.

A closer look at those accidents where cause of death is known suggests that fire has caused proportionately many more deaths where wide cut was involved. In the above 39 fatal 'post impact fire kerosine' accidents 1351 died from 2376, 57%, of which 423 were due to fire. That is of those at risk 39% died due to the impact and 18% died due to fire. However as impact happens first and thus reduces the number subsequently facing the hazard of fire it is convenient to consider that 39% of those on board died by impact and 29% of the remainder who survived the impact died due to fire. Put yet another way 31% of all these fatalities were due to fire.

In the 10 equivalent assumed wide cut fires 477 died from 768, 62%, of which 333 were due to fire. That is 19% died due to the impact and 43% due to fire. Alternatively 19% died by impact and 53% of the remainder died due to fire. Lastly 70% of all these fatalities were due to fire. Thus the impression is that a larger proportion were killed by fire in less severe accidents. Table 3 gives further details of these accidents and figure 7 shows a 'survival tree' for post impact fires.

It can be seen that of the fatal kerosine accidents the majority involved some impact deaths while with wide cut the majority involved no impact deaths at all and were thus almost certainly much less severe accidents. Such a small sample however must be regarded with some suspicion and in fact such a variation might occur by pure chance, perhaps one in ten trials. Nevertheless since it does help to explain satisfactorily the statistically significant difference in overall deaths and since it does confirm predictions based on fuel properties it should not be lightly dismissed. Furthermore there is some considerable similarity between the wide cut and the gasoline sample taken from reference 3. This would be expected if the aircraft concerned were similar and if one ignored the explosion risk, present with wide cut for the majority of accidents but not with gasoline. Thus while it is tempting to combine the two and to incorporate further gasoline accidents to make the sample still larger one would still have to treat the difference with caution, even though it were now statistically significant, because of possibly significant aircraft structural differences.

In flight fires

The type of inflight fire accident that ends up with a fire after landing could be argued to belong to the post impact fire group. However while accidents involving severe in flight engine fire and subsequent forced landing might have many similarities those involving severe cabin fire may have seriously affected passengers before a landing can be accomplished, thus for the more detailed analysis the two groups have been kept separate.

Table 2 lists those accidents where fire occurred first during flight. In the 78 fires involving kerosine powered aircraft, 662 people died out of the 4938 at risk, that is 13%. Of these 11 caused the death of all 401 onboard, usually due to eventual loss of control of the aircraft. A further 6 were also fatal killing 261 or 61% of the 428 at risk. In two of these the cause of death is known, all 128 from the 261 onboard died due to the effects of fire. The remaining 61 non fatal accidents involved a further 4109 people.

The small sample of 8 inflight fires probably involving wide cut killed 191 from the 302 onboard, 63%. These include one classic, the B707 that exploded near Elkton on 8 December 1963 and one hybrid, the DC8 on 5 July 1970 that exploded while continuing to fly apparently under full control, after impact with the ground had caused an engine fire. This accident could perhaps also be classified correctly as 'post impact'. Both of these are known wide cut accidents and, since both involved fuel tank explosions with little or no heating up period, neither explosion is likely to have occurred had kerosine been the sole fuel. This statement although based on knowledge of fuel vapour/air mixtures in normally vented tanks also seems to be confirmed by the accident record since if no significant difference existed between the fuels one should find around twenty examples of kerosine tank explosions in flight. There appear to have been none at all although it is possible that one, an Electra on 24 December 1971 probably using kerosine, exploded in severe turbulence prior to break up rather than vice versa. The remaining 6 accidents include 1 fatal where 1 person died out of the 21 aboard and

5 non fatal accidents involving 91 people. Table 3 compares these numbers with those for gasoline as derived from reference 3 and again one can see that kerosine's advantage lies in the larger proportion of non fatal in flight fires, a difference that is statistically significant.

Figure 8 shows a survival tree for kerosine, although one can easily be drawn for wide cut the large discrepancy between the number involved in different types of accident makes it difficult to pick a realistic trend for such a small sample. However this need not prevent a reasonably detailed 'all accident' tree from being drawn, an example being figure 9. In flight fires involved some 10% of all the people involved in kerosine accidents, 6% of those involved in wide cut accidents and 10% of all turbine accidents. The ARB list for gasoline accidents has not yet been studied with this in mind but from reference 3 and others it is estimated that the equivalent figure for gasoline is 12%.

A closer examination of these in flight fires shows that the principal killer has been fire other than in and around the engine, that is fire originating in the cabin itself or in an electronics bay, under the cabin floor, in the undercarriage bay or behind the pressure bulkhead. Although a few of these may have eventually reached fuel pipes the fatal accidents have more often killed by causing loss of control of the aircraft or by poisoning or asphyxiating occupants before the fuel was involved. Thus unless the resulting crash allowed some to survive the impact to face also a post impact fire the fuel used was irrelevant. Engine fires on the other hand very often involved the fuel, at least until the supply was shut off (on several occasions it was not shut off when it should have been). However no significant difference is apparent, nor should one be expected, except in the case already mentioned, when the fire caused a fuel tank explosion before the aircraft could land. With kerosine it seems that even extremely severe and unextinguished engine fires often allowed sufficient time for a landing to be made, probably because of the time required to heat tank fuel to above the explosive weak limit.

CONCLUSIONS

The evidence of the last twenty years' accidents does support predictions based on the fuels' properties that kerosine is, from the point of view of fire hazard, the safest of the fuels currently used in transport aircraft. However it also confirms that there is still considerable room for improvement as all fuels have caused many deaths in accidents where no one died as a direct result of the impact. It is impossible to be categorical about the magnitude of the differences between fuels since far too many accident reports deal only with the cause of the accident and make no mention of the type of fuel, nor of other important factors affecting survival, nor of the cause of death. Despite the reduced sample size resulting from these deficiencies simple statistical checks on those survivable accidents where fire is known to have occurred do show the differences in fatality rates to be both considerable and statistically significant and that if the necessary details can be produced for the majority of the remaining accidents recorded then the existing sample is large enough for the magnitude of the difference to be determined with some precision.

In the meantime it appears that with kerosine about 5 or 6% of all deaths are caused by fire due to in flight fires not necessarily involving fuel. A further 13 to 15% actually die as a result of burns, asphyxia, poisoning or some combination of these, the fire occurring as a result of the impact. The presence of wide cut introduces a fuel tank explosion risk which appears to have increased the in flight fire hazard by a factor of four or five but with current safety measures this is probably overstating the present difference. About 23 to 25% of all deaths involving wide cut appear to have been due to fire following impact.

Although in many ways the two volatile fuels, gasoline and wide cut gasoline, show similar results the overall record is confused by the different types of aircraft with gasoline powered aircraft being more likely to be involved in non survivable accidents. While the dominating effect of non survivable accidents is to reduce that of differences in the remaining survivable accidents it is to be hoped that in the future more equal emphasis will be placed on the two classes of accident and that accident reports will reflect the need for much more information concerning survival.

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TABLE 1 POST IMPACT FIRES - TURBINE POWERED AIRCRAFT

Date y m d	Aircraft type	Airline	Prob. Dead fuel	Abroad	% dead	Fire dead	Date y m d	Aircraft type	Airline	Prob. Dead fuel	Abroad	% dead	Fire dead
560120	Viscount	BEA	0	5	0	-	650326	B707	PanAm	0	170	0	-
580417	B707	Boeing	0	4	0	-	650327	Electra	TEAL	0	6	0	-
580428	Viscount	BEA	0	5	0	-	650516	B707	BOAC	0	93	0	-
580809	Viscount	CAAC	36	54	67	?	650520	B720	PIA	121	127	95	108
581110	Viscount	TCA	0	2	0	-	650704	Argosy	BEA	0	2	0	-
580217	Viscount	Thy	14	24	53	14	650913	Cv880	TWA	0	4	0	-
590409	Comet	BOAC	2	73	0	-	651014	Argosy	Zantop	0	3	0	-
590814	Viscount	PIA	0	3	67	?	651108	B727	AA	58	62	94	?
600107	Viscount	BEA	0	59	0	-	651111	B727	United	43	91	47	43
600220	Comet	Argentinas	0	6	0	-	651212	Lear Jet	Harold Q	1	80	3	2
600509	B707	TWA	0	109	0	-	660215	Caravelle	Indian	0	79	0	-
600914	Electra	Aa	0	76	0	-	660302	DC8	Iberia	0	72	89	?
600926	Viscount	Austrian	31	37	84	?	660304	DC8	CPA	64	72	89	?
601029	B707	sAA	0	91	0	-	660321	CL44	?	0	6	0	-
610119	DC8	Aero de Mexico	4	106	4	-	660422	Electra	Am. Flyers	83	98	85	12
610612	Electra	KLM	20	36	56	?	660704	DC8	Air NZ	2	5	0	-
610615	B707	Air France	0	103	0	-	660725	Lear Jet	Lear Jet Corp.	0	6	0	-
610711	DC8	United	17	122	14	17	660831	Britannia	Britannia	98	117	94	0
610727	B707	Air France	0	41	0	-	670123	Cv6J0	CBA	0	28	0	-
610729	B707	AA	0	52	0	-	670125	HS125	Dept. of Civ. Av.	0	2	0	-
610923	F27	Turkish	28	29	97	?	670216	Electra	Garuda	22	92	24	22
611221	Comet	BEA	27	34	79	21	670228	F27	PAL	12	19	63	?
620425	Caravelle	Swissair	0	72	0	-	670305	DC8	Varig	51	90	57	28
620427	Viscount	Northeast	0	27	0	-	670331	B707	BOAC	0	5	0	-
620708	Viscount	Air France	130	132	98	0	670419	Britannia	Globe Air	126	130	97	?
620722	Britannia	Continental	27	40	68	-	670425	Cv640	Caribair	0	57	0	-
620806	Electra	AA	15	105	14	-	670427	F27	Fokker	19	19	100	?
620820	DC8	Pan de Brazil	0	72	0	-	670503	Viscount	Channel	0	3	0	-
630101	Cv880	TWA	0	64	0	-	670801	Hercules	Zambian	0	5	0	-
630201	Viscount	Middle East	14	14	100	-	670623	Comet	UAA	0	83	0	-
630703	Caravelle	Argentinas	0	70	0	-	670826	Viscount	United	0	33	0	-
630802	Comet	BEA	0	96	0	-	670905	I1-18	Czech	37	69	54	0
630909	Viscount	BEA	0	34	0	-	671106	B707	TWA	1	36	3	0
631106	DC8	TCA	0	97	0	-	671120	Cv880	TWA	70	82	85	0
640322	Comet	Malaysian	0	68	0	-	671121	B707	BOAC	0	52	0	-
6406C4	Lear Jet	Lear Jet Corp.	0	2	0	-	671204	Argosy	BEA	0	3	0	-
640701	B720	AA	0	12	0	-	671208	Viscount	?	0	18	0	-
640826	B707	TWA	0	138	0	-	680109	B720	Ethiopian	0	49	0	-
641123	B707	TWA	50	73	68	50	680125	VC10	BOAC	0	120	33	21
641211	HS125	HSA Ltd	0	2	0	-	680216	B727	CAT	21	63	33	0
650227	Cv880	JAL	0	6	0	-	680321	B727	United	0	3	0	-
650317	F27	Ansett	0	23	0	-	680411	Hercules	Zambian	0	4	0	-
			0	23	0	-	680420	B707	SAA	123	128	96	0

* wide cut confirmed

TABLE 1 continued

Date y m d	Aircraft type	Airline	Prob. Dead fuel	Aboard	% dead	Fire dead	Date y m d	Aircraft type	Airline	Prob. Dead fuel	Aboard	% dead	Fire dead
680516	Hercules	AREA	K	6	0	-	720128	Viscount	Lufthansa	K	2	0	-
680613	B707	PanAm	K	63	10	6	720216	Cv600	Texas Int.	K	3	0	-
680802	DC8	Alitalia	K	95	14	?	720218	B747	BOAC	K	271	0	-
680810	FH237	Piedmont	K	35	95	0	720228	Falcon 20	Johns Mans.	K	2	0	-
681025	FH227	Northeast	K	32	76	0	720418	EAAC	Eastern	K	107	40	?
681224	Cv580	Allegheny	K	47	43	0	720518	DC9	Delta	K	10	100	1
681224	Hercules	Interia	W	2	50	0	720533	DC8	JAL	K	87	94	?
681227	Cv580	North Central	K	45	60	0	720614	HFB320	Inter City Flug	K	8	88	0
690105	B727	Ariana	K	62	77	41	720629	B707	JAT	K	186	0	-
690106	Cv580	Allegheny	K	11	39	0	720813	Viscount	Br. Midland	K	45	0	-
690202	Viscount	Thy Midland	K	28	39	0	720920	DC8	JAL	K	122	0	-
690320	Viscount	Br. Midland	K	4	75	0	720924	DC8	JAL	K	62	82	7
690412	1-11	Autair	K	90	0	-	721128	DC8	JAL	K	76	70	27
690624	Cv880	JAL	W*	3	60	3	721208	B737	United	K	61	45	10
690701	B727	National	K	46	0	-	721220	DC9	North Central	K	45	22	10
690826	HS748	Zambian	K	3	75	1	721229	L1011	Eastern	K	176	56	0
690906	HS748	PAL	W	31	3	?	730122	B707	ALIA	K	202	87	?
690912	1-11	Pac. Western	W	47	96	0	730305	B707	AA	K	3	0	-
690917	Cv640	Seaboard World	W*	15	27	?	730424	DC8	Airlift Int.	K	3	0	-
690917	DC8	KLM	W	0	0	-	730501	HS748	Leeward Is.	K	20	0	-
691115	DC8	Boeing	K	11	0	-	730616	B707	Air France	K	86	0	-
691213	B747	Spantax	K	10	50	0	730620	DC8	Overseas Nat.	K	250	0	-
700105	Cv990	Royal Nepal	K	23	4	?	730623	DC8	Loftleidir	K	128	0	-
700125	F27	UAA	K	23	0	-	730722	B707	PanAm	K	79	86	?
700209	Comet	SAS	K	65	0	-	730723	FH227	Ozark	K	39	45	0
700418	DC8	PAL	W	1	23	?	730731	DC9	Delta	K	89	100	1
700509	Hercules	Delta	K	33	3	?	731127	DC9	Delta	K	77	0	-
700515	B707	Air France	W*	166	0	-	731217	DC9	Iberia	K	168	0	-
700609	HS125	Imp. Tobacco	K	2	50	?	731220	Caravelle	Eastern	K	109	0	-
700720	HS125	Universal	W*	3	0	-	731223	B707	Lufthansa	K	57	0	-
700824	Electra	Capitol	W*	47	21	47	740101	F28	Itavia	K	42	90	?
701127	DC8	TWA	K	3	0	-	740116	B707	TWA	K	63	0	-
701130	B707	Trans. Carib.	K	55	4	2	740126	F28	Thy	K	72	96	?
701228	B727	PIA	W	7	35	?	740131	B707	PanAm	K	101	97	96
701231	F27	Air India	K	5	0	-	740208	DC8	UTA	K	162	0	-
710125	B707	Saturn	W	4	0	-	740306	F27	Sudan	K	27	0	-
710318	Hercules	AvioGenex	W*	83	94	78	740315	Caravelle	Sterling	K	96	16	?
710523	Tui34	Allegheny	K	28	31	27	740528	F27	PIA	W	40	0	-
710607	Cv580	Pan Int.	K	22	18	?	740907	F27	Garuda	K	40	90	?
710906	1-11	Malay/Sing	K	2	0	-	740911	DC9	Eastern	K	71	82	46
711123	F27	Thy	K	1	5	?	741120	B747	Lufthansa	K	157	38	?

* wide cut confirmed

TABLE 2 IN FLIGHT FIRES - TURBINE POWERED AIRCRAFT

Date y m d	Aircraft type	Airline	Prob. Dead fuel	Aboard	% dead	Fire type	Date y m d	Aircraft type	Airline	Prob. Dead fuel	Aboard	% dead	Fire type	
560715	Viscount	Capitol	K	14	0	engine	6808C5	B727	FTL	W	3	0	engine	
580830	Herald	HP Ltd	K	9	0	engine	680911	Caravelle	Air France	K	95	100	cabin	
591019	B707	Boeing	K	8	50	engine	681119	B7C7	CAL	K	0	0	cabin	
591114	Electra	Eastern	K	38	0	engine	681119	B707	AA	K	38	0	engine	
606222	Electra	Eastern	K	54	0	engine	690209	B727	PanAm	K	116	0	engine	
610109	S707	Continental	K	24	0	engine	690407	Viscount	Air Canada	W	1	21	5	airf, engine
610517	Cv880	Delta	K	75	0	engine	690726	Caravelle	Air Algerie	K	33	37	89	cabin
610724	DC8	United	K	102	0	engine	690817	1-11	Laker	K	0	0	0	cabin
611105	B707	TWA	W	42	0	engine	691127	SVC10	BOAC	K	69	0	0	engine
621011	Comet	BOAC	K	8	0	engine	691128	DC8	Eastern	K	0	123	0	engine
630408	Viscount	BEA	K	44	0	engine	700122	Viscount	Br. Midland	K	0	38	0	engine
6309C4	Caravelle	Swissair	K	80	100	airframe	700306	Jetstream	Bavaria	K	11	100	engine	
631106	B720	Eastern	K	38	0	engine	700506	Viscount	Somali	K	5	30	17	cabin
631208	B707	PanAm	W*	81	100	fuel	700616	B727	Eastern	K	0	33	0	engine, fuel
640709	Viscount	United	K	39	100	cabin	700622	B707	BOAC	K	0	68	0	engine, fuel
641119	Argosy	Zantop	W	3	0	airframe	700705	DC8	Air Canada	W*	109	109	100	engine, fuel
650314	Caravelle	United	K	54	0	engine	700817	B747	Air France	K	0	193	0	engine, fuel
650503	B720	CAL	K	22	0	engine	700918	B747	AA	K	0	132	0	engine, fuel
650609	DC8	NAL	K	77	0	engine, fuel	701222	B720	TransPolar	K	0	144	0	engine
650628	B707	PanAm	K	153	0	engine, fuel	710410	Learjet	?	Y	0	6	0	cabin
650804	Viscount	Ansett	K	42	0	engine	710411	Learjet	Stocks etc.		0	7	0	cabin
651225	DC8	JAL	K	41	0	engine	710509	F27	Phillips Petr.	K	0	21	0	cabin
660211	N262	Lake Central	K	2	0	engine	710513	B747	North west	K	0	42	0	engine
660213	B720	BNF	K	2	0	engine	710719	B727	United	K	0	99	0	cabin
660605	HS125	Air Affaires	K	127	100	fuel	710721	B707	AA	K	0	113	0	engine
660707	N262	Lake Central	K	19	0	engine	710808	Viscount	Aloha	K	0	22	0	cabin
660804	N262	Lake Central	K	17	0	engine	711108	B747	Eastern	K	0	215	0	engine
660811	N262	Lake Central	K	24	100	engine, fuel	711224	Electra	LANSa	K	0	92	99	fuel
660922	Viscount	Ansett	K	24	0	engine, cabin	720106	HS748	SAESA	K	23	100	0	cabin
661030	Comet	Mexicana	K	41	0	engine, cabin	720111	Cl44	Trans Meridian	K	0	5	0	engine
661216	Caravelle	Air France	K	62	0	engine, cabin	720319	DC9	Delta	K	0	87	0	engine, fuel
661217	Viscount	Air Canada	K	40	0	engine	720319	Electra	Universal	W	0	3	0	engine, fuel
670405	DC8	EAL	K	105	0	engine	720628	Gulfstream	Linden FS	K	0	7	0	airframe
670430	B720	Lake Can. v1	K	9	0	engine	721103	Comet	Egyptair	K	0	101	0	engine
670430	B720	Continental	K	8	0	airframe	730501	B707	AA	K	0	84	0	cabin
670623	1-11	Mohawk	K	34	100	airframe	730622	DC9	Hughes	K	0	108	0	airframe
670624	Cv380	Delta	K	59	0	engine, fuel	730709	DC10	AA	K	0	130	0	cabin
670711	Gulfstream	Honeywell Inc.	K	2	100	engine, fuel	730711	B707	Varig	K	123	134	92	cabin
670731	Viscount	Aloha	K	33	0	cabin	731103	B707	PanAm	K	3	100	0	engine
670901	DC9	Korean	K	72	0	engine	740205	DC8	JAL	K	0	63	0	engine
670909	B707	PanAm	K	174	0	engine	740216	B707	TWA	K	0	52	0	cabin
671111	B707	Olympic	K	158	0	engine, fuel	740317	B707	TWA	K	0	153	0	cabin
680408	B707	BOAC	K	127	4	engine, fuel	740908	B707	TWA	K	88	100	0	engine

* wide cut confirmed

TABLE 3 POST IMPACT FIRES, CAUSE OF DEATH KNOWN**Probable fuel - kerosine**

accident type, deaths by:-	accidents	dead	ab'd	% dead	impact	% imp. of aboard	left	fire	% fire of left	ab'd	dead
impact only	19	785	1125	67.1	755	67.1	370	0	0	0	0
impact & fire	10	462	664	69.6	173	26.1	491	289	58.9	43.5	62.6
fire only	10	134	587	22.3	0	0	587	134	22.8	22.8	100.0
total 'K'	39	351	2376	56.9	928	39.1	1448	423	29.2	17.8	31.3

Probable fuel - wide cut

impact only	2	47	51	92.2	47	92.2	4	0	0	0	0
impact & fire	3	231	264	87.5	97	36.7	167	134	80.2	50.8	58.0
fire only	5	199	453	43.9	0	0	453	199	43.9	43.9	100.0
total 'W'	10	477	768	62.1	144	18.8	624	333	53.4	43.4	69.8

All turbine fuels

total 'W & K'	49	1828	3144	58.1	1072	34.1	2072	756	36.5	24.0	41.4
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Gasoline (from reference 3)

impact only	11	121	314	38.5	121	38.5	193	0	0	0	0
impact & fire	3	72	133	54.1	28	21.1	105	44	41.9	33.1	61.1
fire only	7	185	336	55.1	0	0	336	185	55.1	55.1	100.0
total 'g'	21	378	783	48.3	149	19.0	634	229	36.1	29.2	60.6

Both volatile fuels

total 'W+g'	31	855	1551	55.1	293	18.9	1258	562	44.7	36.2	65.7
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TABLE 4 IN FLIGHT FIRES, SUMMARY**Probable fuel - kerosine**

fire type	accidents	dead	aboard	% dead	accident type, dead		
					all	some	none
engine	52	134	3416	3.9	4	2	46
fuel	2	93	94	98.9	1	1	0
airframe, cabin	24	435	1428	30.5	6	3	15
total	78	662	4938	13.4	11	6	61

Probable fuel - wide cut

engine	5	109	197	55.3	1	0	4
fuel	1	81	81	100.0	1	0	0
airframe, cabin	2	1	24	4.2	0	1	1
total	8	191	302	63.2	2	1	5

All turbine fuels

total	86	853	5240	16.3	13	7	66
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Gasoline (from reference 3)

total	27	184	840	21.9	6	4	17
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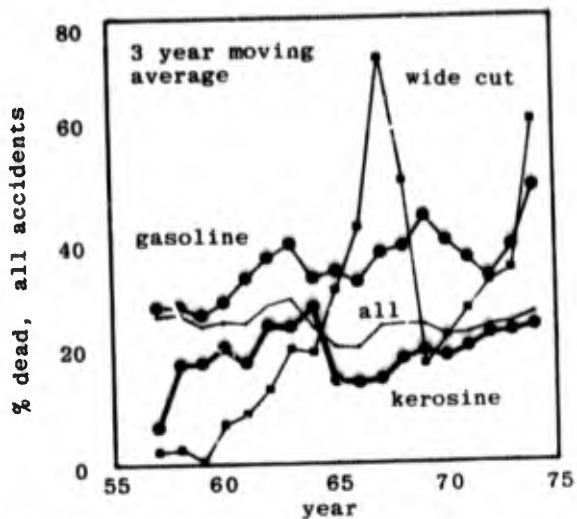


Figure 1 Fatality rate in all accidents

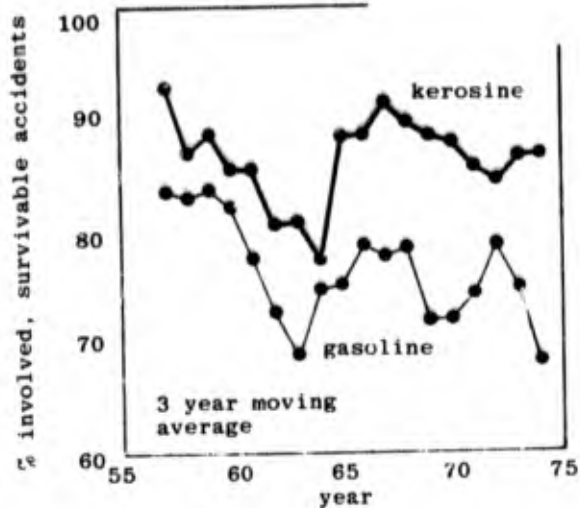


Figure 2 Proportion involved in survivable accidents

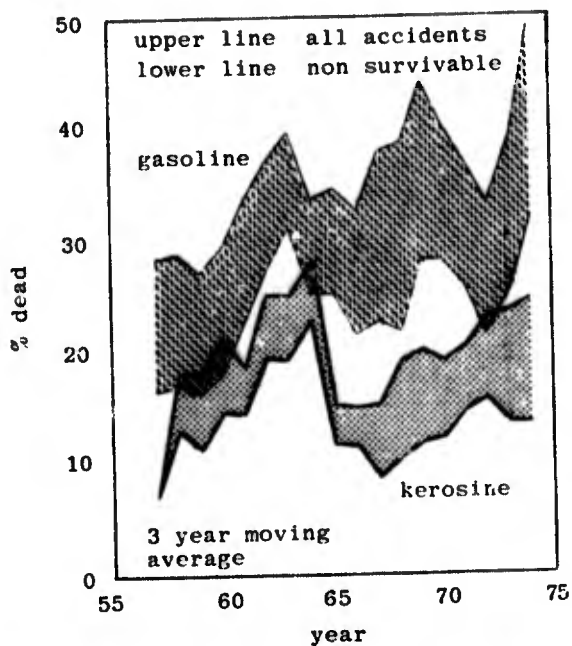


Figure 3 Proportion of those involved in all accidents killed in non-survivable accidents and in all accidents, shaded areas show those killed in survivable accidents

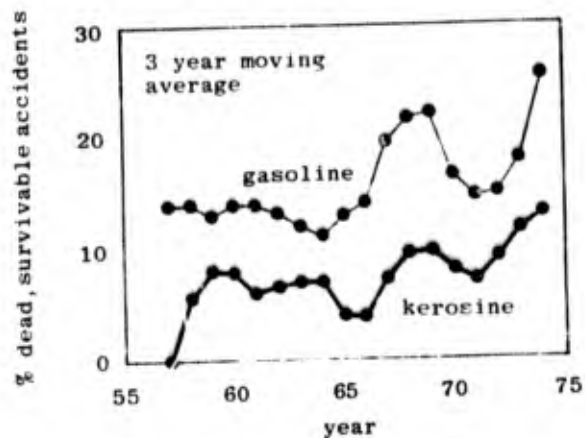


Figure 4 Fatality rate in survivable accidents

Notes
 The numbers shown in these figures and in the other survival trees do not necessarily agree exactly since they represent various estimates based on as yet incomplete information.
 1974 numbers are only provisional.

All accidents, all fuels, simplified								
survivors			at risk			fatalities		
k	w	g	k	w	g	k	w	g
			100	100	100			
			survivable			non-survivable		
			88	88	75	12	12	25
			non fatal			fatal		
			70	60	59	18	28	16
			survive			dead		
			9	14	8	9	14	8
			79	74	67	totals		
						21	26	33

Figure 5 Survival tree, all accidents

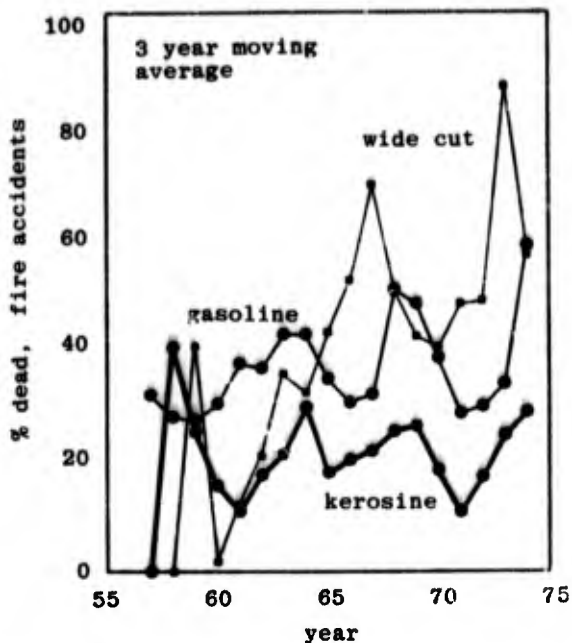


Figure 6 Fatality rates in all accidents involving fire

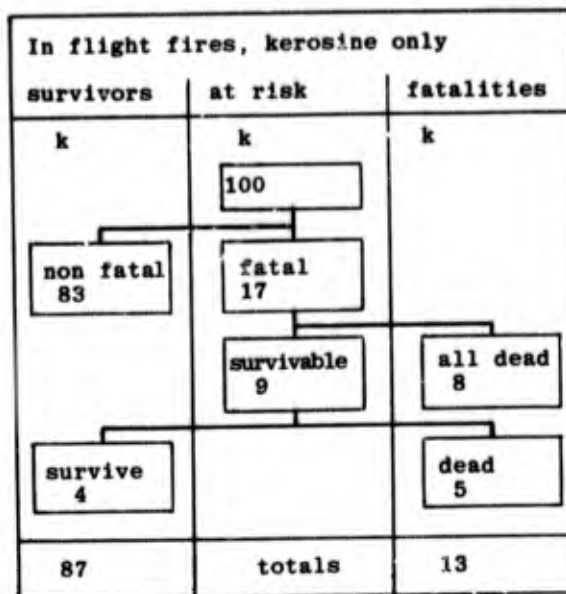


Figure 8

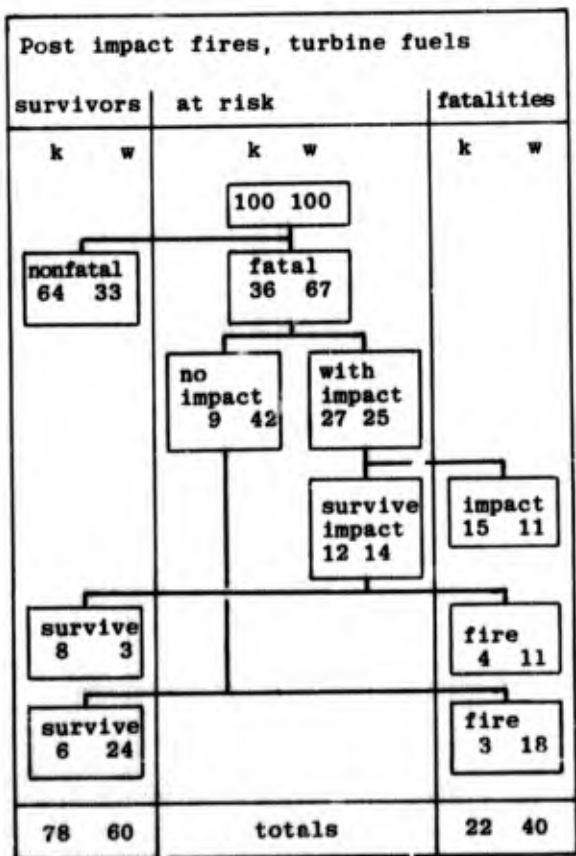


Figure 7

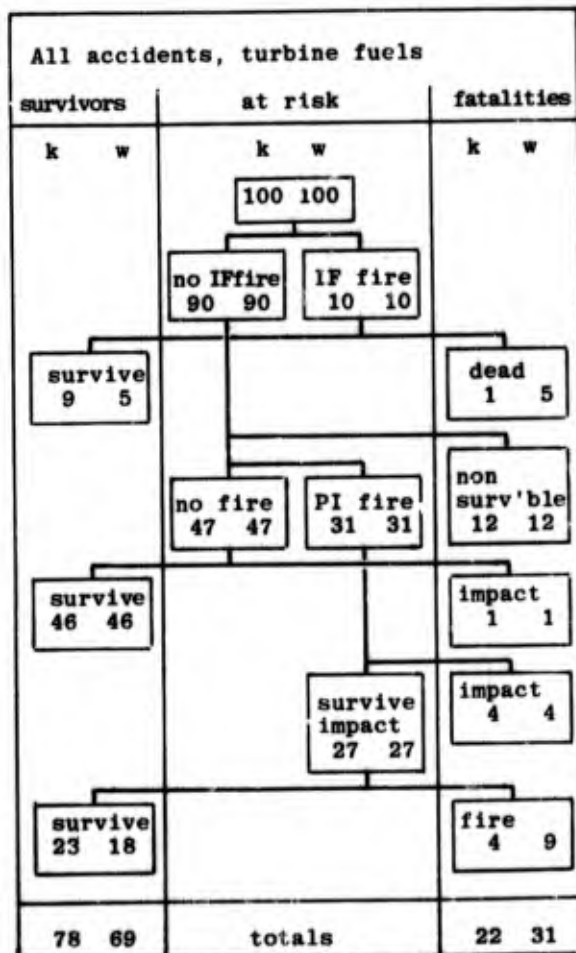


Figure 9

Appendix to paper 26

Since compiling Tables 1 and 2 additional evidence has been received concerning both accidents listed and other accidents not previously known to have involved fire or fire deaths. The following changes, additions and deletion may be made, based on information received up to the time of the conference, the new information being underlined.

Table 1

Date y m d	Aircraft type	Airline	Prob. fuel	Dead	Aboard	% dead	Fire dead
590814	Viscount	PIA	W?	2	3	67	0
600926	Viscount	Austrian	K	31	37	84	0
610612	Electra	KLM	K	20	36	56	15
610923	F27	Turkish	K	28	29	97	13
660828	Cv880	JAL	W*	5	5	100	5
670228	F27	PAL	W?	12	19	63	0
670419	Britannia	Globe Air	K	126	130	97	0
670427	F27	Fokker	W*	19	19	100	19
690207	B707	St'd/CPAL	K	1	57	2	0
690221	F27	Indian AC	K	44	44	100	44
69112C	VC10	Nigeria A	K	87	87	100	?
700125	F27	Royal Nepal	K	1	23	4	0
700509	F27	PAL	W*	1	33	3	0
700720	HS125	Imp. Tobacco	K	1	2	50	0
701231	F27	PIA	W?	7	36	19	7
710730	B747	PanAm	K	0	210	0	-
720418	SVC10	EAAC	K	43	107	40	43
720614	DC8	JAL	W*	86	89	97	?
720629	HFB320	Inter City Flug	K	7	8	88	3
720901	B747	TWA	K	0	335	0	-
721223	F28	Braathens	Z	39	45	87	?
730410	Vanguard	Invicta	K	108	145	74	?
730722	B707	Pan Am	K	78	79	99	0
740101	F28	Itavia	K	38	42	90	38
740126	F28	Thy	W	65	73	89	?
740315	Caravelle	Sterling	K	15	96	16	15
740907	F27	Garuda	K	28	36	78	0

In addition to those listed above wide cut has been confirmed as being present in the following: 650227, 690906, 690912, 691115. Some doubt has been shed on the fuel classification of 650520 and 740528, these may be considered as 'W?'.

Table 2

Wide cut has been confirmed as being present in 661217 and 690407, also in 740205 previously believed to be kerosine. Accident 740908 should be deleted as this has been found to have been due to an explosive device and such accidents are excluded from this study.

Additional information would be most welcome.

Eratum

In paragraph 2 under ACCIDENTS INVOLVING FIRE on page 26-4 the number 4731 should be 4737.

DISCUSSION - PAPER 26

Mr Mahood: Have you considered the application of risk analysis simulation techniques? You mentioned the difficulties in dividing the fatalities. This might help you to quantify the confidence of your judgements in the initial separation of the data.

Mr Taylor: I feel we must get better data from the analysis of the accidents, the pathologists reports etc., first.

Mr Dukek: There is a similar study to Mr Taylor's going on in the US. FAA asked the Coordinating Research Council to update a 1964 study on aircraft fuel safety. Statistics by now might show the significance of volatility, was the thinking. The paucity of data was surprising. The report is expected at the end of this year.

Mr Livermore: In your investigations into in-flight accidents due to fire is there any evidence to support the suggestion that has been made for several years that misting of kerosine fuel inside the fuel tanks makes this fuel no more safe than wide cut gasoline due to lowering of the weak mixture ignition boundary?

Mr Taylor: I have found no accident involving kerosine where an in-flight explosion has occurred, except possibly the one mentioned at the bottom of page 26-5, and I have conducted tests in which a section of fuel tank was shaken at representative frequencies and amplitudes and observed no misting at all, only foaming. My conclusion is that misting in civil transport aircraft hardly ever occurs (one cannot completely rule out a pipe leak above the fuel surface) and the chance of misting being coincident with the presence of an ignition source is virtually zero.

Mr Ansart: L'imputation au seul carburant de la diminution de mortalité n'est pas entièrement satisfaisante. Simultanément avec l'apparition des turbines des progrès considérables ont été réalisés dans la structure et l'équipement des avions, dans le domaine de la prévention et de la résistance au feu.

La corrélation statistique entre le taux de mortalité et le type de carburant serait possible si les types de carburants étaient mentionnés dans les Rapports, ce qui n'est pas souvent le cas. Dans l'étude présente l'échantillon "JP4" est très faible et par conséquent non significatif.

Mr Taylor: I agree that there have been developments in various parts of the aircraft but as, for all classes of aircraft, Figure 1 of my paper shows there to have been no improvement in survival rate over the 20 year period. It would appear that these developments have not been very effective since they were certainly not all incorporated in the first turbine powered aircraft. However this will be the subject of further study.

Fortunately, although the type of fuel is often not indicated in the accident report, this and other relevant information is usually held by the accident investigation team, the airline and/or the manufacturer. I believe that the sample is now large enough to show the difference between widecut and kerosine to be significant but as the Tables give the information on which my belief is based this may be checked; I would be interested to know of any conclusions that conflict with my own.

Mr Pintel: From now on the cost of aviation fuel will be a major concern of the aviation community. Whereas previously the industry could obtain the fuel it specified at reasonable cost, now it faces the prospect of accepting the fuels that offer a cost advantage, or are locally available during shortage times. It is up to the research and development arm of the aviation community to prepare for this possibility by determining what factors in airplane design, servicing, and operation could be modified to reduce the crash-fire risk regardless of the fuel and its volatility. Some air lines have operated for many years with wide cut (JP-4) with excellent crash safety records. The difference between crash-fire incidence with kerosine and wide cut is close enough that tolerable modifications to the airplane could reduce this difference to where it is unimportant. It is important to realize that the probability of crash-fire occurring is in proportion to the rate fuel spills during crash deceleration. If the fuel spill rate is high, a large combustible mist forms which ignites readily regardless of fuel volatility. For the cases in which the fuel spill rate is small, and the fire probability is correspondingly low regardless of the fuel involved, fuel volatility can make the difference in the occurrence of fire. Much of the ignition hazard can be reduced for these small spill rate cases by good engineering. Key to the success of this approach is a detailed review of the mechanism of the start and spread of aircraft crash fires.

PASSENGER AIRCRAFT CABIN FIRES

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After a brief review of the established findings on the crash of a Swissair Coronado CV-990A in Würenlingen Switzerland, on February 21, 1970, an analysis of the cabin fire preceding the crash is given, including origin of fire, its propagation and effects on the aircraft systems. A method of establishment of elevated local temperatures in cargo compartment and cabin by means of uncommon fractures as found in the wreckage will be described. The role played by the major aircraft systems is being discussed. Furthermore, since the smoke spreading in cabin and cockpit is considered the factor rendering the aircraft uncontrollable under the prevailing IFR conditions, the results of tests carried out simulating the smoke conditions are given.

01. Introduction

The overall level of Flight Safety in Civil Aviation is high, maintaining this and further improving it, is - for obvious reasons - one of the prime obligations of the world's airlines. It is this fact which leads responsible airlines to making appreciable funds available for evaluation of accidents and incidents in their industry. The knowledge gained through this is being constantly applied when specifying new equipment or major changes to existing airplanes.

It is an accepted fact that in cases of emergency the condition "fire on board" must, for most instances, be considered fatal. One of these tragic accidents shall in the following be presented whereby consideration is given to the technical/operational facts and findings only, purposely excluding the evaluation of those very exclusive and criminological factors which normally form part of any sabotage case.

02. History of the Flight

On February 21, 1970 at 12:14:00 a Swissair CV-990A took off from Zurich-Airport for its flight SR 330 to Tel Aviv. Seven minutes later at 12:21:00 the flight requested clearance to return to Zurich on account of suspected cabin pressure trouble. SR 330 was immediately cleared for its return flight to Zurich for a landing on instrument runway 16. The flight was executed under instrument flight rules (IFR).

Somewhat later, the crew informed Zurich control that they suspected a bomb explosion in the aft cargo compartment, however, no emergency was declared yet. At 12:26:00 (5 minutes after their request for return) fire-on-board was reported, followed by a request for immediate landing. One minute later, a radar controlled approach was asked for, due to aircraft navigation system troubles.

At 12:30:50 SR 330 called on Zurich tower frequency giving an altitude of 6000 ft and a heading of 329 while on radar an actual heading of 270 was observed. The flight was instructed to turn to 330 and descend to 4000 ft. A short while afterwards radar monitoring revealed that the flight was off track again. It was then instructed to turn to 360 and to further descend to 3500 ft, immediately after this the crew declared an emergency and reported heavy smoke on board with very poor visibility. The aircraft started to turn west again and the crew reported they were crashing.

At 12:33:40 that is 11 minutes after his first reporting of problems the pilot-in-command called again, informing the tower that he was reducing power and stating again that he could "not see anything". After this message radio contact was lost, shortly thereafter the aircraft crashed at very high speed in a left hand turn attitude into a forest, approximately 13 miles west of Zurich-Airport. The aircraft was completely destroyed, 38 passengers and a crew of 9 were instantly killed.

03. Analysis of the accident03.1 General

The crew's suspicion of a bomb explosion, known through the radio communication prior to the crash, in combination with the fact that earlier on the same day an Austrian Airlines Caravelle suffered considerable, although uncritical damage from a bomb explosion in a cargo compartment during climb-out of Frankfurt, has helped the investigators to direct their efforts at an early point of time on securing all possible evidence. Eventhough the weather conditions at the crash site were extremely adverse, snow, sleet and rain, an estimated 95% of the wreckage was recovered and brought back to Zurich. Here the debris were screened, positively identified parts and bits were placed in their appropriate position within an aircraft outline, marked on the hangar floor. Since the origin of the fire was suspected in the aft cargo compartment, the layout of this section was marked up

separately and the recovered respective parts were placed there. Meticulous screening of heaps of wreckage together with careful identification procedures resulted in the recovery of an appreciable portion of the cargo compartment lining. Together with the leftovers of the mail-bags which were loaded into the aft cargo compartment and some items found which were positively identified to be parts of a detonating device, the total evidence permitted a reasonable reconstruction of the sequence of events that led to the disaster.

03.2 Path of fire

One of the mail-bags which were loaded into the aircraft in Zurich, contained an explosive charge with a detonator fused by a barometer all packed in a normal postal parcel. When the cargo compartment pressure gradually dropped during climb, the barometer circuit closed and the detonator was fired. The explosion must have been more thermic than blastlike, inasmuch as no evidence of a thermal type charge was found, it can be assumed, the explosive's shelf life was likely to have been expired. From the heatwave of the explosion the mail-bags caught fire. It could not positively be determined whether the bomb had caused any structural damage to the fuselage as the recovered wreckage contained no such evidence, however, the first indication of the crew - cabin pressurization troubles - and the following intensive fire may be taken as an indication of this. The fire continued to burn, though very localized, confined to roughly the forward 4 feet of the aft cargo compartment only. In this relatively small space the existence of substantial heat gradients could be demonstrated by means of the heat-damaged fiberglass lining panels. In some areas all resin has been consumed by the fire, leaving the glass fibers only, where only a few inches away the evidence of fire exposure consisted of discoloration of the material only. By reviewing the material properties it could be proven that very high temperatures must have existed in this small area at an early stage of the fire.

On the right hand side of the cargo-hold in discussion the cargo door stowage area is enclosed by aluminum panels with an opening into the cabin floor on its top. The latter is covered with coated cloth, containing a hole of approximately 7 cm diameter serving as a pressure equalization orifice. Unexplainably, the fire found its way past the aluminum panel and from there through the ready passage into the cabin. This finding was confirmed through the metallurgical examination of some very uncommon looking type of metal fractures on structural parts found in the wreckage. These debris were parts of the floor structure and the hatrack section just above the mentioned venting hole in the cabin floor. The surfaces of these fractured extrusions presented themselves in a tooth-brush like appearance. Through some additional information obtained, it soon became apparent that this type of fracture could only occur under elevated temperatures. Research work and tests finally proved that the fracture pattern was generated by compression forces at eutectic temperatures of the alloy. This finding, of course, permitted the exact determination of the pre-crash metal temperatures, which was found to have been in excess of 500°C. Together with micro-hardness tests on these extrusions it was furthermore possible to reconstruct temperature profiles which in turn permitted the establishing of heat exposure times. The application of the heat flow theory indicated that for the parts in discussion a heat exposure of 6 to 8 minutes was required to obtain eutectic temperature. This result is in good agreement with the history of the flight. With this a safe assumption for the point and time of fire break-through into the cabin could be made.

Evaluation of wreckage debris and tests carried out afterwards indicate that the fire then propagated into the cabin. Most of the decorative lining in the proximity of the fire entrance area was burnt, seat cushions, covers and carpets were attacked by the high temperatures. It is established that some fire retarding materials used in aircraft interiors can burn violently under certain conditions.

It has been demonstrated by tests that seat cushions, when torn open could be set afire, regardless of their fulfilling the required fireproof tests. It can be safely assumed that crew and passengers have actively fought the fire with the means on board, this is supported by the presence of empty fire-extinguishers in the wreckage. It has not been possible to determine the exact extent of the fire in the cabin, however, time and temperatures indicate that an appreciable portion of the cabin interiors must have been burnt.

03.3 Smoke generation

The question of smoke generation was looked into independently inasmuch as smoke must have played a major role in this accident. The wreckage indicated that approx. 0.5 m² of the upper lining of the aft cargo compartment was consumed by the pre-crash fire or at least heavily attacked by the heat. The lining was of a material composition that fulfilled the relevant design requirements applicable to the CV-990A. Tests in a standard combustion chamber proved that this material would burn only when exposed to an intensive, independent fire, however, a very heavy smoke would then develop. Scale tests proved that alone the burning of the equivalent amount of the fire damaged portion of lining material would, under stationary conditions, fill the entire aircraft with smoke of such density that visibility would be reduced to less than one meter.

Besides this, the cabin fire must obviously have contributed greatly to the generation of smoke in quantity. When PVC and like materials which were being used extensively in cabin interior is combusted, a heavy smoke is generated which in addition is of a very aggressive nature as it contains hydrochloric acids and phosphate components.

Thus the build-up of a dense smoke continued, spreading everywhere including the cockpit. This is the explanation of the crews frantic calls stating "I can't see anything", the heavy smoke made it as tests proved, impossible for the crew to read the instruments.

After detailed performance analysis of the aircraft's airconditioning system it can be safely assumed that even in the selected smoke evacuation mode - which minimizes recirculation - the system did not have the capability to cope with the continuous smoke generation. With respect to the high smoke density in the cockpit the question of venting by opening a cockpit window has been raised. In fact, the ATC man in charge of the airplane, who desperately tried to save the aircraft transmitted "please open your window, SR 330, open your window", but received no response. During the test flights carried out after the accident cockpit windows have been opened. The test results, however, were disappointing as the opening of the windows only generated vortices in the close proximity of the window with no improvement to the cockpit conditions. On the other hand the opening generated noise which made radio communication impossible. By comparison of the radio transmissions background noise it could be established that SR 330 had not opened the cockpit window.

03.4 Aircraft systems analysis

The result of the parts review for pre-crash destruction, the aircraft behaviour and the radio communication with the crew allow for some assumptions on the systems integrity during the fire-on-board.

Neither the hydraulic, the air-conditioning or the fuel system have contributed to the crash and/or the fire. The structural integrity of the aircraft, including the control system have not been reduced by the fire to a critical point. It seems, however, that the coax-antenna cables, running along the floor have been damaged at an early stage by the fire, this based on the crews indication of aircraft navigation problems.

From the recording of the communication the time at which the crew donned the oxygen masks could be established to have been about 3 1/2 minutes before the impact. From the recovered 128 oxygen valves connecting the mask hoses to the oxygen supply system 40 were found in the open or semi-open position. This suggests that the passenger oxygen masks were dropped some time prior to the crash, to enable the passengers to breathe in the existing dense and aggressive smoke environment. The fact that relatively high temperatures did exist in the hatrack area suggests that some oxygen may have leaked out thus contributing to the fire by creating hot torching flames.

03.5 Summary of analysis

The local cargo-hold fire, ignited by an explosive charge, was not contained in the cargo compartment but spread approximately 6 minutes after ignition through a cabin floor vent hole into the cabin. Very high local temperatures ignited cabin and cargo-hold lining materials, including upholstery, thereby generating a very heavy smoke. It cannot be ruled out that oxygen system leakage may have contributed to the fire.

The established emergency procedures, such as smoke evacuation fire fighting, etc. were carried out, but could not cope with the situation. There are no findings which would indicate that the aircraft was uncontrollable or in any other non-flyable condition prior to the impact. It must therefore be assumed that the heavy smoke environment in the cockpit, preventing the crew to fly the aircraft by instruments, as the weather situation required, was the final cause of the crash.

04.0 Conclusion

Crash - Evaluation - Methods:

- Very detailed crash analysis, using modern scientific methods is producing very accurate results even under adverse conditions, such as high degree of destruction, etc.

Aircraft design:

- Fire containment is of major importance, special attention must be given to the design of the pressure equalization system between the cabin and the below floor compartments.
- Reliable, dependable fire and smoke detection systems shall be installed in any fireprone area of the aircraft.
- Materials used in the aircraft industry must undergo proof-testing under realistic conditions. Minimum smoke generation must be a criteria for the approval of materials such as interior linings, upholstery, etc.
- The requirement for oxygen systems and its design criteria must be reviewed to

assure minimized fire hazards.

Aircraft Operation

- Fire hazard shall be minimized by allowing smoking on board under controlled condition only and by carefully selecting, defining and limiting transportation of all restricted article cargo categories.
- On-board emergency procedures for fire- and smoke-fighting shall, in cooperation with the aircraft designer, be optimized using most modern technology.

It is clearly understood that drawing general conclusions from single accidents may be very difficult, however, the grave nature of any emergency with fire on board warrants some special attention. It is hoped that some of the afore-mentioned facts and recommendations will help to improve the flight safety by receiving the attention of the responsible functions in the industry.

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Mr Taylor: Can you just clarify how the smoke might have got from the cabin to the cockpit? Was it through the door or is there any chance that it might have been through the circulation system?

Mr Schurter: From the examination of the wreckage it became evident that the smoke did not enter the cockpit via the airconditioning system, therefore, it can be safely assumed that the smoke entered the cockpit via the cockpit door.

Mr Parker: This seems to be a classic case where the "smoke goggles" would be of no use. I think we need some means to clear the smoke from the instrument panel.

I also noted the indication of data that there were much higher temperatures at the hatrack indicating oxygen involvement.

I also note that you tend to agree with NASA's viewpoint that hardening the cargo bay is worthwhile in managing fire.

Mr Schurter: The crew had used smoke goggles but they were apparently of no value; I also agree on the cargo bays. The temperature at the hatrack had to be at least 500°C as proved by the condition of the material.

Mr Glasman: These are diffusion flames and the presence of oxygen would only have a limited influence, if any. I think it also critical to remind ourselves that what is meant by NON-flammable material is that the flame will not spread. It has nothing to do with the burning rate of the material. They are two separate phenomena. It is unfortunate that we have used the label "non-flammable" with regard to a spreading problem rather than a consumption problem. You can even make pure carbon burn if you plunge it into an intense enough flame. Non-flammable simply means if it is ignited the flame will not spread very fast.

Mr Vincent:

(1) For many years we have supplied on military aircraft a ram air scoop which is pilot operable for emergency use, for example, to disperse engine oil smoke. Has not such a simple system been provided on civil aircraft cabins to disperse smoke or fumes as you experienced?

(2) From your answer, the second question, has nothing been incorporated on later aircraft designs to improve emergency cabin environment?

Mr Schurter: This aircraft has a plenum chamber in the belly of the airplane; it does not take airconditioning air from the engine but it was not sufficient to overcome the smoke in the cockpit. There was no evidence of smoke in the plenum chamber. I believe more can and should be done in the ventilation area, however, we doubt that the ram effect will render enough pressure at the required level for passenger aircraft. There is no such installation on any civil aircraft to our knowledge nor has anything been planned for future incorporation.

Mr Madgwick: Could Mr. Schurter please clarify the design type of baggage hold. If it had been designed to the FAA "D" classification we know from test experience that this type of design is capable of containing and controlling a "normal" baggage type fire by oxygen starvation. This assumes that the baggage hold linings have not been structurally damaged by a possible explosive device. Perhaps the basic difficulty is controlling the type of items carried inside baggage and freight.

Mr Schurter: This was a "C" type cargo hold but if the bomb opened the shell even slightly you have lost your containment. The intensity of the fire seems to indicate there may have been additional air. Also the pressurization trouble indicates that this might have occurred.

Mr Bourgeat: Air Inter pour sa part a procédé des essais de dégagement de fumée en col, et, au cours de ceux-ci il est apparu au poste de pilotage que la fumée venait masquer entièrement les instruments de bord de la vue des pilotes, un matelas d'air de 10 à 15 cms empêchant la fumée de noircir les équipements. En utilisant les tubes de désembuage il a été possible de récupérer une certaine visibilité des instruments. Mais l'installation de ceux-ci est propre à la Caravelle.

Mr Schurter: We have not attempted to design a smoke evacuation device that would be able to cope with the extreme smoke generation.

On the other hand we have checked the possibility of smoke evacuation by opening of the window with negative results.

L'Accident du PP-VJZ

P.GUILLEVIC

Secrétariat Général à l'Aviation Civile

PARIS
FRANCEExposé n°30

L'accident du PP-VJZ

Le bureau des enquêtes sur les accidents du secrétariat général à l'aviation civile a conduit au cours des dernières années deux enquêtes sur deux catastrophes aériennes qui avaient comme commune origine un incendie dans les toilettes.

Le premier cas est celui de la Caravelle F-BOHB qui s'est abîmée en mer au large du cap d'Antibes le 11 septembre 1968 et le second celui du Boeing 707 PP-VJZ qui s'est écrasé à Saulx-les-Chartreux près d'Orly le 11 juillet 1973, entraînant respectivement la mort de 95 et de 123 personnes. L'auteur expose brièvement les circonstances de ces deux accidents qui se sont déroulés l'un et l'autre très rapidement, la méthode employée pour le repêchage des débris de la Caravelle qui gisaient par 2300 mètres (7000 pieds) de fond, les analyses et expertises auxquelles il a été procédé, et leurs conclusions. Il évoque les mesures immédiatement applicables sur les avions de transport pour éviter la répétition de semblables catastrophes.

L'accident du Boeing 707 PP-VJZ qui s'est écrasé à Saulx-les-Chartreux près d'Orly le 11 juillet 1973 à la suite d'un incendie qui s'était déclaré dans une toilette est encore présent dans toutes les mémoires. Ce qui a sans doute particulièrement frappé tous ceux qui s'intéressent à la sécurité aérienne est le contraste entre l'apparente futilité de l'incident survenu à bord et ses tragiques conséquences.

Cette catastrophe n'était pourtant pas la première de cette nature : le 11 septembre 1968 la Caravelle F-BOHB s'était abîmée en mer au large du cap d'Antibes, dans des circonstances presque semblables, entraînant dans la mort ses 95 occupants. Il nous est donc apparu digne d'intérêt de rappeler le déroulement de l'accident du F-BOHB et les conclusions auxquelles l'enquête avait alors abouti.

Le F-BOHB avait décollé à 9h09 d'Ajaccio pour une courte étape à destination de Nice. Son vol s'était déroulé normalement jusqu'à 9h30m, en l'absence de tout phénomène météorologique dangereux.

A 9h30m20s, l'équipage qui 30 secondes plus tôt correspondait encore très normalement avec le centre de contrôle régional d'Aix-en-Provence signale pour la première fois :
"on a des ennuis"

et demande à faire une approche directe sur Nice.

Il reçoit l'autorisation de se diriger directement sur l'aérodrome de Nice et de descendre de son niveau de croisière 160 au niveau 50.

Il entre en contact avec le contrôle d'aérodrome de Nice peu avant 9h32 ; en disant :
"nous avons le feu à bord - nous demandons l'atterrissage d'urgence".

A 9h32, il indique :
"nous sommes en vue du sol, en bonne visibilité"

A 9h32m30s "...on va crasher si ça continue"

Le contrôle d'approche de Nice observe l'écho de l'avion à 25 milles nautiques puis à 22 milles nautiques de l'antenne radar.

Cet écho s'évanouit quelques secondes après 9h33.

L'alerte est immédiatement déclenchée et des avions, hélicoptères, bâtiments et vedettes se dirigent aussitôt vers le lieu de l'accident.

La distance de la côté, invisible en surface de la zone du crash et la visibilité médiocre au niveau de la mer rendirent les recherches difficiles et ce ne fut qu'à 11h22 qu'un Constellation du service recherches et sauvetage découvrit à plus de 20 milles au sud du cap d'Antibes une nappe de kérosène, de menus débris et des cadavres flottants.

La reconstitution de la trajectoire devait ultérieurement montrer qu'à peine plus de 3 minutes s'étaient écoulées entre la première annonce d'ennuis à bord par l'équipage et la chute de l'avion à la mer ; l'équipage lui-même n'avait émis aucun signal de détresse et ce n'est que quelques dizaines de secondes avant le crash qu'il semble avoir eu conscience de la gravité et de l'imminence du danger.

Les corps recueillis étaient indemnes de trace de brûlures pour la plupart ; seuls quelques uns d'entr'eux portaient des traces très superficielles. De même seul un très petit nombre de débris flottants portaient des traces de fumée ou de début de combustion.

Le caractère insolite de l'accident et sa soudaineté incitèrent la commission d'enquête à mettre tout en oeuvre pour tenter de repêcher les débris engloutis qui seuls pouvaient lui permettre d'établir les causes de la perte de la Caravelle.

Au cours de leur repêchage dans la journée de l'accident, corps et débris inégalement soumis au vent et à un courant faible, mais non négligeable, variable et difficile à estimer comme il est fréquent dans cette zone, étaient déjà dispersés dans une ellipse de plusieurs milles nautiques de grand axe. Les positions données par les bâtiments sauveteurs différaient entr'elles de plusieurs milles, également.

L'observation de l'écho de l'avion sur l'écran radar de Nice était elle-même de peu de secours car elle n'avait pas été enregistrée et après la disparition de l'écho, l'avion avait traversé à grande vitesse une couche d'atmosphère d'environ 2000 pieds dans une direction inconnue.

Des calculs, d'ailleurs approximatifs, aboutirent à la définition d'une zone de recherches de l'ordre de 35 milles carrés.

A la dimension considérable de cette zone, la profondeur de la mer aux environs du point de chute qui était comprise entre 2200 et 2600 mètres ajoutait des problèmes techniques tout aussi importants.

Les moyens et techniques divers jusqu'alors employés pour des opérations de récupération en profondeur paraissaient inadaptés à une opération d'une telle difficulté et il fut nécessaire d'étudier et de mettre en oeuvre un procédé original.

Le système utilisé était essentiellement constitué par un filet dont la forme avait été choisie en fonction de sa vitesse de déplacement, dont l'ouverture latérale était assurée par deux navires câbliers, choisis en raison de la longueur des câbles nécessaires (5 à 6 kilomètres), et remorquant l'engin suivant des caps légèrement divergents.

L'ouverture verticale était obtenue par des flotteurs spéciaux capables de résister à la pression correspondant aux profondeurs citées.

Les dimensions d'ensemble du système : environ 1 mille nautique entre les deux bateaux, 5 à 6 kilomètres de câbles derrière chacun d'eux, 2 kilomètres à 2 kilomètres et demi dans le sens vertical posaient un problème particulier de localisation de l'engin de dragage qui fut résolu par l'emploi d'un interrogateur et de récepteurs acoustiques associés à un petit calculateur. Ce système permettait de connaître la position de l'engin qui mesurait 100 mètres de large à quelques dizaines de mètres près.

Les opérations effectives durèrent en tout environ 120 jours mais les servitudes normales des navires câbliers imposèrent de répartir ces 120 jours en quatre périodes dont la première commença le 30 novembre 1968, moins de deux mois après l'accident et dont la dernière ne put avoir lieu qu'au mois d'avril 1971, soit environ deux ans et demi après l'accident.

En raison des conditions propres aux grandes profondeurs les 10 ou 12 tonnes de débris récupérés ne présentaient heureusement aucune altération physique ou chimique depuis leur immersion.

L'enregistreur de bord fut repêché mais le film photographique support de l'enregistrement était voilé dans la partie correspondant à la trajectoire finale de l'avion ; les paramètres de trajectoire étant seuls enregistrés, la lecture de la bande n'aurait d'ailleurs apporté que peu d'éléments utiles.

Les débris repêchés provenaient de toutes les parties de l'avion et leur examen permit d'exclure un certain nombre d'hypothèses notamment celle d'une avarie réacteur, celle d'un incendie provoqué par les accumulateurs ou les circuits de kérosène ou d'hydraulique, - du liquide ayant été retrouvé dans les bâches -.

Il apparut que la seule partie de l'avion qui avait subi l'incendie était la partie arrière de la cabine. Sa reconstitution partielle sur un gabarit permit de localiser avec certitude le foyer de l'incendie dans la toilette droite et de faire apparaître, toutefois, que le feu avait trouvé un étroit chemin de propagation au plafond de l'avion le long de la garniture des luminaires facilement combustible. Cette zone brûlée très localisée ne s'étendait cependant pas au-delà du couple 50.

Dans la toilette elle-même la partie correspondant au meuble contenant le chauffe-eau et la boîte à déchets était la plus touchée, bien que la cloison avant de ce meuble ait été simplement chauffée sur sa face intérieure et soit demeurée presque intacte. Le bac de Boltaron formant la partie inférieure de ce meuble n'était que partiellement détruit ; la résine du tapis compartiment de la toilette n'avait été consumée qu'en un seul endroit, sur une surface de quelques décimètres carrés.

L'examen des débris fit également apparaître que les extincteurs qui étaient alors disposés à l'extrême arrière des cabines des Caravelles, et donc au-delà de la zone qui avait subi l'incendie, n'avaient pas été utilisés.

L'équipage avait procédé à une manœuvre d'évacuation de fumée, la vanne de régulation ayant été trouvée ouverte et portant des traces de suie. Des traces de fumée sur la paroi externe du fuselage indiquaient également que les glaces latérales du poste de pilotage avaient été ouvertes.

Les examens et analyses permirent d'écarter l'hypothèse d'un acte criminel, par engin explosif ou incendiaire et de retenir parmi les causes possibles de l'incendie soit une avarie de régulation du chauffe-eau, soit l'imprudence d'un fumeur.

Il apparaissait enfin que, le feu ne s'étant pas communiqué au liquide hydraulique, l'étendue limitée de l'incendie ne compromettait pas la navigabilité de l'appareil.

Les expériences de laboratoires révélèrent par contre que certains des constituants de l'aménagement intérieur de la cabine touchés par la combustion pouvaient dégager rapidement des gaz suffocants de grande acidité (PH de 2 à 3).

Pour expliquer la catastrophe, la commission retenait, en définitive, deux hypothèses :

soit une panique des passagers, refluant vers l'avant et envahissant le cockpit jusqu'à rendre tout mouvement efficace impossible pour les pilotes,

soit la suffocation de l'équipage au cas où les masques n'auraient pas été employés assez tôt ou n'auraient pas assuré une protection suffisante.

L'analyse des circonstances de l'accident du PP-VJZ devaient apporter une certaine lumière sur les processus de nature à provoquer l'accident du F-BOMB.

Le Boeing 707 PP-VJZ avait quitté Rio de Janeiro le 11 juillet 1971 pour un vol direct à destination d'Orly.

Entré en contact à 13h40 avec l'ACC de Paris il était autorisé à monter à l'altitude de croisière et à effectuer sa descente, par paliers intermédiaires, jusqu'à l'altitude de 10000 pieds atteignant à 13h55.

L'avion entrait en contact avec Paris-Contrôle à 13h58 et indiquait les faits suivants :

"I have a problem aboard....fire.....request immediate descent....."

Il était immédiatement autorisé à descendre à 3000 pieds et à s'apprêter pour la piste 07 qui lui permettait une approche directe.

L'avion accusait réception et à 13h59, Paris contrôle lui indiquait sa position à 22 milles nautiques de la piste, puis lui assurait un guidage radar.

A 14h01, Paris indiquait au PP-VJZ qu'il se trouvait à 12 milles de la piste, en bonne position pour l'ILS.

L'avion accusait réception à 14h01m20s ; ce fut son dernier message.

Le PP-VJZ effectue un atterrissage de fortune sur un terrain plat et dégagé à Saulx-les-Chartreux. Cet atterrissage, train sorti, bien qu'assez dur n'occasionne pas de dommages sérieux mais pendant la course au sol de l'avion l'aile gauche se brise en heurtant un arbre ; une branche d'arbre pénètre dans le poste de pilotage blessant grièvement les deux pilotes ; l'un des mécaniciens heurte violemment de la tête un des panneaux du cockpit et il ne pourra pas être réanimé après son évacuation par les sauveteurs. L'atterrissage et la décélération de l'avion ne paraissent, par ailleurs,

pas susceptibles d'avoir causé des blessures aux occupants notamment aux passagers attachés.

Dix membres d'équipage évacuent l'avion par les fenêtres latérales du poste de pilotage, la porte des passagers de l'avant et la porte du galley avant.

Les pompiers de la ville la plus proche (Longjumeau) arrivent sur les lieux environ huit minutes après l'atterrissage forcé mais dès ce moment l'ensemble de la cabine est la proie des flammes. Pompiers et sauveteurs pourront cependant retirer par la porte avant deux membres d'équipage et un passager qui sera le seul à survivre.

Les témoignages des survivants ont permis de reconstituer au moins en partie le développement du sinistre et les actions tentées pour le combattre.

Ce furent les 3 stewards en service à l'arrière de l'appareil qui furent les premiers alertés par une passagère s'enfuyant de la toilette babord arrière. Par la porte ouverte, ils aperçurent une fumée blanche qui envahissait la partie supérieure de la toilette mais ne virent aucune flamme.

L'un des stewards, qui n'a pas survécu, utilise un extincteur tandis qu'un autre se rend au poste de pilotage pour prévenir l'équipage. Le steward, chef de cabine et l'un des mécaniciens (l'équipage était doublé) se dirigent alors vers l'arrière mais la fumée a déjà envahi une partie de la cabine et rend impossible l'accès aux toilettes. Le mécanicien revient alors au poste de pilotage pour se munir d'un masque, d'une bouteille d'oxygène portative et d'un extincteur et repart vers l'arrière. Ce mécanicien n'ayant pas survécu, il n'a pas été possible de savoir ce qu'il a pu faire.

Dès ce moment une épaisse fumée noire remplit la cabine touriste et malgré le rideau de séparation envahit la cabine de 1ère classe, puis le cockpit. Un certain nombre de membres d'équipage mettent les masques disponibles, le commandant de bord lui-même ne peut y parvenir par suite de la rupture d'une courroie.

La fumée remplit rapidement le poste de pilotage et rend les instruments invisibles ; les glaces latérales sont ouvertes sans apporter d'amélioration sensible. L'atterrissage de fortune est décidé.

Le mécanicien avait demandé entre temps à l'un des stewards d'ouvrir les issues de secours mais celui-ci n'avait pu remplir sa mission en raison de l'obscurité totale. Il est à noter que les seuls survivants se trouvaient dans le poste de pilotage ou contre la cloison et ont pu ainsi profiter de l'entrée d'air frais par les glaces latérales. Ceux qui ne disposaient pas de masques se sont pour la plupart protégés à l'aide de serviettes humides.

L'autopsie des victimes révélait que la plupart d'entr'elles avait succombé à l'inhalation de monoxyde de carbone dont on sait qu'une concentration très faible dans l'air (0,2%) suffit à provoquer le coma asphyxique, une concentration de 1% entraînant la mort quasi immédiate. Les autres victimes, environ le dixième, ont succombé par suffocation provoquée par les gaz agressifs (acides chlorhydrique, cyanhydrique, composés de brome) dégagés par la combustion ou la pyrolyse des matières plastiques ou des autres constituants de l'habillement de la cabine.

Il est remarquable que les survivants de l'équipage n'aient pas fait état, sauf au tout début de l'incident, d'une panique des passagers ou d'un reflux de ceux-ci vers l'avant de l'appareil afin de s'éloigner des fumées venant de l'arrière. Cette absence de réaction s'explique sans doute par l'action toxique extrêmement rapide des fumées inhalées aussi bien par les passagers de classe touristes que par les passagers de première classe, pourtant partiellement protégés par une cloison et un rideau.

La commission a fait prélever 17 échantillons de matériaux composant l'habillement de la cabine du PP-VJZ. Parmi ces 17 échantillons, un seul, la fibre de verre peut être considéré comme incombustible et non susceptible d'émettre des vapeurs toxiques.

Parmi les autres, une dizaine peuvent être classés comme facilement combustibles, s'inflammant parfois par simple chauffage et entretenant leur propre combustion.

Sauf quatre d'entr'eux ces matériaux dégagent par pyrolyse ou combustion des vapeurs toxiques : acide chlorhydrique et plus souvent encore acide cyanhydrique. Il est à noter que certains, à base de bois par exemple, sont rendus toxiques par les produits ignifuges dont ils sont recouverts ou imprégnés.

La plupart des échantillons prélevés dégagent en brûlant des fumées blanches ou noires, ou parfois les deux selon le stade de leur combustion.

L'enquête sur l'accident du Boeing PP-VJZ a permis de déterminer que l'incendie s'était bien déclaré dans la zone des toilettes arrière au-dessus du plancher de la cabine mais il n'a pas été possible d'en préciser avec certitude le foyer initial.

L'expertise des chauffe-eau, en particulier, n'a pas révélé les détériorations qui avaient été constatées à l'occasion d'incidents survenus à des appareils de même modèle.

La restitution des données de l'enregistreur a d'autre part montré que celui-ci s'était arrêté au niveau de vol 80, c'est-à-dire environ 3 minutes avant que l'équipage ait aperçu les fumées s'échappant de la toilette babord arrière.

Aucune anomalie mécanique n'ayant été découverte sur l'enregistreur, cet arrêt ne peut s'expliquer que par l'interruption de l'alimentation électrique, interruption qui peut être corroborée par le fait qu'au début de l'incident l'équipage a constaté qu'un des disjoncteurs, s'était déjà déclenché. On ne peut donc écarter l'hypothèse selon laquelle au moment où la fumée s'est manifestée le feu sévissait déjà depuis plusieurs minutes sous forme discrète dans la toilette babord ou dans la toilette tribord avec laquelle elle présentait plusieurs orifices de communication.

L'équipage du PP-VJZ n'a pris que tardivement conscience de l'importance du danger et de l'imminence de la catastrophe et n'a pas été en mesure de lutter avec efficacité contre l'incendie. Les témoins survivants ont tous déclarés qu'ils n'avaient aperçu de flammes à aucun moment et les extincteurs ont été déchargés au hasard, dans la fumée.

Les accidents du F-ROHB et du PP-VJZ ont en commun une même origine, un déroulement extrêmement rapide et leur très lourd bilan en vies humaines. Les informations recueillies par la commission d'enquête fournissent d'autres exemples d'incidents de même nature, dont certains se sont produits après la catastrophe du Boeing d'Orly et que l'action immédiate et judicieuse de l'équipage a seul empêché de se développer aussi tragiquement. Dans certains cas l'utilisation de tous les moyens du bord et l'utilisation de haches pour dégager l'accès au foyer de l'incendie ont été nécessaires.

L'expérience des deux accidents cités permet d'affirmer qu'en certains cas un délai de quelques dizaines de secondes dans l'attaque du feu aurait très vraisemblablement entraîné des conséquences semblables.

Les cas de la Caravelle et du Boeing soulignent, une fois de plus, l'importance de la diffusion immédiate à l'échelon mondial des informations sur les accidents et sur les incidents comportant des enseignements pour la sécurité.

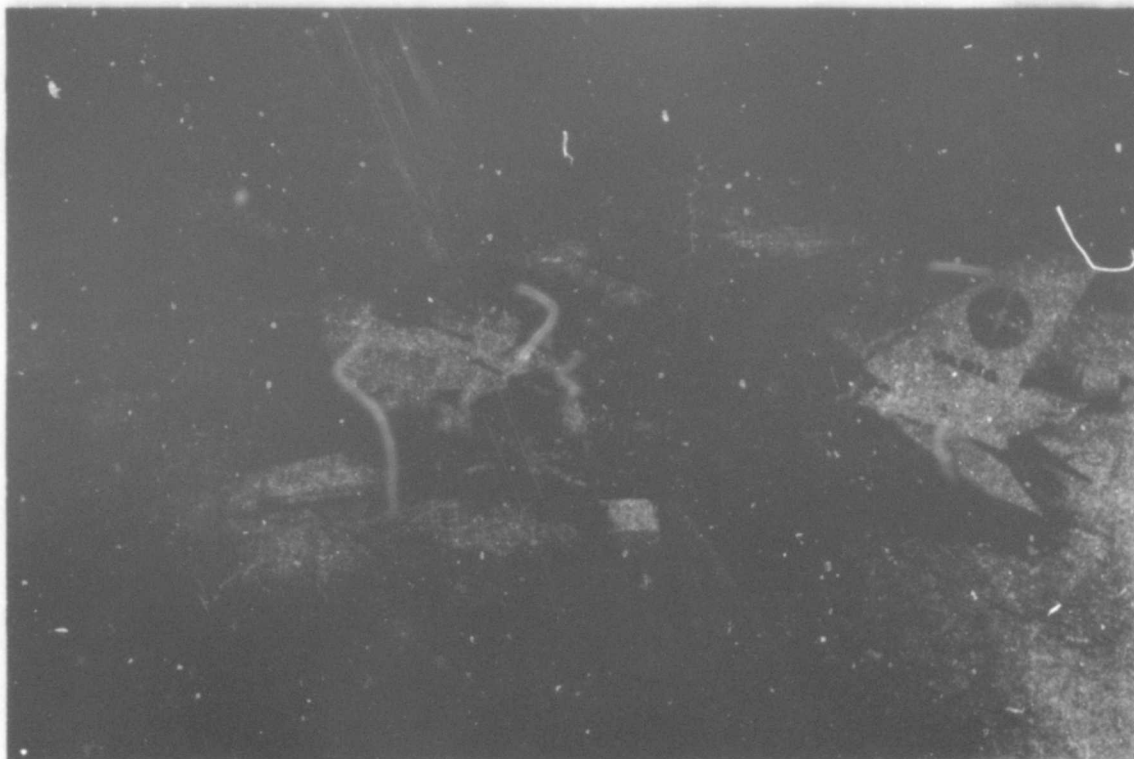
Les incendies de cabine demeureront pendant longtemps encore un danger sérieux pour la sécurité des vols.

Les phases de vol de montée et de descente au cours desquelles les passagers demeurent à leur siège et le personnel est occupé à des tâches multiples sont les plus critiques pour cette catégorie d'incidents.

Les études entreprises montrent que si des progrès sont souhaitables quant au choix des matériaux d'aménagement des cabines et à la protection des personnes à bord, équipage et passagers, ces progrès ne pourront apporter, à court terme, une solution complète au problème posé.

Dans l'intervalle les autorités chargées de la navigabilité, les constructeurs et les exploitants devront étudier avec un soin particulier :

- l'élimination des sources d'incendie à bord
- les moyens de détection des fumées et des élévations de température, en particulier dans les volumes clos,
- l'accessibilité de tous les foyers d'incendie éventuels,
- l'équipement de l'avion en moyens de lutte,
- enfin et peut être, principalement l'instruction et l'entraînement des équipages dans ce domaine.



DISCUSSION

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Mr Parker: Do you think the fire could have spread through the overhead plenum and into the aircraft from there? Did it appear that the passengers were incapacitated prior to the fire?

Mr Guillevic: Oui, très probablement, car il n'y a eu aucune panique à bord. Les passagers qui étaient à l'arrière, c'est à dire près du foyer, n'ont pas pu essayer de quitter la zone. Alors que tout l'équipage s'est réfugié à l'avant, aucun des passagers sauf un n'a eu la possibilité de défaire sa ceinture et d'aller vers l'avant. Par conséquent, si la mort n'a pas été immédiate, je pense que l'incapacitation des passagers a été elle-même immédiate; peut-être même a-t-elle précédé la fumée visible.

Mr Sarkos: Since one passenger survived out of 120 it seems quite likely that the passengers were incapacitated at the time of the crash and were killed by the ensuing fire, perhaps if the fire-fighters could have been on the scene quicker there could have been more survivors.

Mr Guillevic: Les pompiers qui sont arrivés sont ceux de la ville la plus proche. Ils sont arrivés relativement rapidement compte tenu des circonstances: en 8 minutes. Néanmoins, certaines personnes ont vu l'accident et ont fait très courageusement ce qu'elles ont pu: elles ont demandé à l'équipage où étaient les issues de secours par où elles pourraient essayer de sauver les passagers et ont vraiment fait leur possible. Elles ont pu tirer trois corps qui étaient près d'une issue, dont celui de ce passager qui, finalement, a été sauvé. Je ne pense pas qu'une intervention des pompiers, même rapide, aurait changé les choses.

Mr Bourgeat: D'après Mr.Morsch, Coordinateur Sécurité de la Compagnie VARIG, le passager rescapé provenait de la classe touriste et s'était échappé de ce compartiment dès le début de l'incendie et avait pris place soit en première classe, soit dans le poste repos équipage. On ne sait pas s'il se trouvait assis sur un siège ou couché par terre. Il y aurait peut-être une explication à rechercher en ce qui le concerne.

Mr Guillevic: Je ne suis pas absolument sûr de la réponse; je le vérifierai. Cependant, je pense que, lorsqu'on l'a sorti, il était effectivement couché par terre près d'une issue à l'air libre. Je précise que c'était un garçon d'une très solide résistance physique, jeune et très résistant.

Mr Blavy (Aerospatiale): Compte tenu du fait que la première fumée a été détectée dans une toilette arrière, en haut d'une cloison, je crois me souvenir, ce qui tend à prouver que le feu n'est pas forcément celui d'une poubelle, et que les fumées sont arrivées jusqu'au milieu de la cabine et sorties par le plafond, ce qui confirme l'hypothèse de Mr.Parker, je voudrais savoir quelles raisons vous ont poussé à abandonner l'hypothèse d'un feu en soute. De plus, pendant la descente, un témoin au sol avait vu une flamme s'échappant de la partie inférieure du fuselage.

Mr Guillevic: L'hypothèse de l'incendie en soute est complètement écartée. La soute avant est absolument intacte. La partie inférieure n'est pratiquement pas touchée, sauf en un point particulier où se trouvaient les bouteilles d'oxygène. Par contre, la partie au-dessus du plancher et dans les toilettes a sérieusement brûlé. A mon avis, ce n'est peut-être pas dans la toilette babord que le feu a pris, mais plus probablement dans la toilette tribord, les deux communiquant très largement par la garniture et le faux plafond. J'imagine mal, en effet, qu'une passagère ait pu sortir malgré le volume de fumée qu'il y avait déjà. Je pense donc qu'elle devait se trouver dans la toilette qui n'était pas la toilette touchée. Il est très difficile de se faire une idée car l'avion a considérablement brûlé ensuite et que la présence des bouteilles d'oxygène qui se sont décapsulées fausse l'étude du cheminement des flammes.

A P P E N D I X

**ROUND TABLE DISCUSSION HELD AT
CONCLUSION OF THE MEETING**

Professor I.GLASSMAN (Chairman) :	USA
Mr B.P.BOTTERI	USA
Mr M.GUILLEVIC	FRANCE
Mr I.I.PINKEL	USA
Dr R.B.WHYTE	CANADA
Mr A.F.TAYLOR	UK

ROUND TABLE DISCUSSION

The Round Table session was opened by Professor Glassman who noted that a group of experts were present who rarely have a chance to meet on an international basis. The critical question for the round table session was what can actually be done to improve aircraft fire safety and survivability in the event of a fire; whether this fire takes place in flight, as a result of a crash, or as a result of sabotage. The key comments of the round table experts, as well as the other meeting participants, are grouped under six major headings. These are: Analysis, Fuels and Fuel Systems, Materials, Emergency Procedures, Protection Systems, and Approach. A Summary of the discussion in each of these areas follows. In some cases where individuals provided written versions of the text of their comments, these are also included.

CRASH ANALYSIS

While a standardized or mil spec aircraft crash or aircraft fire does not exist to be used as a design criteria, there are certainly many common characteristics or fundamental analyses possible for the crash situation. The work of the NASA Lewis group in the 1950's has shown the value of this type of analysis. It is unfortunately a very expensive approach, but clearly shows that there are several fundamental methods of crash evaluation which can be analyzed. Major considerations are, of course, the fuel spillage patterns, the basic rupturing of the fuel system, how it takes place, and ignition sources which occur. The approach also clearly shows that under no circumstances is it possible to design a system which is completely guaranteed fireproof, or crash proof. There is always the unexpected means by which a fire starts, but much knowledge can be gained through testing. A key point made in this area was that as aircraft grow larger, the fire hazards do not increase, in fact they tend to decrease. This is true not only of the fire hazards but also the deceleration effects on individuals in the event of a crash landing. The reason is that larger aircraft can better survive collisions with obstacles which are generally of a fixed size; that is, objects which could ordinarily stop small aircraft are simply overpowered by the larger aircraft. Trees and rocks may not penetrate the stronger structure of larger aircraft, or if they do, the openings that may be made in fuel tanks will still be no larger than what they were in a small aircraft. It would appear that with the advent of larger craft, the chances of surviving the deceleration effects of a crash landing would be significantly increased and the fire hazard not increased proportionately. In fact, if fuel is spilled only on one side of the aircraft, it should be possible for people to exit at a reasonable distance from the area of the fire. Thus the optimism for success in life-saving fire suppression efforts is greater with the advent of larger aircraft.

There was general agreement at the meeting that more emphasis should be placed on analysis of incidents. Several times throughout the meeting in discussing actual accidents, it was related that incidents on board which at first appeared very minor, eventually resulted in the loss of the aircraft. It becomes critical for the designer to pinpoint these hazard areas. Hazard areas can be determined more effectively in analyzing incidents where injuries have not occurred, where emotion is not involved and where there is no litigation. There is also the tremendous advantage of witnesses who can be quite objective. This type of investigatory analysis probably does not receive the full emphasis that it is due. In the area of fatal accidents the need for the use of more modern techniques of physiological investigation was also emphasized. Dr. Einhorn made the point that autopsies cannot be performed days after an accident because of changes in blood chemistry. The presence of hydrogen cyanide can simply indicate the body's processing of burned tissue and not necessarily its presence from inhalation. On the other hand, it could be a correct cause of death, but this must be determined very shortly after death, not days later or after bodies have been in cold storage. He also stated that while carbon monoxide is frequently listed as a major cause, quite often very minute amounts of other substances could cause a condition whereby a person could not act properly to save himself and would as a result inhale too much carbon monoxide resulting in his death. The combined effects of alcohol, carbon monoxide and smoking on the capabilities of people who are caught in the fire situation were discussed at length and it was pointed out that these factors work to strongly decrease survivability. It was also pointed out that it is not so much the level of CO present but the rate of acquisition which has drastic effects on the human body. The direct quote from Professor Einhorn on the subject is included at this point.

- "(1) The LD₅₀ values cited do not relate to the response of humans in a fire. This test was developed for evaluation of single components only. A behavioural test such as one which measures time to incapacitation is more realistic for evaluation of fire hazards.
- (2) Carbon monoxide by itself is not the major cause of fire death. CO, CO₂, O + temperature in combination with other noxious and toxic species result in incapacitation and death due to fire."

Professor Einhorn also discussed sections from another paper on toxicity which reported very rapid, effective and inexpensive analysis methods for the effects of toxic gases. His technique is basically the use of small animals rather than being dependent on very expensive mass spectrometry techniques. By the use of small animals, simple

techniques, such as cannulating the arteries and veins and monitoring the partial pressures of gases in these animals, can be of great value. It is quite easy to detect gas levels of carbon monoxide and hydrogen cyanide within their body and determine their reactions. He suggests even simpler techniques for the first analysis of the toxic effects of various materials by simply performing tests like taking the animal and determining its reactions in a short fall. Techniques such as drawing a circle on the ground, putting the animal into it and seeing how quickly it moves out can also be of value. While there are differences with different animals and it is not directly related to humans, this is a very quick way to get an indication of which gases should be investigated further. The first indications of depressed reactions in the animal's nervous system are a very inexpensive way to get clues as to what materials need investigation.

FUELS AND FUEL SYSTEMS

In the area of fuels there was considerable discussion on the statistics presented in several papers to show the differences in results after many years use of kerosine and wide cut fuels. The advantage of kerosine and wide cut fuels over gasoline can not be clearly defined because, as was pointed out by several participants, the piston-engine aircraft using gasoline are quite different from jet aircraft and there are much different ignition sources and spillage opportunities in a crash. Some of the possible disadvantages of anti-misting fuels were discussed: inability to be absorbed into the ground during a crash, storage, and evaporation problems. Other questions are how these additives will react with water and cause clogging. The positive side is well summarized by the quoted statement by Mr. Miller, of RAE, which follows:

"There appears to be some doubt about the progress made in the safety fuel area since the 1971 meeting of this Panel. At this meeting I showed a film and talked about the fire resistance of anti-misting fuels which were then being studied in the UK only. At that time we anticipated problems in virtually all areas from the refinery to the jet pipe, some of which appeared very severe indeed. Since then we have improved our fuels considerably. The latest fuel appears to give either complete or very much enhanced fire resistance in a severe but survivable crash occurring at 120 mph with a wide range of ignition sources including a running engine. The efficiency of centrifugal pumps at low temperature (-35°C) with our latest fuel approaches that with Avtur instead of being down by a factor of 4-10 as in 1971. As I said earlier there are a number of aircraft problems remaining including filtration, heat transfer and compatibility with the engine fuel control system but we have a solution to most of these problems by degrading the fuel. The search for an efficient mechanical degrader suitable for aircraft use is currently absorbing a large part of our effort. The other area which appeared daunting in 1971 was that of ground handling. Our later fuels are capable of being added at the aircraft fuelling point and we have achieved some preliminary success in doing this in the laboratory although much work on full scale testing needs to be done. Given success in this area we can bypass the ground handling area. We have only recently carried out an engine test on an anti-misting fuel which proved very successful and certainly indicated no insuperable problems in this area with FM9 modified fuel, providing it can be predegraded.

The other area in which we have made progress is in that of cooperation with workers in the USA who are now joining us in work on anti-misting fuels rather than the thickened fuels which occupied so much of their effort before 1971. The US Navy, Army and Air Force have all carried out programmes on anti-misting fuels, as has FAA, and NASA is now entering the field. I was encouraged by a slide shown here, by Dr. Weatherford which showed schematically the way in which he thought these fuels could be used in an aircraft. The slide was almost identical with one of my own and shows that we are all coming to very similar conclusions about the basic problems to be solved and ways of solving them. I believe that progress in this area since 1971 has been very considerable indeed. Nevertheless it is clear that we should not underestimate the problems of introducing into an aircraft fuels with physical properties significantly different from those of kerosine. These problems are very great and quick solutions cannot be expected".

The fuel and fuel additive problem will become more critical as oil shortages force the use of fuels which are not necessarily optimum. Wide cut fuels and the use of various grades of JP which are not necessarily optimum for additives are all influencing the additive programme and have in fact resulted in some de-emphasis of these programmes at this time. The key problem discussed in the use of additives was the degrading necessary to process the fuel through the engine. It was also pointed out that with the current high level of fuel and oil temperatures in operational aircraft any additional heat from a degrading process could be prohibitive. The early experience in degrading of petroleum products, specifically with multiviscosity oils showed that degradation takes place very easily, to a point. It was possible to degrade some of the early multi-viscosity oils simply by shaking the can. But after a certain percentage of degradation the molecular breakdown becomes much more difficult to achieve and fairly substantial quantities of energy may be involved. It was mentioned that volatility alone is certainly not the only criteria, the spontaneous or auto-ignition considerations as well as the flashpoint and the vaporization characteristics are equally important. The vaporization characteristics are in fact critical in the consideration of battle damage or projectile impact where low pressures can exist for a short time after the skin is ruptured. The ignition possibility is extremely high because of the sources present and the vaporization occurring under these conditions.

In the area of overall fuel systems the discussion opened on the rather bright note that design improvements have made this a rather insignificant area as far as current accident statistics are concerned. The chances of fuel

systems being responsible for a fire in natural flight are extremely limited and statistics show more emphasis on more sources such as aircraft cabin interior fires.

Although nitrogen inerting systems, or systems which result in oxygen poor inert air over the tanks, can be very effective, participants pointed out that these procedures introduce one more system for the pilot to monitor. Such inerting systems are only used on a demand basis such as: for take-off, hostile situations, and landing. Another workload item for the pilot could have a detrimental effect on safety. The results of tests with these systems, however, seem to indicate that they were very promising and perhaps quite worth the extra workload involved for the pilot. Many more things could be effected in the area of fuel system safety: automatic shut-off systems for the condition under which a major part of the aircraft such as a wing torn off in a crash has ruptured the body; automatic systems which shut off flow through connecting lines at the time of break away, etc., There are, in fact, thousands of crash worthy fuel systems flying which are very effective. Most are in helicopters which use break away fuel lines. Of course there can be problems in applying this technology to large aircraft. The technology is by no means directly transferable, but there are certain techniques which can be modified and used. Looking at the fundamentals of the design involved in the crash worthy systems for helicopters could inspire techniques applicable to large aircraft. These helicopter systems use JP-4 successfully, which is a very high flash point fuel. Urethane foam systems for safety, both internal and external to the tank, were discussed from the aspect of the difficulties that they present in inspection and it was mentioned that some new foaming techniques may overcome this obstacle. However, there is suspicion of deterioration of these foams in service and during exposure to fuel. The point was made that certainly there must be a very specific distinction made between designing for hostile conditions and designing for normal fires, but that this difference does become smaller as one looks at possible sabotage efforts on aircraft.

MATERIALS

The discussion on materials was opened with the comment that this area is certainly an extremely important one, has many spin-off applications into other fields, and therefore research dollars spent in this area have an extremely high rate of return. A materials discussion was also used to point out the classic problems of working in the fire safety field; that is, solving one problem area brings out others that would not have even been noticed before. The basic question in the materials technology discussion was the generation of possibly toxic fumes and large quantities of smoke from the non-flammable materials which are being widely used in cabin interiors. Many of the materials which aid in the rapid extinguishment of fires or support combustion to a very limited extent generate products which are toxic or at least intoxicating and can result in a decreased capability of people to react to a fire situation. An equally important part of this discussion was the discussion by Dr. Einhorn on quick ways to determine toxicity of materials in combinations to be used in typical aircraft interiors. The combination of the oxygen system perchlorate candles and urethane foam used in some aircraft comes close to a solid propellant composition. Here is a case where improved safety and design changes combined can bring new problems to the front. Materials was an area where all members felt strongly that considerable research and improved techniques were needed, as well as development of new non-flammable materials with very limited or no fume or smoke generation. In the field of exterior materials there was also some discussion relating to fuel spillage. The important criteria was possible ignition sources. The primary sources are the sparks generated by the aircraft sliding over the ground. Titanium is probably the worst material since it generates very high potential sparks. Comments on the sparks generated from projectiles striking titanium skinned combat aircraft confirmed this fact. The next worst situation is steel which varies with its carbon content and alloys. Aluminium is obviously the safest because the sparking which occurs has a very limited potential and chances of ignition are therefore also extremely limited. Possibly, a combination of materials used on the lower half of the aircraft or even a cladding which would cut down possible spark generation would be an extremely worthwhile investment, although it does of course present design problems.

In many countries, after initial designs are reviewed, the requirements are then frozen. By the time the aircraft is certificated and in service it is quite possible to be five years behind the existing technology. The question of getting new technology into aircraft quicker and finding ways to fund changes in materials for aircraft in service is an important one. In many cases even though better materials are available, they are not available in quantity or not approved for use by the aircraft manufacturers nearly as quickly as they would like to have them. Of course, all these changes are cost factors which influence airline operations. Safety, while a very important feature to all aircraft companies, is not a marketable item, simply because it is not an area which can receive emphasis in the relationships with the public.

EMERGENCY PROCEDURES

Procedures to improve fire safety were discussed over a very large range of approaches. Initial comments were that perhaps before consideration is given to establishing new restrictions and new safety equipment requirements, that a complete analysis of existing safety equipment be made to determine whether some changes are truly required in view of past experience. Life rafts and life jackets supplied in an aircraft along with their inflating candles amount to 1750 pounds for 150 passengers. These are items which have extremely limited use and the weight could possibly be used better, for example, in sprinkler systems for hazard areas such as the toilet cabins where several fires have

been known to start. Little weight would be necessary for a sprinkler system in these areas. Suggestions were made that the aircraft could even carry its own limited supply of extinguishment agents in the hull for spillage at the time of a crash impact. Break away fittings in fuel systems involve some small weight penalties, but other equipment which has very limited use could be considered as having a weight penalty, also.

Specialized training for crews operating in a cabin interior filled with fumes and smoke would seem to be a necessary item. Emergency exit operations in this type of environment are extremely difficult. Under these conditions some type of protection system for passengers is needed to reduce the possibility of inhaling incapacitating fumes. It was also mentioned that this is an extremely difficult type of action for which to prepare all passengers. Smoking on aircraft received a fair amount of attention ranging from recommendations by Government committees for there to be absolutely no smoking on aircraft, to a comment that smoking is really an emotional issue, and that the inflight fire risk is reasonably small compared to the post impact risk. The attendant hazards that some pointed out were that smoking would probably take place in rest rooms where there would be additional hazard of fire threat.

PROTECTION SYSTEMS

As was mentioned in several papers, it is impossible to defend against all possible threats to the aircraft. Monsieur Guillevic made the analogy that the airplane is in effect a small city where people are living for many hours and it is certainly not possible to control everything brought on board by these individuals. Therefore, protection must be designed against the worst situations. Strengthening of cargo holds so that they cannot rupture to admit air with small explosions is one answer but the level of structural strengthening required is a serious problem for the designer. As was stated, it is impossible to make the aircraft safe against all conditions. It was agreed by most present that fire detection systems in these areas capable of dumping halon extinguishant very rapidly would be extremely valuable. It was also pointed out that the use of halon extinguishers in the cabin interior was of great value despite some possible side effects of the halon. It is a very efficient extinguisher and only a small quantity is required if it is used rapidly as the primary attempt device. Automatic detection systems and automatic extinguishing techniques should be used only in those areas where people are not normally present. When the cabin crew is present, they should be properly trained to react rapidly to emergencies. The idea of pilot warning lights for interior cabin fires brings to mind the discussion of explosion suppression systems in tanks. If the pilot must be aware of the operation of all these systems in addition to his normal workload, the workload can perhaps be increased to the point where he cannot safely pilot the aircraft.

APPROACH

Most attendees agreed that if the approach to improved fire safety is brought about only by government regulations, it will probably work to the disadvantage of everyone. When regulations are established by government agencies, they are usually more stringent than what would have been necessary to combat the basic problem.

In the fire safety area there is a limited amount of funding and it must be used in the best possible way. It was hoped that through the discussions taking place at this meeting, it would be possible to realize where there may be some duplication and that efforts could be parcelled out to groups so that each works in complementary areas.

Mr. Lewis commented that powerplant safety regulations are updated quite frequently and generally seem to be more severe than those for the rest of the aircraft. However, the result as far as fires in engines has been quite favourable. He also commented on some of the techniques mentioned for protecting engines in crashes, specifically the water cooling of all engine surfaces to get them below spontaneous ignition temperature. He felt that this technique may not be workable in the high temperature turbine engines used today. He stated that the quantities of water that would be necessary and the time required to achieve such cooling would make the system impractical. It was agreed that a global view and review of accidents is necessary and that the greatest and minutest detail reported so that sources which could result in catastrophe if not properly controlled can be identified through incident investigation. It was deemed essential to disseminate accident data as rapidly as possible, but not to put such information into a central computerized information bank where it is not in a really usable form. Mr. St. John, of the Civil Aviation Authority, (UK) made a recommendation on the groups approach to this problem which is quoted below.

"There is no single panacea to the serious problem of fire hazards. We are clearly making great progress towards the four main objectives:

- (1) To prevent or reduce fire propagation — here there is outstanding work on safety fuel research, ably described by Dr. Miller and others. Work is also needed on ignition sources.
- (2) To improve fire survivability by designing or treating the structure to give longer protection, and by controlling the products of combustion. Here there is a vast and valuable program described graphically by John Parker of NASA.
- (3) To provide better extinguishing agents.

- (4) Only then should we aim to evacuate the passengers rapidly. A concerted attack along all four lines is advocated and collaboration at a higher level rather than a mere exchange of information. It is suggested that, out of this conference an AGARD Working Group might examine the areas of overlap and those where work is not being done in order to establish an efficient joint program, which will be more cost-effective and more rapidly implemented." At the end of this comment by Mr. St. John, Professor Glassman pointed out that this is already being discussed by the Panel as a result of the meeting and that a group is in the formation stage. Terms of reference are to be drawn up for such an effort.