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A Review of the Flammability Hazard of Jet A Fuel Vapor in Civil Transport Aircraft Fuel Tanks

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15. Supplementary Notes

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16. Abstract

This report documents the findings of a Fuel Flammability Task Group made up of recognized fuel and combustion specialists investigating the flammability and explosiveness of fuel within an aircraft fuel tank. The task group reviewed all available reports on the subject and met and discussed the data with technical experts from Boeing Commercial Airplane Co., California Institute of Technology, and the National Transportation Safety Board. The scope of the report includes jet fuel definitions and specifications, jet fuel flammability data, influences of various factors on fuel flammability, and predictive analyses and models for flammability. The report discusses the impact of this knowledge on the needs for in-flight fuel fire prevention.

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EXECUTIVE SUMMARY

This report documents the findings of a Fuel Flammability Task Group of recognized fuel and combustion specialists that investigated the flammability and explosiveness of fuel within an aircraft fuel tank. The task group reviewed all available reports on the subject and met and discussed the data with technical experts from Boeing Commercial Airplane Co., California Institute of Technology, and the National Transportation Safety Board. The scope of the review included jet fuel definitions and specifications, jet fuel flammability data, influences of various factors on fuel flammability, and predictive analyses and models for flammability. The report discusses the impact of this knowledge on the needs for in-flight fuel fire prevention. The report cannot offer a single, definitive answer to the question of when fuel tanks contain a flammable vapor, but it does identify the research necessary for a better understanding of fuel flammability in aircraft fuel tanks. It also presents a methodology that, within limits, can be used to compare the probability of a flammable mixture in a tank when the fuel temperature, flash point, and/or aircraft altitude are varied. While adequate for a fuel tank safety analysis to be carried out in the near term, it should be recognized that the correlation formulas are based on several assumptions and, therefore, have serious limitations. The formulas represent only an interim solution to a complex problem. Accordingly, it is strongly recommended that it be replaced with an improved approach when new data are developed.

In addition to finding a need for more data on the flammability of Jet A fuel, the task group found present methods for predicting in-flight fuel temperatures to be inadequate. The development of reliable heat transfer models and the ability to calculate the flammability of the ullage space in an aircraft fuel tank under different environmental and operational conditions are in the early stages. Therefore, the ability to reliably evaluate different strategies to reduce the flammability of fuel in the center wing tank of a B747 has not been proven.

1. INTRODUCTION.

1.1 BACKGROUND.

The July 17, 1996, crash of TWA flight 800, a Boeing 747 airplane, was blamed on a fuel-air explosion within the center wing tank, with the ignition source still unidentified. As a consequence of the accident, the Federal Aviation Administration (FAA) is evaluating improved safety requirements for the fuel tanks on commercial aircraft. One technique, recommended by the National Transportation Safety Board (NTSB), is to maintain sufficient fuel in the center wing tanks of transport aircraft to limit the liquid fuel temperature rise and evaporation, thus keeping the vapor fuel/air ratio below the explosive limit. Initial attempts to determine the benefit of additional fuel in the center tank were frustrated by the lack of an acceptable method for determining the explosive hazard in the tank under varying conditions.

1.2 FUEL FLAMMABILITY TASK GROUP.

In order to evaluate the recommended technique and various alternative solutions to the fuel explosion problem, the FAA formed a Fuel Flammability Task Group. The task group was made up of recognized fuels and fuel explosion experts who have no present affiliation with the industry that might be affected by any FAA action. The task group was comprised of:

Richard Hill - Federal Aviation Administration

Merritt Birky - National Transportation Safety Board

Robert Friedman - National Aeronautics and Space Administration (NASA)
        Alternate - Chi-Ming Lee - NASA

Tom Madgwick - British Aerospace (retired)

Francesco Tamanini - Factory Mutual Research Corporation

Bernard Wright - Southwest Research Institute

Robert Zalosh - Worcester Polytechnic Institute

(Additional information on task group members can be found in appendix A.)

The task group was tasked to review past and recent data on the explosiveness of Jet A fuel in aircraft fuel tanks and on the minimum energy required for the initiation of an explosion. The review was to include the effects of both temperature and altitude. The task group was also tasked to review data on possible conditions in a center fuel tank, including heating rates from external sources. From these reviews the task group was asked to present its opinion as to the applicability of the reviewed data in predicting the conditions that could lead to an explosion in a fuel tank during operation of a commercial transport aircraft.

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This report presents the findings and conclusions of the task group. The scope of the report includes jet fuel definitions and specifications, jet fuel flammability data, influences of various factors on fuel flammability, and predictive analyses and models for flammability. The report discusses the impact of this knowledge on the needs for in-flight fuel fire prevention. The report cannot offer a single, definitive answer to the question of when fuel tanks contain a flammable vapor, but it does identify the research necessary for a better understanding of fuel flammability in aircraft fuel tanks. It also presents a methodology that, within limits, can be used to compare the probability of a flammable mixture in a tank when the fuel temperature, flash point, and/or aircraft altitude are varied.

1.3 PAST FUEL SYSTEM DESIGN FOR FIRE SAFETY.

Relevant to the present study of explosions within aircraft fuel tanks is an appreciation of the historic data and how those data were used by the aircraft constructors to achieve the highest possible level of safety in airline operations. All reasonable and practical precautions have been taken based on the level of knowledge at the time. Nevertheless, safety design standards have changed in the light of operational experience. In particular, the lessons learned from accident investigations and data generated by various research programs have enabled new airworthiness requirements to be evaluated and some implemented.

Civil transport aircraft have used the wing structure as an integral fuel tank to store fuel; the fuel is in direct contact with the outside skin. In larger aircraft, in addition to fuel being carried in the wing external to the fuselage, fuel is also stored in the structural wing box within the fuselage. Many commercial aircraft designs have the cabin environmental conditioning system, commonly referred to as ECS packs under the center wing tank (CWT). As a result of heat losses from the environmental conditioning system being transferred to the CWT, the fuel temperatures are elevated. There are many factors that determine how and how much this heat transfer affects the fuel tank temperature and the flammability of the ullage space. These factors include the operational environment, flight operations, condition of the aircraft, the amount and temperature of fuel loaded in the tank, and other variables. In many cases, the fuel temperature is sufficiently high that the fuel-air mass ratio in the ullage space is above the lower flammability limit (fuel/air > 0.03).

Since the introduction of kerosene fuel for civil aircraft use in the late 1940's, the aircraft designers have been aware that the ullage, or space above the liquid fuel, would contain a mixture of fuel vapor, or mist and air, which could be ignited in the presence of a spark, flame, or hot surface provided the mixture concentration was within certain limits. The conditions required for ignition and subsequent flame propagation through the mixture were dependent on a number of parameters including fuel type, temperature, tank pressure, and oxygen concentration. In addition, it was recognized that fuel froths and fuel mists could be generated during refueling and in flight by aircraft vibration and oxygen release from the fuel, each of which could extend the flammable limits.

Information on flammability has been obtained from various technical reports, such as those published by AGARD (Advisory Group for Aerospace Research and Development) and others.

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It is noted that different sources quote different envelopes of flammability. Traditional flammability envelopes that have been available for many years are shown in figures 1, 2, 3, and 4. The envelopes shown in figure 4 date back to 1956 while the envelopes shown in figure 5, together with ignition energies, were derived by British Aerospace in the 1970's from literature searches and discussions with fuel supply companies. It should be noted that the flammability limits are not specification requirements, which include instead flash point, vapor pressure, and distillation of the particular fuel type.
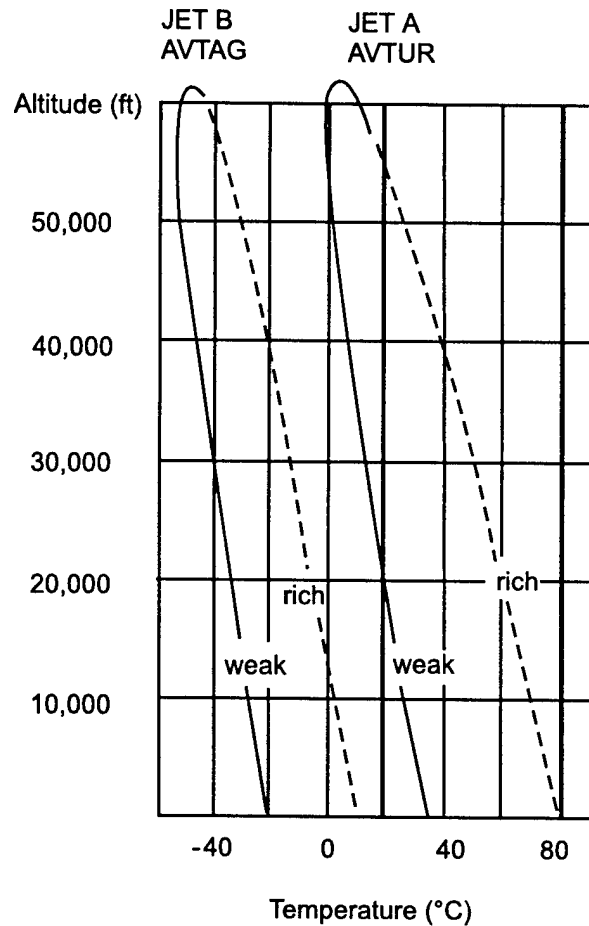
FIGURE 1. FLAMMABILITY LIMITS FOR AVTAG/JP-4 AND AVTUR/JP-8

3
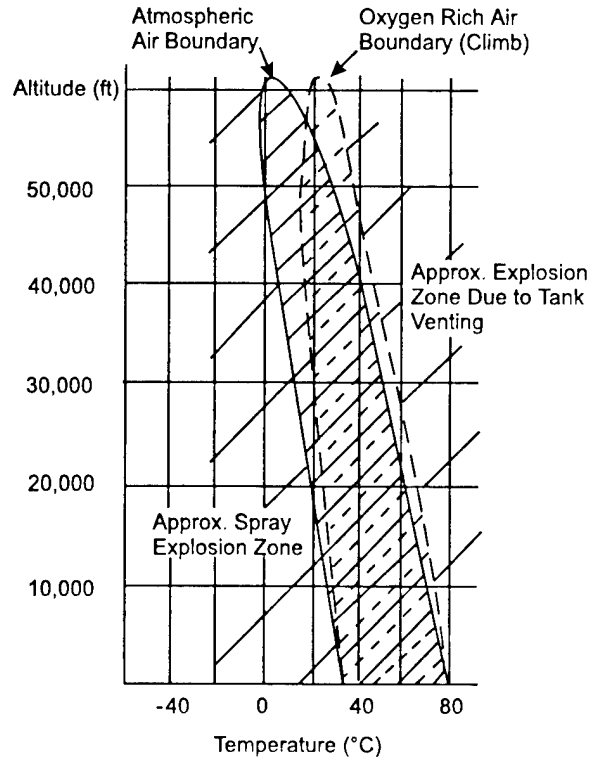
FIGURE 2. NONEQUILIBRIUM FLAMMABILITY LIMITS FOR AVTUR/JP-8
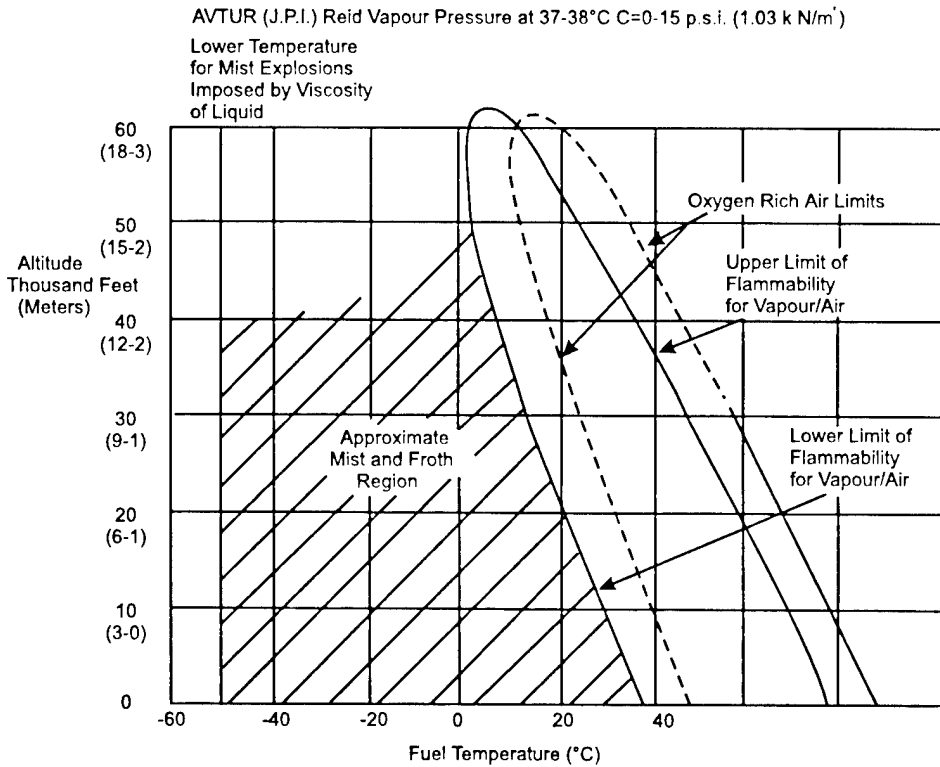
FIGURE 3. FLAMMABILITY LIMITS FOR AVTUR FUEL VAPORS AND MIST

4
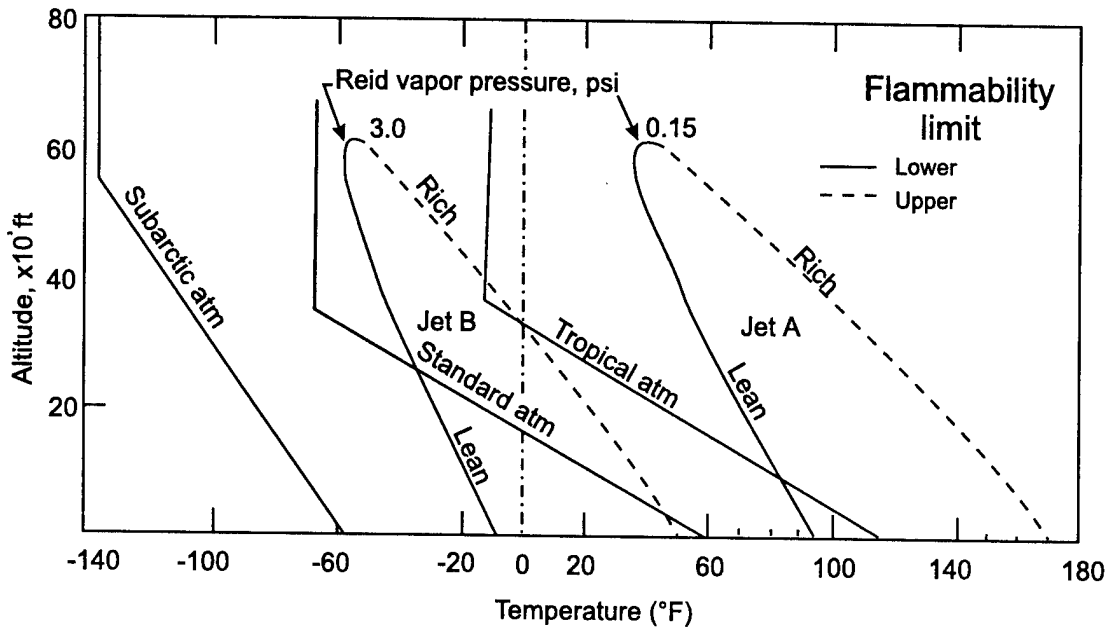
FIGURE 4. PRESSURE ALTITUDE—TEMPERATURE LIMITS OF FLAMMABILITY FOR
JET A AND JET B TYPE FUELS IN AIR
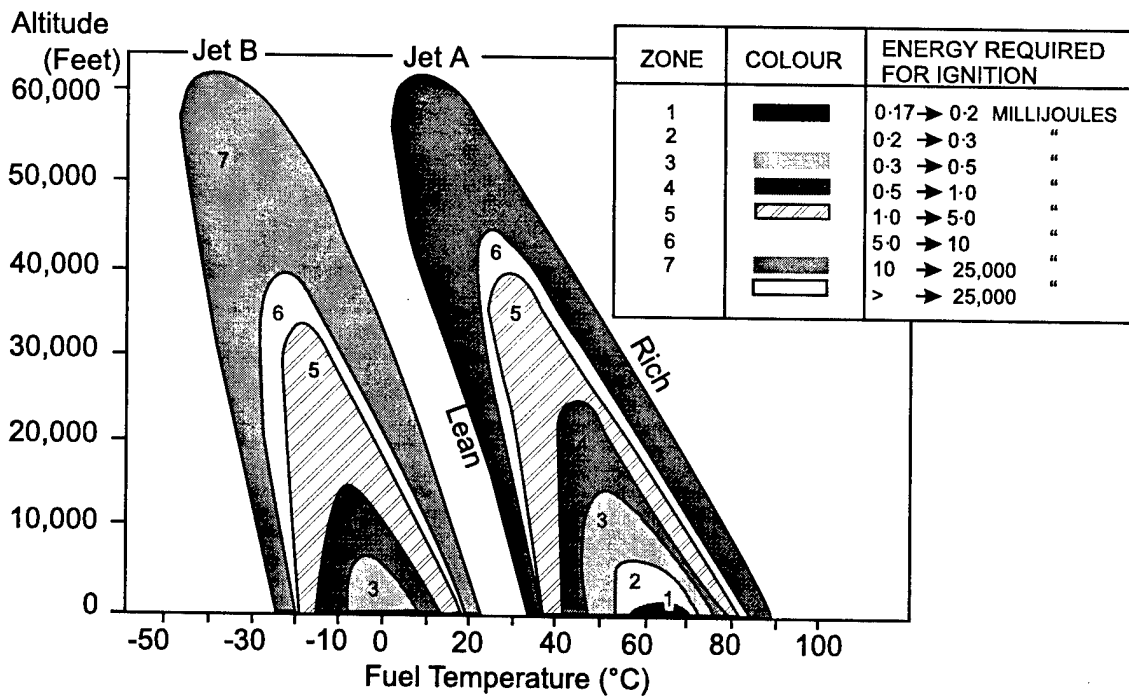
FIGURE 5. ESTIMATED MINIMUM ELECTRICAL IGNITION ENERGIES FOR
JET A/JET A-1 AND JET B FUELS

Aircraft are designed to operate on either Jet A or Jet B type fuels [1, 2]. The preponderance of commercial transports use Jet A type fuel. Jet B fuel is primarily used in commercial operations

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where lower temperatures necessitate use of higher flash point fuels for engine starting or as an alternate fuel. However, since the early 1950's, Jet A, being the less volatile fuel, has been strongly promoted in the belief that it was safer in ground handling operations and in crash situations, figure 6. In Australia, the use of Jet B type fuel was banned by the Department of Civil Aviation.
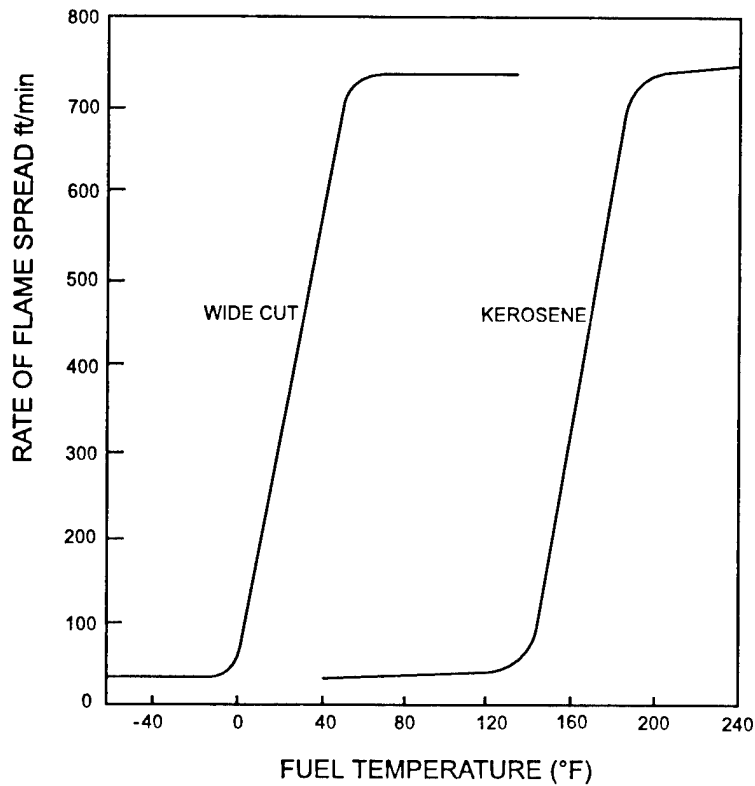
FIGURE 6. RATE OF SPREAD OF FLAME ACROSS A LAYER OF FUEL

Figures 7 and 8 show a typical presentation of the relative safety of Jet A and Jet B in airline operations taken from Reference No. 1660 of the AGARD Conference Proceedings [42]. These show the flammable vapor zones compared with the bulk fuel temperature changes over a 7-hour flight. It is generally assumed that the temperature of the bulk fuel in the wing tanks would closely follow the outside ambient air temperature, and in this example, the longest exposure to a flammable vapor zone would be when using Jet B fuel because of its lower flammability zone.

Information and understanding of spark ignition is incomplete. Suffice to say that the estimate of energies for ignition presented in figure 5 (for vapor) and figure 9 (for spray) suggests there is some order of probability of ignition. This observation, coupled with the knowledge from some researchers that fuel mists and foams could be present in a fuel tank at temperatures below the equilibrium lean limit for vapor air mixtures, leads to the conclusion that there are times in the life of an aircraft when the fuel tank ullage is potentially at risk of ignition and subsequent explosion.

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JET A

CONDITIONS INSIDE A KEROSENE FUEL TANK

FUEL TEMPERATURE (°F)

120 — RICH LIMIT

100

80 — FLAMMABLE VAPOUR ZONE

INITIAL FUEL TEMPERATURES

60

40 — LEAN LIMIT — 100°F — 80°F

20

0

-20 — 60°F

-40

-60

ALTITUDE 20,000 — CLIMB — CRUISE — DESCENT

1 2 3 4 5 6 7

ELAPSED TIME AFTER TAKEOFF, HOURS
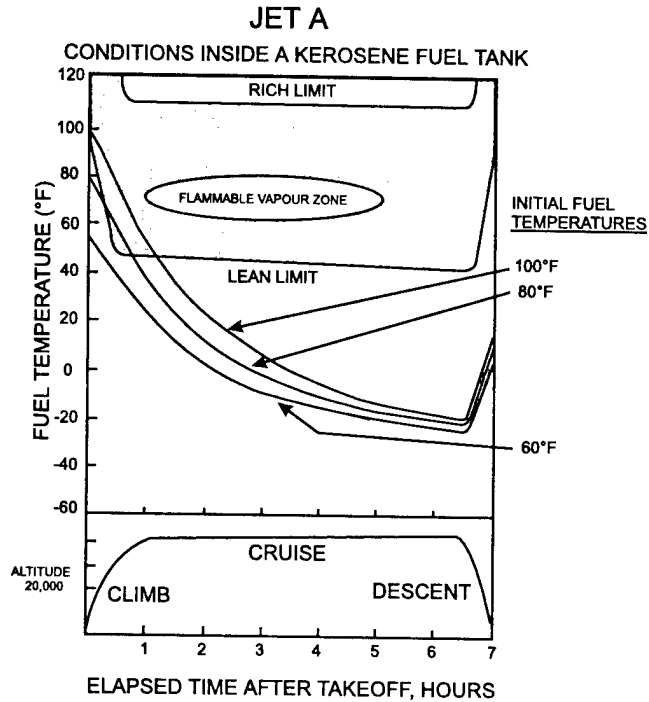
FIGURE 7. TYPICAL JET A FUEL TEMPERATURES IN FLIGHT—JET TRANSPORT CRUISING AT 525 MPH. BASED ON BOEING AIRPLANE COMPANY AND DEHAVILLAND AIRCRAFT COMPANY, LTD. DATA

JET B

CONDITIONS INSIDE A JP-4 FUEL TANK

INITIAL FUEL TEMPERATURES

FUEL TEMPERATURE (°F)

100 — 80°F — 60°F — 40°F

80

60

40

20 — RICH LIMIT

0

-20

-40 — FLAMMABLE VAPOUR ZONE

-60 — LEAN LIMIT

CLIMB — CRUISE — DESCENT

1 2 3 4 5 6 7

ELAPSED TIME AFTER TAKEOFF, HOURS
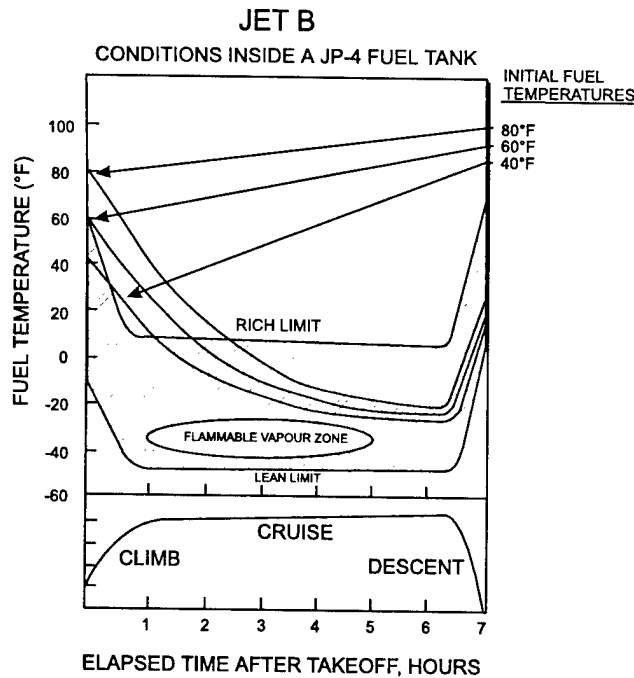
FIGURE 8. TYPICAL JET B FUEL TEMPERATURES IN FLIGHT—JET TRANSPORT CRUISING AT 525 MPH. BASED ON BOEING AIRPLANE COMPANY AND DEHAVILLAND AIRCRAFT COMPANY, LTD. DATA

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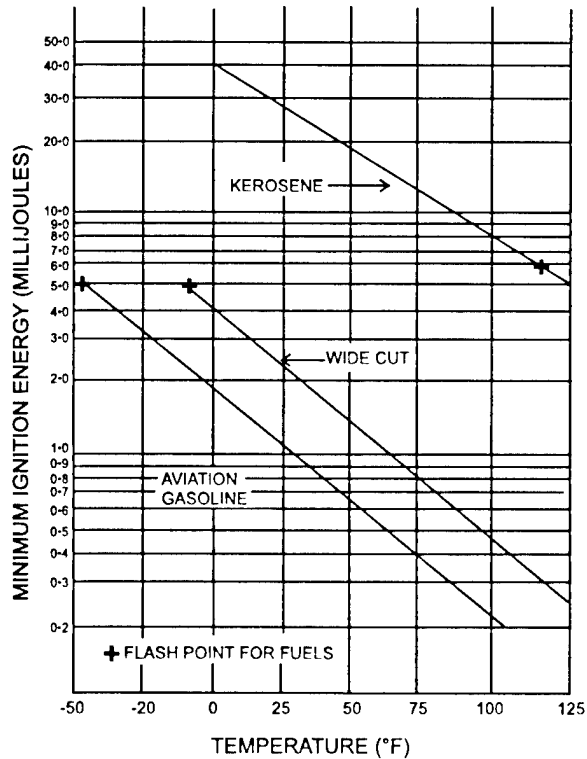
FIGURE 9. MINIMUM SPARK IGNITION ENERGIES FOR FUEL-AIR SPRAY MIXTURES

Given this background information on flammability, ignitability, and probability, actions could reasonably be taken to reduce the risks to an absolute minimum. It should be noted that the flammability envelope for equilibrium conditions has not previously been used as a design tool in dictating tank design or flight operations.

To prevent tank explosions, designers have always assumed a flammable vapor exists in the fuel tanks and adopted standards to preclude ignition sources from the fuel tanks.

The following are some of the design measures taken to satisfy that philosophy:

a.   Surface temperatures inside the tanks, under normal and failure conditions, are kept at least 50°F below the minimum necessary to ignite a fuel-air mixture. Pump motors are kept cool by an integral passage of circulating fuel. The motors have a temperature fuse, which cuts the electrical supply before an unsafe surface temperature is reached. In addition, the pumps and other similar equipment inside the tanks, are designed and tested to explosion-proof standards. Where hot air-conditioning pipes external to fuel tanks are routed close to tank walls, such as the engine bleed air pipes in the wing leading edge, it is current practice to position heat-sensitive detector wires on the structure to protect it from overheat in the event of pipe failure or joint leaks.

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b.   Electrical components and wiring within a fuel tank are designed to handle 1500 volts ac which is well in excess of the power available on the airplane and the operating voltage of the fuel quantity gauging system.

c.   Electrical energy applied to any component in the fuel tank is limited to a value that is 10 times lower than the minimum energy necessary to ignite a fuel-air mixture. The minimum ignition energy (MIE) for hydrocarbon vapors is thought to be about 0.25 mj.

d.   During the flow of a hydrocarbon type fuel through pipes, valves, filters, etc., an electrostatic charge can be generated in the fuel, which, if relaxed sufficiently fast, could allow the accumulation of hazardous potential levels inside a receiving tank. This is kept within acceptable safe limits by avoiding very high rates of fuel flow in the refueling system and by controlled distribution of the fuel in the tanks, such as bottom loading and the use of diffusers on pipe outlets. In addition, meticulous attention is paid to electrical bonding of all metallic parts to dissipate the charge. Some countries around the world insist on the use of static dissipater additives in the fuels to increase the fuel electrical conductivity.

A major consideration of fuel system safety is protection against the affects of lightning. When an aircraft is struck by lightning, a pulse of high current flows through the aircraft from the entrance to the exit points. Protection against this phenomenon is provided in a number of ways:

- By ensuring that the structure is well bonded.

- By using wing skin panels sufficiently thick that penetration should not occur.

- Removable doors and panels located in critical vapor areas are designed to maintain electrical continuity to preclude sparking.

- Tank vents are not located in primary strike areas.

- Tests are conducted to demonstrate the safety of the design.

2. DISCUSSION.

2.1 JET FUEL.

2.1.1 Jet Fuel Specifications.

The international availability of fuels with common and predictable qualities is a critical need for safe, efficient, and economical air transportation. The International Air Transport Association (IATA), a trade group with the participation of nearly all worldwide passenger and freight airlines, maintains the standards and monitors fuel handling at most international airports [1]. In the US, the voluntary standard American Society of Testing and Materials ASTM D 1655 defines

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the exact requirements for the purchase of aviation turbine (jet) fuel [2]. Within the IATA realm, the fuel supply at almost all international airports is purchased to standards nearly identical or traceable to those defined by ASTM D 1655.

ASTM D 1655 specifies three grades of aviation turbine fuel: the kerosene-based Jet A and Jet A-1 (approximate boiling point range of 160 to 300°C) and the wide-cut or naphtha-based Jet B (approximate boiling range of 50 to 300°C). Jet A and Jet A-1 differ only in the freeze point of -47°C for the Jet A-1 and -40°C for Jet A. Jet B is little used today except in some Arctic operations although it is essentially the same fuel as JP-4, the standard US military fuel in use until about 10 years ago. (The current US military aviation fuels are JP-8, which is nearly equivalent to Jet A, and JP-5, which has a high flash point specification. The phase in of JP-8 began in 1988 and was completed in 1996.) The history and development of commercial and military aviation turbine fuel specifications have been documented in reviews of testing procedures [3], standards development [1], and property trends [4].

Aviation turbine fuel quality is strictly regulated. There are at least 23 specifications in ASTM D 1655 for Jet A or Jet A-1 fuels, which set maximum or minimum limits for stated properties or measurements. This number may be compared to that of nine specifications in the ASTM Diesel fuel requirements or six specifications in the motor gasoline requirements [5]. The requirements exist primarily to define common fuel quality for user purchases under contract. They do not define the composition or exact properties of any fuel batch. ASTM D 1655 states only that aviation turbine fuel shall consist of refined hydrocarbons derived from crude petroleum, natural gasoline (light hydrocarbons), or blends thereof with synthetic hydrocarbons (processed or alternative-source streams). Thus, Jet A/A-1 and JP-8 fuels typically are mixtures of hundreds of compounds, controlled only by the defined boiling point ranges. Current analyses can identify over 200 chemical species in sample fuels [6]. The actual composition of a fuel batch is very dependent on the crude sources, but generally Jet A type fuels consist of the order of 75% to 85% paraffin, both straight chain and cyclic, with the balance almost entirely aromatic compounds [7]. Unsaturated compounds (olefins) and oxygen, nitrogen, and sulfur compounds, if present, constitute less than 1 percent of the jet fuel composition, although, of these items, only the maximum sulfur content is limited by specification.

2.1.2 Flammability Properties.

Jet A properties of major concern to fire safety predictions, such as flammability limits, ignition energy, quenching distance, electrostatic charging tendency, autoignition temperature, and rate of fire spread, are not covered by fuel specifications nor are they measured routinely during fuel inspection. Flammability characteristics for typical aviation turbine fuels are found in recent literature, but these are usually based on very limited measurements or on simplified correlations [8, 9, 10, and 11].

The ASTM D 1655 requirements for Jet A include distillation temperature, flash point, and net heat of combustion. Of these properties, flash point is the measurement related to the relative flammability hazard of fuels in ground handling and flight storage and transfer. The vapor pressure of the fuel, which is temperature dependent, determines the amount of vapor in the

ullage space and thus controls the flammability limits, and it is specified and measured for more volatile fuels, such as Jet B/JP-4 or aviation and motor gasolines. In a fuel tank partially filled with fuel, the hydrocarbon molecules escape from the liquid into the vapor space above it. If the space above the liquid is closed, vapor will accumulate until equilibrium is reached. That is, if the temperature remains constant and there is no turbulence, the number of fuel molecules leaving the liquid equals the number of molecules returning to the liquid surface. The pressure exerted in the vapor space by the fuel molecules is the vapor pressure. Therefore, if the vapor pressure at a particular temperature is known, calculations can predict the amount of fuel existing in the vapor space if the volume of the vapor space is known. Vapor pressures, as determined by ASTM D323, are based on the Reid Method which uses an absolute pressure at 100°F. Since the vapor pressures of mid-distillate fuels, such as Jet A, are very low at 100°F, this procedure is limited for predicting flammability. The ASTM D323 procedure is designed for fluids with high vapor pressures such as gasoline. As an example, gasoline vapor pressures are determined in the approximate range of 5-10 pounds per square inch (psi), while for Jet A the vapor pressure at 100°F is less than 1 psi. For liquids of lower vapor pressures, the flash point is used to estimate at what temperature there are enough vapors for ignition. The Jet A fuel flash point specification is 100°F minimum, and other fuels are different. For example, JP-5 specification is 140°F, which means that the fluid has to be heated to at least 140°F in order to give off enough vapors to be flammable.

2.1.3 Flash Point Specifications and Measurements.

The flash point is defined as the lowest temperature, corrected to 101.3 kPa of pressure, at which the application of an ignition source causes the vapor of a liquid sample to ignite momentarily under specified conditions of testing [12]. The tests are conducted in an apparatus where a test flame is applied to the vapor space above the fuel sample of a known temperature contained in a cup. The operator observes whether the flame instantaneously propagates within the vapor space. If it doesn't propagate, the procedure is repeated at increasing temperature increments until the lowest temperature for the flash occurrence is determined. There are several accepted flash point test methods, differing in the size of the sample, the rate of heating, the method of flame introduction, and other procedures. Flash point can be determined by several test methods, which do not always give equivalent results. Some of the methods and the differences are detailed below.

For current Jet A fuel, specification ASTM D 1655 recognizes two flash point test methods, the Tag closed-cup tester (ASTM D 56) and the Setaflash closed tester (ASTM D 3828). Both methods are so-called "dynamic" tests, in which the temperature of a single charge of sample is increased at a specified rate. This is in contrast to "equilibrium" procedures in which a fresh charge of sample is used for testing at each temperature increment. Equilibrium procedures can yield flash points slightly more conservative (lower temperatures) than dynamic procedures, but they are much more time consuming [13]. Both the Jet A fuel methods use closed containers, which minimize convective and diffusive vapor dispersion [10], although open-cup procedures are available for testing of other commodity liquids. Another dynamic closed-cup method, the Pensky-Martens tester (ASTM D 93), was used for jet fuel flash determinations in the past, and flash points by this procedure were often cited in early literature [10, 11].

The ASTM procedures used to determine this specification property are the D-56 Tag closed-cup and the D-93 Pensky-Martens closed-cup tests. It is interesting to note that the repeatability may be approximately 2°F, but there may be as much as 8°F variation from laboratory to laboratory for the D-56 procedure. However, for the D-93 procedure, the repeatability range may be as high as 9°F, and the laboratory-to-laboratory reproducibility variation may be as high as 18°F as reported in the procedure.

The Tag closed-cup tester is detailed in the ASTM D 56 Test. This is a dynamic test in which 50 ml of sample are measured into a cup surrounded by a water bath. The sample is heated at 2°F (1°C) per minute and tested at every 1°F (0.5°C) rise in temperature until the flash is observed.

The Pensky-Martens closed tester is detailed in ISO 2719, ASTM Test for Flash Point by Pensky-Martens closed tester (D 93), and Flash Point by the Pensky-Martens Closed Tester (IP 34/71). This is also a dynamic test in which a 75-ml sample, placed in a cup surrounded by an air bath and stirred at a rate of 90 to 120 rpm, is heated at the rate of 10°F (5°C) per minute and tested every 2°F (1°C) until a flash is observed.

The flash point in British military specifications (for example, Turbine Fuel, Aviation: Kerosene Type—D ENG RD2494) is usually defined by the Abel method (Institute of Petroleum Flash Point by the Abel Apparatus (IP-170)). For high-flash kerosene, the flash point is defined by the Pensky-Martens (PM) Closed Tester as specified by the International Standards Organization Determination of Flash Point—Pensky-Martens Closed-Cup Method (ISO 2719/D 93/IP 34). The ASTM Specification for Aviation Turbine Fuels (D 1655) lists the Tag Closed Tester (ASTM Test for Flash Point by Tag Closed Tester (D 56)) and the Setaflash Closed Tester (ASTM Test for Flash Point of Aviation Turbine Fuels by Setaflash Closed Tester (D3243)). The International Air Transport Association (IATA), Guidance Material for Aviation Turbine Fuels, lists the Tag Closed Tester and the Abel method.

The determination of a flash point by the Abel apparatus is detailed in the IP 170/75. This is also a dynamic test in which a 75-ml sample, stirred at a rate of 30 rpm (1/2 the stirring rate used in the PM tester), is heated at the rate of 1°C (2°F) per minute and the test flame applied to the cup every 0.5°C (1°F) until the flash is observed. In both the PM and Abel tests, the stirring is stopped during test flame application.

The methods described above are dynamic tests; that is, the temperature of the sample is increased at a specific rate and the test flame applied at specified intervals until the flash is observed. In these cases, the temperature of the sample is constantly changing, and the test flame is applied to a single charge of sample as many times as necessary to obtain a flash.

The Setaflash Tester was designed as an equilibrium type tester and the IP Rapid Tests for Flash Point (303/74) describes a method for its use as an equilibrium-type tester. However, ASTM, in the interest of reduced testing time, described a dynamic procedure when it adopted the Setaflash Tester. ASTM Test D3243 details this dynamic procedure, which gives results somewhat higher than the equilibrium procedure.

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As a result, the ASTM Committee D02 on Petroleum Products and Lubricants has reversed its position and has approved revision of D3243 making it an equilibrium test. This revision, which bears the number D3243-77, and all subsequent revisions will be equilibrium methods. At the time D3243-77 was issued, dynamic-type Setaflash methods became obsolete. In the discussion below only the equilibrium-type tests discussed use the Setaflash tester. It will be assumed that both give identical results on identical samples.

In equilibrium tests, such as the Setaflash, the sample is heated to a specified temperature where the sample and vapor above it are allowed to come to equilibrium before the test flame is applied. The test flame is applied only once, even if a flash is not observed. If one wishes to retest for flash, at the same or different temperature, the sample is removed from the cup, a new charge is placed in the cup and allowed to come to equilibrium, and the test flame is applied. Each time the operator wishes to apply the test flame to the sample, no matter what the temperature, a new sample must be used.

As indicated earlier, all of the tests do not give identical results on identical samples. The conditions for each test are different enough so that slightly different values can be obtained on identical samples. Data comparing the four flash test methods applicable to jet fuels are given in table 1.

TABLE 1. FLASH TEST DATA. SUMMARY OF DATA FROM TCC (ASTM D 56), PM (ASTM D 93), ABEL (IP-170), AND SETAFLASH (IP-303)

Method	Comment on Flash Point Level
IP-303, Setaflash	3°F lower than TCC
	3°F lower than PM
	equivalent to Abel
IP-170, Abel	3°F lower than TCC
	4°F lower than PM
	equivalent to Seta
ASTM D 56, TCC	3°F higher than Abel
	3°F higher than Seta
	2°F lower than PM
ASTM D 93, PM	2°F higher than TCC
	4°F higher than Abel
	3°F higher than Seta

Conversion factor $\Delta°C = \Delta°F/1.8$

2.1.4 Typical Jet Fuel Flash Points.

Jet A and A-1 flash points are currently specified to be a minimum of 37.8°C (100°F). This limit was set in 1975, when it was reduced from 40.6°C (105°F), in order to conform to commodity classifications of "nonflammable" liquids [4]. A maximum flash point specification of 65.6°C (150°F) was rescinded in 1973. It is advantageous for refiners to manufacture jet fuels with flash

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points well above the specification minimum for several reasons. The light refinery streams that contribute to low flash point are often more valuable as gasoline blending stocks. The Jet A product is often made as a dual-purpose fuel that conforms to the legal flash point (higher than 38°C in some states) for domestic kerosene [14]. Furthermore, some multiproduct pipelines impose higher flash point limits to avoid off-specification fuels due to contamination by traces of gasoline. The result of these manufacturing and economic factors is that typical Jet A flash points are greater than the specification minimum. A past survey of 12 years of inspection data for domestic Jet A fuel indicates a median flash point of 53°C [4]. Of the 741 fuel samples in this survey, only 3 samples had flash points of 40°C or below and just 1 was at 38°C. A similar survey of the military equivalent fuel, JP-8, showed average flash points of 41 to 53°C, depending on supplier location [15]. Only 2 out of 89 JP-8 samples had flash points less than 40°C, and again just 1 was actually at 38°C.

The flash point of a multicomponent fuel depends on the mixture composition (not fixed by specification), particularly the concentrations of low-boiling components or "light-ends". This is well illustrated by the sensitivity of standard Jet A/Jet B blending charts for flash point determination to small quantities of Jet B [9 and 11]. The preferential loss of low-boiling constituents with time influences the flash point, increasing its value. A quantitative measurement is reported by Ott, where the flash point of a JP-8 sample was 118°F (48°C) before testing and 123°F (50.5°C) after the nondestructive testing [16]. On the other hand, recent studies by Shepherd show an unexplained decrease in the flash point of a Jet A from 48°C initially to 46°C after testing [17].

2.1.5 Flash Points and Flammability.

The primary purposes of flash point specifications are for commodity labeling and for relative ranking of liquid product fire hazards. For scientific measurements or predictive hazard assessments, the principal determinator of liquid fuel flammability is the lower (or lean) limit of flammability. This limit is the lowest fuel-air ratio that will support propagation away from an ignition source. The flash point of a pure compound in theory is the temperature at which the vapor pressure is sufficient to establish the lower flammability limit. Generally, the flash points are higher than defined by the lower limit temperature due to nonequilibrium conditions in the testing, the different modes of ignition, and the inherent nonconservatism in representing real upward flame propagation by a device with downward propagation [9]. A recent paper reviewing published data on pure compounds examined the relationship of the vapor pressure at the Pensky-Martens flash point to the vapor pressure at the lower flammability limit (ASTM E 681), determined at 25°C. In general, the fuel-air ratio at the flash point was at least 15% greater than that at the lower limit, although there is much scatter in the data [18].

For multicomponent fuels, the relationship of flash point to practical flammability is more tenuous. Since the vapor composition varies from that of the liquid, relative liquid-vapor mass loading and other factors influence the fuel-air ratio, and hence flammability, in generally unpredictable ways [19]. Nevertheless, some attempts to correlate jet fuel flammability characteristics have appeared in the literature. For example, the flash point of fuels or petroleum fractions has been reported to relate directly to a constant vapor pressure, 0.7 kPa according to

one source [9], and 0.9 kPa but increasing slightly at higher flash points, according to another source [20]. Affens related flash points to a flammability index, which is the actual fuel-air ratio in the vapor divided by that at the lower flammability limit [21]. The flash points of JP-5 and JP-8 show agreement with a flammability index of one (the lower limit of flammability).

In general, it is agreed that the flash point is useful for at least qualitative ranking of fuels. On the other hand, it is also evident that fuels in tanks and pools will propagate flames at temperatures below those established by the flash point. More investigation is necessary on the relationship of flash points of fuels to practical hazards and flammability.

2.1.6 Hot-Surface Ignition.

Hot-surface ignition (or autoignition) of fuels is the phenomena of fuels being ignited without the presence of a flame or a spark. While it is generally recognized that spark ignition energies are very difficult to quantify, perhaps even less is understood about autoignition. The classic illustration of autoignition (without source) is the "oily rag" experiment where some combustible material such as cloth that has been wetted with hydrocarbons may self-ignite for apparently no cause. The underlying cause is the rate of oxidation of the hydrocarbon, which gives off heat in the oxidation process. If the heat is not removed, the material can reach its ignition point and ignite.

Autoignition in petroleum fuels is determined using several different procedures and is referred to in slightly different terms. ASTM E-659 is an autoignition test that uses a 500-ml round bottom flask and is heated to some temperature in a heated furnace. When the desired temperature is reached, a very small amount of fuel is injected. Autoignition is evidenced by the sudden appearance of a flame inside the flask and a sharp rise in temperature of the gas mixture. The lowest internal flask temperature at which hot-flame ignition occurs is reported as the autoignition temperature (AIT). In addition to the temperature, the ignition delay time (time lag) is measured in order to determine the ignition delay/ignition temperature relationship. A lapse time up to 10 minutes is reported after which, with no ignition, a higher temperature is tested.

Another autoignition test procedure commonly used is a Federal Test Standard 791C Method 6051. This procedure uses an internally heated 3-in manifold and provides surface temperatures up to approximately 1500°F. The procedure calls for the fluid to be dripped onto the heated surface until ignition occurs.

Comparisons of autoignition temperatures for hydrocarbon fuels versus hot-manifold test temperatures indicate that minimum AIT temperatures range between 400-500°F and 1000-1200°F for hot-manifold test temperatures. It should be noted there is no unique threshold temperature for hot-surface ignition since it is influenced by numerous factors, such as geometry of surface—whether concave or convex, whether in a closed environment or open environment such as the hot-manifold test, local air velocities, and residence time of the fluid. Threshold ignition temperatures can be compared only when the various fluids have been tested using the same defined apparatus and procedure.

2.2 JET A FUEL FLAMMABILITY DATA.

Jet A fuel flammability is discussed here in the context of fuel vapor ignition criteria relevant to aircraft fuel tanks. The emphasis is on spark ignition data, but there is also a brief review of hot-surface ignition data.

2.2.1 Spark Ignition Data.

Table 2 is a listing of the Jet A spark/arc ignition test programs brought to the attention of the task group. There are many other references that review and discuss Jet A fuel flammability, but the task group is not aware of any other data sources. The graphs in section 1.3 are examples of data extrapolations and generalizations that have been presented in aircraft industry publications.

TABLE 2. JET A IGNITABILITY TEST PROGRAMS

Author (year)	Fuel Flash Point* (°F)	Vessel Size (liter)	Fuel Loading (kg/m³)	Ignition Source	Vessel Pressures (atm)
Nestor (1967)	118, 120, 125	Flame tube 9.9	100	Multiple sparks (5 and 20 J)	1 and 0.58
		Tank 9.5	100	Spark (16 – 24 J)	1
Ott (1970)	118 - 123	Tank 303	100	Moving arc (Jacob's ladder)	1 and 0.68
Air Force (1992)	130, 140	Flame tube 12.4	100	Spark (3 mJ to 16 J)	1 and 0.69
Shepherd (1997)	118	Cylinder 2	3 and 200	Spark (1 mJ to 100 J)	0.59

* Flash point measured per ASTM D56 (Tag apparatus) except for Nestor who used the Pensky-Martens (ASTM D 93) apparatus.

Test methods and test parameters differed in the programs listed in table 2. Nestor [22] conducted tests in a 4-ft (1.2-m) -long vertical transparent tube with an ignition source, at the bottom, that delivered multiple sparks with nominal spark energies of 5 and 20 J. Successful ignitions at various fuel temperatures were observed as upward flame propagation to the top of the tube. The level of Jet A in the tube corresponded to about 1/8 of the tube height. Nestor also conducted some additional tests in a tank with the capability to generate fuel mists by vibrating and sloshing the fuel.

Ott [16] conducted an extensive series of tests designed to determine tank vibration and sloshing effects on fuel ignitability. The ignition source in Ott's tests was a moving arc that traveled up and down a pair of 1-ft-long electrodes. This type of traveling spark is inherently different than the usual capacitance discharge stationary sparks and is not amenable to a simple measure of spark energy. Ott used the pressure generated during combustion as a measure of fuel flammability for both static fuel tests and sloshing fuel tests.

The 1992 Air Force [23] tests were similar to the Nestor [22] flame tube static ignition tests, except that the 1992 Air Force tests involved higher flash point samples and a broader range of spark energies. The spark was generated from a capacitance discharge in both sets of tests.

Shepherd [17] conducted Jet A ignitability tests designed to determine the effect of fuel loading and spark ignition energy at various fuel temperatures. The spark ignition energy, E (J), reported by Shepherd for his capacitance discharge single sparks is the value of

$$E = \frac{1}{2}CV^2 \tag{1}$$

where C is the capacitance (farads) and V is the voltage (volts). It is thought that a large fraction of this nominal spark energy is dissipated in the electrical circuit, but there is no simple way to determine the energy that was actually deposited in the spark gap. Nestor [22] measured the capacitor discharge energy by recording both the voltage drop and current and integrating the product over one spark cycle. The discharge energy is less than the stored energy given by the preceding equation.

Shepherd used two different fuel loadings: 200 kg of fuel per m^3 of tank volume (corresponding to a 25% full tank) and 3 kg/m^3 (corresponding to a thin layer of residual fuel). The tests had a tank pressure of 0.585 bar, which corresponds to the elevation (13,800 ft) at which the TWA Flight 800 explosion occurred.

Shepherd reported his ignitability data as a plot of ignite and no-ignite data points on a graph of spark energy versus Jet A temperature. These data points were converted into the curves shown in figure 10 for minimum ignition energy as a function of temperature. Each point delineating the curves in figure 10 represents the average between the lowest energy pair of ignite and no-ignite points at a given temperature. The error bars denote the gap between the ignite and no-ignite spark energies. (In the two cases in which there were two pairs of ignite and no-ignite points, the error bars denote the spread between both pairs of points.) There are also two points denoting no-ignite data at the maximum energy (100 J) in Shepherd's experiments.

The data in figure 10 clearly show how the minimum required spark energy decreases with increasing fuel temperature. This trend is due to the increasing fuel-vapor/air ratios at higher temperatures because of the associated higher fuel vapor pressures.

There are some differences in the results in figure 10 for the two different fuel loadings, but these differences are not consistent at all of the temperatures tested. In particular, there are no differences at temperatures of 95°F and 124°F. However, the minimum ignition energy data in figure 10 are incomplete at temperatures below 95°F, because the required ignition energies approach or exceed the maximum available 100 J.

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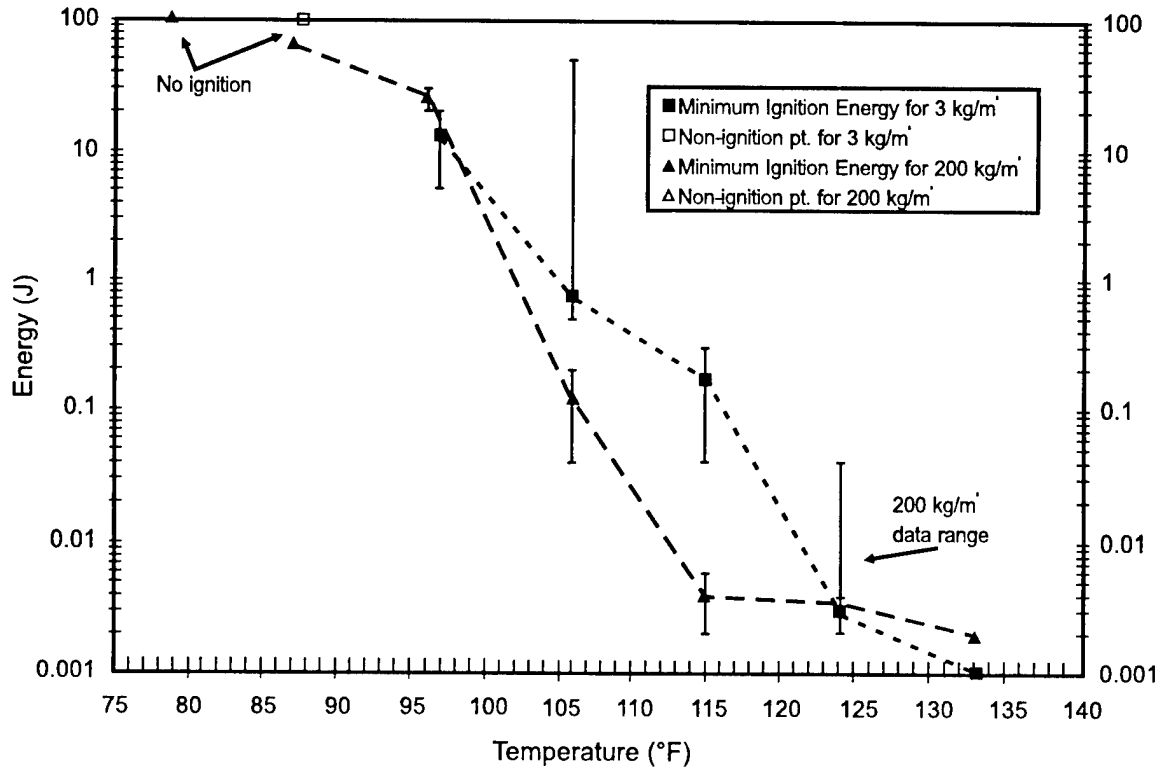
FIGURE 10. JET A MINIMUM IGNITION ENERGY VERSUS TEMPERATURE
AT 0.585 atm

Figure 11 is a comparison of the spark ignitability data obtained by the various researchers. The data are plotted in the form of tank altitude versus fuel temperature for specified spark ignition energy. The two curves designating Nestor's data [22] at a spark energy of 20 J represent the fuel-lean and fuel-rich branches of the flammability curve. Between these two curves, the minimum required spark energy is less than 20 J. Similarly, inside the Nestor [22] 5 J curve, minimum ignition energies are less than 5 J.
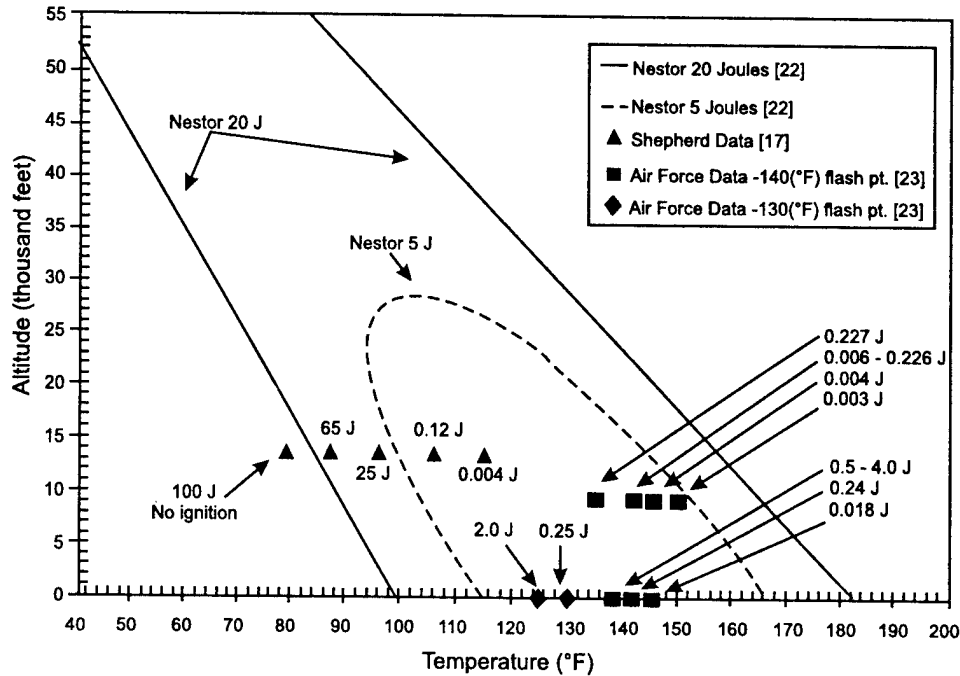
FIGURE 11. COMPARISON OF JET A FLAMMABILITY DATA

Several of Shepherd's data points [17] from figure 10 are also plotted in figure 11 at the 13,800-ft elevation. The Nestor 5 J curve at this elevation is consistent with the Shepherd data. Shepherd's 25 J and 65 J energy data occur at slightly higher temperatures than the Nestor [22] 20 J data at this altitude. This difference may be attributable to different ignition circuits (Nestor's [22] circuit produced multiple sparks) and/or to Nestor's reported spark discharge energy being less than Shepherd's reported spark stored energy. These differences may be more pronounced at higher spark energies. Shepherd is in the process of refining the ignition energy measurement and plans to do an energy balance to determine the energy in the spark.

The 1992 Air Force data [23], which were obtained for 130°F and 140°F flash point fuel, are also plotted in figure 11 at altitudes of zero and 10,000 ft. The 1992 Air Force data are consistent with the Nestor data in that the required spark energies were all less than 5 J, and all the data fell within Nestor's 5 J contour.

There have been some previous attempts to generalize the type of data shown in figure 11 to generate contours for many other spark ignition energies. However the accuracy and reliability of such plots cannot be quantified because of the lack of a detailed description of the procedures used to obtain the resulting contours.

One interesting question that can be addressed using the zero elevation data in figure 11 is whether or not there is a unique relationship between flash point data and spark ignition data. In other words, is the minimum spark energy at the flash point the same value for all samples? According to the 1992 Air Force data [23], this value is about 0.25 J for their 130°F flash point sample and 0.5 to 4.0 J for their 140°F flash point sample. Nestor's data [22] for his 118°F to

125°F flash point samples are roughly consistent with the 0.25 to 4.0 J range of spark energies at the flash point.

Both Ott's data [16] and Nestor's data [22] for fuel sloshing effects on Jet A ignitability demonstrate that the formation of a fuel mist can extend the ignitability limits down to substantially lower temperatures. For example, Ott found that under static conditions his Jet A sample would not ignite at temperatures lower than about 112°F. When the tank was subjected to a sloshing motion, this low temperature limit was reduced by at least 60°F. The precise extension depended on the frequency and amplitude of sloshing and the minimum pressure increase criterion, i.e., the extent of flame propagation.

Figure 12 shows some of Ott's slosh data and Nestor's vibrating fuel tank data for a minimum pressure increase of 10 psig, which is approximately half the strength of a center wing tank on a Boeing 747. When the Jet A was subjected to sloshing at a frequency of 14.5 cycles/min, 10 psig pressure increases were observed at temperatures as low as 92°F at one atmosphere pressure. When the sloshing frequency was increased to 17.5 cycles/min, which was approximately the resonant frequency of the tank, 10 psig pressure deflagrations occurred at temperatures as low as 75°F. The 17.5 cycles/min tests were also conducted at a pressure corresponding to an elevation of 10,000 feet, and the line connecting the zero elevation and 10,000-ft elevation data is shown in figure 12. The Nestor 20 J static and dynamic data shown in figure 12 indicate an even larger extension of the minimum temperature for ignition when the fuel is in motion and an ignition source is situated in the resulting spray. Three other effects relevant to aircraft fuel tanks need consideration before using the ignitability data shown in figures 10 to 12. These effects are (1) oxygen enrichment of the tank ullage, (2) fuel weathering, and (3) vapor convection.
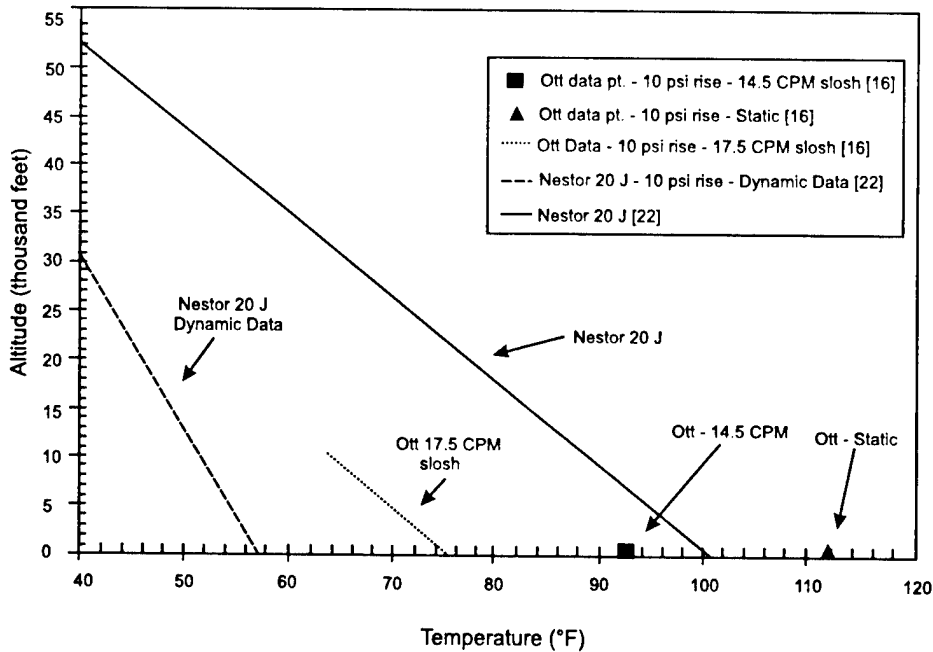

FIGURE 12. COMPARISON OF JET A FLAMMABILITY DATA (SLOSH AND STATIC CONDITIONS)

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Oxygen enrichment of the tank ullage occurs because oxygen is more soluble in Jet A than is nitrogen. The degassing of fuel that occurs because of pressure equilibration at higher altitudes causes the oxygen to be disproportionately (relative to air composition) released into the ullage. When there is a relatively small ullage volume, the increase in oxygen concentration can be substantial. Oxygen enrichment is known to reduce the minimum ignition energy of hydrocarbon fuels, and extrapolations of the existing database by Ural et al. [24] suggest that the minimum ignition energy decreases with oxygen concentration to the −2.5 power. Thus, increasing the oxygen mole fraction from 0.21 to 0.25 (often observed in full tanks) would decrease the minimum ignition energy by 35%. Data to confirm this effect is needed for full fuel tanks but is not likely to be relevant to tanks that are less than half full.

Fuel weathering is the gradual release and depletion of lighter and more volatile hydrocarbons due to some combination of temperature increase, pressure decrease, and/or ventilation-induced evaporation. This can be manifested in the form of a reduction in fuel vapor pressure, flash point, and lean limit temperature at a given altitude. Laboratory analysis of fuel vapor sample compositions obtained by Woodrow and Seiber [25] in the TWA Flight 800 simulation flight demonstrate that there is substantial weathering in the form of carbon string reductions in C_5 to C_8 concentrations. Although there is a lack of data on the effect of those concentration reductions on fuel ignitability requirements, one would expect that the qualitative effect would be an increase in fuel flash point and a corresponding increase in required spark energy at a given temperature. However, preliminary results do not support this conclusion.

Vapor convective motion in an aircraft fuel tank is induced by temperature gradients, particularly those between the hot fuel and the cooler walls and roof of the tank. The magnitude of this convective motion is currently being evaluated by Shepherd [17] through mathematical modeling. Vapor-air mixture flow is known to increase the required ignition energies of a particular composition and temperature. If this effect is important for the vapor velocities in a center wing tank, the existing database on minimum ignition energies for heated fuel under isothermal test conditions may have an inherent level of conservatism. However, the level of conservatism is not expected to be very large if convective velocities in the tank are on the order of 1 m/s or less.

2.2.2 Need for Additional Data on Spark Ignition.

It would be useful to obtain additional data on Jet A flammability to further explore the low temperature (lean fuel vapor) limits discussed in section 2.2.1. This might entail conducting additional tests with samples of Jet A fuel at flash points lower than the 118°F, which is the lowest flash point for the fuel samples listed in table 2. Some spark ignition tests have been conducted by the Air Force [23] with Jet A samples of 100°F (Air Force, Attachment B [26]), but the tests were conducted at 150°F. For purposes of establishing low temperature limits of ignitability, testing would have to be conducted at temperatures under 100°F.

It would also be useful to extend the 20 J and 25 J contours shown in figures 11 and 12 to substantially higher spark energies (greater also than the 100 J limit of Shepherd's [17] ignition circuit). These higher spark energies might also be extended to include energetic ignition sources

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that produce a shower of hot fragments (such as occur in pyrotechnic igniters). The hot-fragment energetic ignition sources might simulate aircraft incident scenarios involving either explosive device fragments or impact sparks.

Tests to explore the effects of variations of electric spark duration would also be useful since it has been observed that the minimum ignition energies of hydrogen-air mixtures are reduced considerably by increasing the spark duration (Lewis and von Elbe [27]). Similarly dramatic reductions in required ignition energies of combustible dust clouds are well documented (Eckhoff [28]). These increases in spark duration result from inclusion of either resistance or inductance in the spark discharge circuit.

2.2.3 Hot-Surface Ignition Data.

The limiting case of hot-surface ignition is a uniformly heated vessel or tank. The fuel temperature required to autoignite in a uniformly heated vessel is measured in standardized tests. Results obtained with Jet A fuel in an 18-inch spherical vessel at various pressures are shown in figure 13. At atmospheric pressure, autoignition occurred at temperatures as low as 210°C (410°F) to 300°C (572°F) depending on the air-fuel ratio. According to the data in figure 13, there is a much wider range of air-fuel ratios for autoignition than there is for spark ignition.
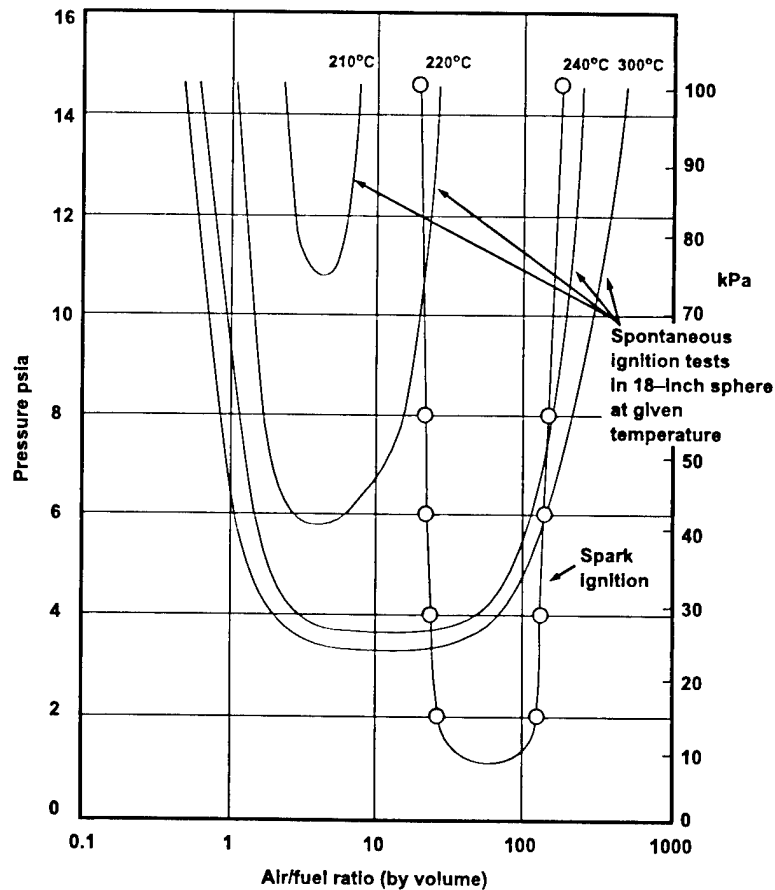

FIGURE 13. SPARK AND SPONTANEOUS IGNITION LIMITS FOR AVTUR

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As the tank/vessel pressure decreases, the fuel autoignition temperature increases. Data in figure 13 indicate that, at a tank/vessel pressure under 3.5 psia, autoignition temperatures would be far in excess of 300°C no matter what the air/fuel ratio was in the tank.

When the hot surface occupies only a small fraction of the total surface area of the tank/vessel or when a small hot surface is inserted in the tank, the required surface ignition temperature increases sharply. For example, data in AGARD AR–132 [29] show that a 15.2-cm-diameter 310°C (590°F) cylindrical surface in a 46-cm-diameter sphere would cause Jet A to ignite, but a 3.8-cm-diameter surface would have to be heated to about 650°C (1200°F) to trigger ignition. Other tests indicate that a 15-cm-diameter cylindrical heated surface produces similar results as a flat plate heated to the same temperature.

The authors of AGARD AR-132 [29] suggest that the temperature of all surfaces on which Jet A might come in contact should be maintained under 240°C (464°F) to preclude hot-surface ignition. FAA Advisory Circular 25.981 provides designers with guidelines for hot-surface ignition prevention.

2.2.4 Ignition Probability Formulation.

The need for additional data notwithstanding, this task group was requested to recommend flammability criteria that could be used to explore the value of various proposed modifications to center wing tank fuel management. The rationale proposed for this purpose is to use the flammability regions suggested by figure 11 in the context of ignition probability in a center wing tank. In other words, low ignition energy requirements imply high probabilities of ignition by some unidentified spark ignition source, such as the unidentified ignition source in the TWA Flight 800 explosion. The opposite would be true with high ignition energy requirements. Some test data and statistical data generalizations have been conducted by Crouch [30] and by the Air Force (Attachment B [26]) to develop ignition probabilities for a few different hydrocarbons including Jet A at one particular temperature and spark energy. More data are needed to develop any confidence in extrapolating these probability distributions to other fuel temperatures and flash points.

Assuming the additional spark ignition probability data become available, the representation of the conditional (conditional on some type of spark occurring in the fuel tank) probability of ignition, $P_{ign| spark}$, could be represented as

$$P_{ign| spark} = P(E_{ign} < E_{spark})$$ (2)

That is, the conditional ignition probability is the probability that the spark energy exceeds the required energy for spark ignition.

If the probability density function for spark energy is denoted by FE_{spark} (E) and, if the cumulative probability distribution function for required ignition energy is denoted by FE_{ign} (E), then from the method of competing risk equations,

$$P(E_{ign} < E_{spark}) = \int_0^\infty FE_{spark}(E)FE_{ign}(E)dE \qquad (3)$$

Development of the distribution function $FE_{ign}(E)$ requires consideration of the fuel temperature, T_{fuel}, fuel flash point, T_{FP}, and aircraft altitude, Z, i.e.,

$$FE_{ign}(E) = FE_{ign}(E, T_{fuel}, T_{FP}, Z) \qquad (4)$$

This distribution function needs to be developed from existing and future ignitability test data, while the corresponding distribution function for spark ignition energy needs to be developed from considerations of the electrical equipment, circuits, and wiring in and adjacent to the center fuel tank. Electrostatic spark discharges should also be included in the development of $FE_{spark}(E)$.

2.3 DETERMINATION OF THE FUEL/AIR MIXTURE.

2.3.1 General Considerations.

The discussion of flammability data presented in the previous section has introduced temperature as a meaningful parameter to define the conditions required for jet fuel vapors to be ignitable. Reference to this quantity is in part rooted in the use of temperature by standardized tests (flash, fire point) to express the propensity of a vaporizing liquid to support combustion. In practical contexts, however, this characterization method loses much of its usefulness since most real-life situations are sufficiently complicated to prevent the identification of a unique system temperature to represent the explosion hazard. For example, during transient vaporization from a flammable liquid layer, the temperature of the liquid only defines the concentration of the fuel vapors at the interface. The concentration field above the liquid is determined by diffusion and mixing processes in the gas phase. While these processes are affected by the presence of boundaries and by the temperature field in the gas, there is no a priori general relationship between temperature and vapor concentration at a particular location in the gas.

A quantity that has been shown to be practically convenient in defining the flammability limits of mixtures is the fuel/air (F/A) mass ratio, since its value at the lower flame propagation limit is quite constant over a wide range of fuels. Literature data indicate that the F/A ratio at the lower limit is about 0.03 kg/kg (or 0.035 kg/m^3 [0.0022 lb/ft^3] in sea level air). The approximate constancy of this limit ratio extends to alkanes and aromatics which represent the main constituents of jet fuel. Another practical advantage of this quantity is the fact that, for concentrations between the lower limit and up to near stoichiometric, the F/A ratio provides a measure of the energy (pressure) that would be released (developed) by reaction of the mixture. This type of information is necessary to advance hazard analyses beyond pure ignition questions and quantify the consequences of the ignition event. In conclusion, the ignitability of a mixture is a function of the F/A ratio at the locations of postulated ignition sources, while the potential damage resulting from the ignition is a function of the F/A ratio distribution through the affected volume(s).

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Following this discussion of the parameters that best characterize the flammability problem, it must be recognized that current modeling technology is not sufficiently advanced to allow for detailed predictions of the temporal and spatial evolution of the concentration field produced by a particular set of boundary conditions. Therefore, it appears likely that the assessment of fuel tank flammability will continue to rely on more approximate methods which neglect spatial variations. For the immediate future, it is expected that calculations will be based on an appropriate average F/A value, possibly represented as an equivalent saturation temperature. While the suitability of this approach will have to be assessed for each practical application, the following discussion provides comments with regard to the anticipated limitations introduced by the simplification.

2.3.2 Fuel Loading Effects.

Unlike the case of single-component liquids, multicomponent systems introduce the additional complexity that the composition of the vapors is not the same as that of the liquid, with the vapors containing a higher percentage of the more volatile (i.e., lower molecular weight) fractions. Because of this fact, vaporization tends to shift the composition of the liquid towards the heavier compounds. In practical terms, this effect is negligible if the fractional mass of the liquid that needs to be vaporized to saturate the gas space is small. The parameter commonly used to characterize the magnitude of this effect is the mass loading, defined as the mass of the fuel per unit volume of the tank holding it. If the tank is full, the mass loading is equal to the density of the fuel (about 800 kg/m^3 [49.9 lb/ft^3]); if the tank is half full, the mass loading is half the density of the fuel, and so on.

In the case of a near empty central wing tank (CWT), 50 gal (0.19 m^3) of fuel in a 13,200-gal (50-m^3) tank correspond to a fuel loading of 3 kg/m^3 (0.19 lb/ft^3), or in other words, the fuel occupied about 0.4% of the volume of the CWT in TWA 800. Since the vapor concentration at lower limit conditions is 0.042 kg/m^3, at a fuel loading of 3 kg/m^3, saturation of the vapor space to achieve flammability requires evaporation of 1.4% of the available liquid. This is a significant quantity, as it probably represents a non-negligible percentage of the low molecular weight compounds in the mixture. For the case of the CWT in TWA 800, fuel fractionation effects have been identified as being worthy of consideration and have been the object of more detailed analyses [17].

There is evidence, however, which indicates that the impact of fuel fractionation effects on system safety may be relatively small. While the vapor pressure has been shown (as expected) to decrease significantly when the mass loading drops to values of the order of 3 kg/m^3 (0.19 lb/ft^3), the corresponding decrease in mixture flammability is not as large. For example, recent California Institute of Technology (CIT) results [31], which have already been presented in figure 10, indicate little difference between data on minimum ignition energy as a function of temperature from experiments at the two mass loading values of 3 and 200 kg/m^3 (0.19 and 12.5 lb/ft^3). Similarly, the mass loading appears to have an influence on the energy release near the limit, but the effect goes away at temperatures about 5-10°C (9-18°F) above the limit. The detailed analysis of Jet A fuel flight test samples reported in reference 32 reaches similar conclusions. Despite a gradual increase in the average molecular weight of the vapors sampled during successive flights, the total mass of fuel vapors present in the CWT was essentially

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unchanged. An approximate explanation for this result can be provided by the observation that low molecular weight components make a greater contribution to the total pressure than to the mass of the vapors. As a result, their reduced presence has a proportionately lower influence on flammability, since this depends mainly on the F/A ratio.

2.3.3 Fuel Tank Geometry (Compartments).

The design of aircraft fuel tanks introduces certain complexities that impact on the estimate of the distribution of fuel vapors. Typically, these structures consist of a large, box-like volume subdivided in compartments mainly for structural reasons but also to minimize fuel slosh. These compartments communicate with each other through small openings, most of which are found at the bottom and top corners of the internal partitions. The bottom of the tank is generally concave and its orientation relative to the direction of the apparent gravity experienced by the aircraft can change during flight. This causes movement of the fuel which, when the liquid level is low, can lead to successive wetting and drying of portions of the tank bottom. To equalize the tank pressure with external conditions, venting outlets are provided in some but not all of the compartments. In the case of the CWT in B747s, for example, these outlets are located as follows: two at the outboard sides the forward bay (bay 1, between spanwise beams 2 and 3), one on the left side of the left mid bay, and one on the right side of the right aft bay. This arrangement implies that pressure changes in compartments without direct access to the vent line will induce flow to and from adjacent compartments.

From the perspective of determining the F/A ratio, a very important source of nonuniformity is contributed by the localized nature of the heat input to the bottom of the tank from the environmental conditioning system (ECS) packs. The data from the flight tests [33 and 34] indicated that at the end of a 3-hour gate hold the skin temperature of the bottom of the tank had reached a maximum of 200°F (93°C) in the left mid bay, where pack 2 is located. At the same time in the test, temperatures as low as 140°F (60°C) were recorded at other points of the bottom tank surface. The clear implication of this result is that, in the B747 design, much higher vapor concentrations would develop in the left mid bay than in the other compartments, since the fuel would be significantly warmer and compartment-to-compartment vapor transfer would be minimal under static conditions. From this brief discussion, it is apparent that acceptable accuracy in the prediction of tank ullage conditions requires calculation methods that properly take into account the details of the internal geometry and of the heat flux distribution. Preliminary calculations of the two-dimensional heat transfer through the tank bottom surface have been already carried out at CIT [35], confirming that large temperature gradients are induced by the nonuniform heating from the ECS packs.

2.3.4 Vertical Mixing.

The preceding section has presented evidence supporting the conclusion that horizontal variations in the fuel tank vapor distribution are generally important. The next question is whether vertical gradients within each compartment are also important. The short answer is that it probably depends on the phase of the transient that is being considered. More detailed comments are offered below.

During the initial heating of the fuel tank that takes place on the ground under static conditions, unstable thermal stratification can develop since the tank is being heated from below and held at lower temperatures on its top and side surfaces. Flight test data have shown that vertical gradients can develop with temperature differences as high as 20°F (11°C). This data point refers to conditions in the left mid bay after the 3-hour gate hold for the fuel load conditions of TWA 800 where peak temperatures of 124 and 144°F (51 and 62°C) were recorded near the top and bottom of the compartment, respectively. In a system of uniform composition, this temperature difference should promote vigorous convective mixing. The fact, however, that the fuel vapors have a molecular weight which is higher than that of air tends to decrease the mixing predicted by neglecting composition differences. The combined effect of vapor composition and temperature on the density can be assessed using perfect gas calculations. For example, if the molecular weight of the vapors at the interface is assumed to be equal to 162, a fuel layer at 125°F (52°C) with an ullage space filled with air (no fuel vapors) at 98°F (37°C) produces a stable stratification. If a molecular weight value of 93 is assumed instead, neutral stability is achieved for the same fuel layer at an air temperature of 112°F (44°C).

Experimental data on the departure of the gas space composition from equilibrium conditions have been presented by Kosvic et al. [36]. These experiments, which involved a 50% full tank held at constant temperature, simulated both ascent and level-flight conditions with fuel withdrawal. Because of this choice of parameters, the results cannot be easily extrapolated to the case of a near empty tank which is being heated. However, the observation of evaporative lag under some of the conditions of these tests suggests that, in general, it may not be possible to assume that the gas space composition is mapped by the temperature field.

Another useful set of data is contributed by the work in reference 37. This project involved tests in a 581-gallon (2.12-m³) tank for different wall temperature conditions. In cases where stable thermal stratification was simulated (isothermal walls, hot top wall, or cold fuel), the concentration data confirmed that mixing was taking place only by molecular diffusion, as expected. When unstable conditions were created, either by cooling the side walls or the top of the tank 25°F below the other surfaces, mixing clearly became dominated by natural convection. In this case, two regions were identified in the tank volume: a thin—about 50-mm (2-in.) -thick—layer near the fuel surface with a large variation in vapor concentration, and the bulk of the tank with essentially uniform composition. For the conditions of these tests, which involved a 10% full, 3-ft (0.91-m) -high volume, the composition of the bulk reached 50% of the vapor concentration at the liquid surface after about 1 hour. This result shows that, even in the case where convective mixing is present, the well-mixed bulk of the volume requires time to reach equilibrium with the liquid since the evaporation at the liquid surface is the rate controlling step in determining how rapidly vapor can be supplied to the bulk of the ullage volume. Unfortunately, no temperatures were measured in these tests. It is, therefore, not possible to evaluate whether the ullage concentration could be approximated by assuming saturation at the bulk gas temperature. This is clearly an issue that requires further analysis before equilibrium assumptions can be used by models.

2.3.5 Fuel Degassing.

The air which is dissolved in the fuel tends to be released into the ullage space as the pressure in the system drops during climb. Owing to the higher solubility of oxygen compared to nitrogen, the fuel degassing process tends to increase the oxygen concentration in the fuel-air mixture in the tank. Oxygen enrichment of the atmosphere increases the hazard by broadening the flammable range, mostly by raising the upper flammability limit, and by decreasing the energy required for ignition. This change in oxygen concentration, however, has a small effect on the lower flammability limit. The rate of gas desorption from the fuel is accelerated by the presence of vibrations, a factor that can be quite significant in military planes but appears to be of secondary importance in the case of commercial aircraft [33].

A final consideration revolves on the dependence of oxygen enrichment on fuel loading. Clearly, the effect is maximized in situations that involve a small ullage (i.e., near-full tanks). With a near-empty tank, particularly if the fuel has aged by undergoing a few degassing cycles, the effect would probably be small. In conclusion, it would appear that consideration of oxygen enrichment of the ullage space can be given a relatively low priority in evaluating the explosion hazard of the fuel tank.

2.3.6 Fuel Misting.

The role of mist in reducing the lower flammability limit has long been recognized and is well documented (see the data for Jet A fuel in reference 16). Vigorous sloshing of the fuel is the mechanism that is typically associated with mist formation. If violent motion of the frame is absent in commercial aircraft, misting would not appear to be a factor to be considered in fuel tank safety assessments. Two situations represent possible exceptions. The first arises in connection with the presence of a return stream of cooling fuel from the fuel pump back into the tank. The characteristics of this flow are ill defined but are understood to potentially vary significantly depending on the particular pump design. Splashing of the fuel against a tank wall, in those cases where the exit velocity is high, would be a clear source of concern. The potential for this mechanism to be present should be evaluated on a case-by-case basis.

The second situation would involve flights through highly turbulent air masses which could shake the aircraft to the point of inducing significant sloshing. While affecting a relatively small fraction of total flight time, this event may have an impact on overall safety due to the coincidence with a higher probability of presence of an ignition source (by lightning strike, for example). Because of these two scenarios, the potential for broadening of the flammability range due to mist formation appears to be real and deserving some consideration. On balance, however, it is probably not of sufficient importance to warrant extraordinary efforts to include its effects in safety analyses.

2.3.7 Mass Exchange With External Environment.

When the aircraft is on the ground, pressure equalization between the tank and the external environment becomes necessary if there is expansion or contraction of the gas space due to temperature changes or if fuel is being withdrawn from the tank. The mass exchange between

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the tank and the external environment induced by these effects is probably small compared to that which occurs as the aircraft climbs to cruising altitude. In a climb from sea level to 14,000 ft (4,300 m), about 35% of the initial gas inventory escapes from the ullage. At a climb rate of 1500 ft/min (7.6 m/s), the outflow of this mass has to take place in about 9 minutes. In a 13,200-gal (50-m^3) tank, this implies an average outflow during the climb of 66 scfm (0.031 m^3/s). If inlets to the venting system are not present in every compartment, a portion of this total flow has to transit through some of the passages that provide communication between the various compartments.

Flight test data indicate a drop in the ullage temperature of about 10°F (5.6°C) during a 14,000-ft climb. Since adiabatic expansion for the same pressure excursion would predict a temperature drop of 80°F (44°C), the ullage gas expansion takes place under energy addition from the fuel and the tank walls. This observation on the thermal transient behavior has implications in terms of the evolution of the F/A ratio. Adiabatic expansion of a gas volume initially saturated with vapors would cause condensation of some of the vapors. The fact that, instead, the temperature during the climb is seen to remain essentially constant implies that the vapor space is likely to go below saturation as the total pressure drops. This will drive additional vaporization of the fuel. The available data from the flight tests indicate vapor concentrations that are in equilibrium with the ullage temperature. Since temperature differences (both in the fuel and gas space) during this phase are small, it is somewhat surprising that the mixing processes would be sufficiently strong to maintain a vapor-saturated atmosphere in the forward compartment (bay 1, between spanwise beams 2 and 3) where the gas samples were taken. As already noted, the absence of a vent pickup point in bay 2 (the compartment between spanwise beam 2 and the mid spar) will cause some of the volume exhausted from bay 2 to travel through bay 1 in order to reach the vent line. The effect of this flow in promoting compartment mixing is not well understood at this point.

Similar considerations apply to the situation during descent, in which case the processes are reversed. During this phase, the fuel tank is being repressurized by introduction of fresh air from the outside. At least initially, this must cause composition nonuniformities, particularly near the points where the air enters the ullage. In the perspective of the explosion hazard assessment, an accurate prediction of the conditions during this phase may not be as important as other portions of the transient. Barring a decision to side step the problem, the modeling task would involve consideration of the same issues of evaporation lag and nonuniformities already discussed.

2.3.8 Determination of Fuel/Air Mixture Summary.

The preceding discussion has brought up the fact that a rigorous determination of the F/A ratio in the fuel tanks used in commercial aircraft would require proper consideration of several factors. Given the current state of modeling technology, however, it is likely that near-term estimates of this quantity will be based on approximate methods which make reference to an equivalent equilibrium temperature. Hazard conditions would then be assessed by comparison with a flammability threshold also expressed in terms of a lower limit temperature. Within this perspective, the various problem parameters will play different roles, whose degree of importance is discussed in the following comments.

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The fact that fuel tanks are divided into compartments is a factor that must be properly taken into account. Due to the relatively small area of the passages connecting neighboring compartments and the nonuniform distribution of the heat input to the bottom of the tank, it is hard to envision how this aspect of the problem could possibly be neglected. It is, therefore, recommended that this level of geometry discretization be included in all simulations of fuel tank behavior. Determination of flammable conditions in one compartment should be interpreted as potentially leading to failure of the entire tank.

The second aspect deals with the question of evaporation lag and spatial concentration gradients in the gas phase of each compartment. At this point, it is not possible to quantify the inaccuracies that would be introduced by assuming that the ullage is saturated and in equilibrium with the liquid. The magnitude of the error would clearly depend on the details of the scenario being considered. It is possible, however, to make approximate estimates of the impact of this assumption during various phases of the flight. For the purpose of the present discussion, it will be assumed that the fuel has low volatility (i.e., flash point above standard ambient temperature). This implies that hazardous conditions arise because of crossing into the flammable range from the lean side. For this situation, conservative calculations will be those that provide upper bound estimates of the fuel vapor concentration in the ullage.

During heating of the fuel tank on the ground, neglect of evaporation lag should lead to a conservative estimate of the vapor concentration in the ullage, if this is calculated as the value corresponding to saturation at the fuel temperature. A similar level of conservatism should also prevail during the climb to cruising altitude, provided that the temperature of the fuel remains higher than that of the ullage. Cruising at altitude, on the other hand, may be characterized by net cooling of the fuel, with the possibility of thermal lag leaving the ullage warmer than the liquid. In this case, proper conservatism could be achieved by assuming saturation at the ullage temperature. Conditions during descent involve heat addition into the tank and air injection from the outside. Most evidence indicates that, even in this phase, the vapor concentration lags behind that corresponding to saturation at the temperature of the liquid.

In summary, it appears that the assumption of fuel vapors at equilibrium with the liquid is generally acceptable (i.e., conservative) for all phases of the flight. Again, this statement applies to conditions that do not approach the rich flammability limit, where an overestimate of the fuel vapor concentration leads to nonconservative conclusions. Oxygen enrichment of the ullage from degassing effects, liquid composition changes due to fractionation, and to a lesser extent, misting from sloshing do not appear to be critical and can probably be neglected without major penalty in most situations. The potential for misting from fuel pump return flows, however, should be evaluated on a case-by-case basis, and oxygen enrichment effects in nearly full tanks should not be ignored.

2.4 THERMAL MODELING.

2.4.1 Need for Numerical Simulations.

It is impossible to carry out instrumented flight tests for the infinite number of environmental and operational conditions under which commercial aircraft operate. Therefore, a computer-based

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computational code has great appeal for use in evaluating the effects of the multitude of conditions that affect the center wing tank flammability. In addition, it would be valuable to have a reliable model to evaluate different strategies to reduce this flammability. These strategies include but are not limited to design changes, changes in ground and flight operations, adding insulation or radiation shielding or both between the ECS and the tank, carrying extra fuel, changing the fuel flammability, etc. Although the issue of center wing tank flammability has been raised by the TWA 800 accident, the concern is for the entire commercial fleet, not just the B747 design. Therefore, a code should not be limited to a single aircraft design, such as a B747, but should be applicable to those aircraft in the entire fleet that are similarly configured with packs below the CWT.

The purpose of computational modeling is to adequately simulate the principal features of the tank heat up process to get a quantitative picture of flammability conditions in the tank ullage. To be reliable, the computer code must be based on fundamental thermodynamic and fluid dynamic principles. The heat transfer to the CWT is made up of two components, radiation and convection. Radiation is dependent on the geometry of the hot surfaces on the ECS, distance between the ECS and the tank bottom, and the surface conditions and properties (emissivity). The geometrical configuration is quite intricate if all the features are represented and for that reason, will probably have to be simplified. The distance between the ECS and tank bottom is variable depending on location, but can be obtained from the design. The surface properties (emissivity) depend predominantly on the materials used including paint and the condition (cleanliness) of the aircraft. Convective heat transfer is dependent on distance between the ECS and the tank bottom and the amount of ventilation. Heat transfer measurements can be obtained experimentally from flight test data and compared with the values used in a computational model for validation. Tank surface, ECS components, and ullage temperature measurements made in the flight tests can be used for validation.

In addition to the thermal modeling of the ECS packs and the CWT structure, heat transfer to the fuel, evaporation of the fuel, mixing of fuel and air in the ullage, and heat transfer to the ullage contents must be considered in order to predict fuel vapor concentrations.

Any model that is developed should include the following features:

a. The effects of nonuniform heating on the tank bottom.

b. Calculation of fuel temperatures in each tank compartment because there may be large temperature gradients. These calculated fuel temperatures should include different fuel layer thickness including layers that are thin enough to include dry areas in the tank.

c. Calculation of the effects of stringers and other internal structure on heat transfer into the tank.

d. Calculation of the tank wall temperatures.

e. Inclusion of the ECS heat dissipation rates.

f.   Calculation of the vapor composition based on the fuel evaporation and condensation effects.

2.4.2 Codes Being Developed.

Two groups, the Boeing Company and the California Institute of Technology (CIT), have or are in the process of developing computational codes to evaluate the flammability characteristics of the center wing tank. The code development at CIT is supported by the National Transportation Safety Board. Neither group has provided, at this stage, written documentation for the computer codes.

The Boeing effort is more advanced and preliminary results of their efforts to predict the effect of various strategies to reduce the temperature in the fuel tank have been provided in briefings. The model is frequently referred to as a simplified computational model and is undergoing continual refinements to improve the sophistication. However, these early efforts at modeling have shown the difficulties of developing a model of the complex system. The model is based on fundamental heat transfer equations. Results from two different codes have been compared and apparently gave similar results, although comparison results were not presented. Boeing compared the model results with the ground and flight test data. This comparison was based on the average temperature in the tank during selected flight tests. Boeing concluded from the model calculations that (1) adding insulation between the tank bottom and the ECS packs and (2) limiting the use of the packs at the gate reduced the amount of time the CWT conditions were above the lower flammability limit for Jet A fuel. As stated earlier, the Boeing effort is continuing.

The modeling effort at CIT is in the early stages of development. Two approaches are being pursued. One uses thermodynamic and fluid dynamic principles to estimate heat transfer from the ECS packs via radiation and convection to the tank bottom. These estimated values are being refined using the available flight test data and additional testing requirements are being developed for ground tests using heat flux instrumentation mounted on the tank bottom. The measured heat flux will have to be used as input into the thermal model of the CWT.

The second approach and the main emphasis at this point is to obtain a heat flux distribution over the entire tank bottom plate by reducing the difference between the calculation and the measurement at each surface measurement point on the CWT bottom plate. Validation of the thermal model will have to be made against existing flight data and proposed ground tests.

To date, the Boeing and CIT efforts have been limited to the B747 aircraft in response to the TWA 800 accident. Obviously, since other aircraft also use a center wing tank with the environmental conditioning system below the tank, there is a need to extend the modeling effort beyond the B747 design.

There is a long history of ullage flammability modeling within the Department of Defense (DOD). These previous modeling efforts (Kosvic, et al. AFAPL-TR-71-7 [36], and Roth, AFWAL-TR-87-2060 [37]) need to be reviewed carefully to determine their reliability and to

determine how much modification is needed for the civilian aircraft. If appropriate, they can be incorporated into the next generation models that are currently under development.

2.4.3 Thermal Modeling Summary.

It is clear that the development of reliable heat transfer models and the ability to calculate the flammability of the ullage space in a center wing tank of an aircraft under different environmental and operational conditions is in the early stages. Therefore, the ability to reliably evaluate different strategies to reduce the flammability of fuel in the center wing tank of a B747 has not been proven. The extension of a given computational model to another aircraft design, such as a B737 or A320, will require ground or flight tests for validation of each design. Certainly, the process requires long-term research and testing programs.

The flight tests carried out in July of 1997 were designed to measure the temperature in and under the tank and to assess the flammability of the vapors in the tank under very limited environmental and operational conditions. These flight tests were also the first step in collecting the necessary information for the development of a computer based model. The flights were basically limited to simulating the TWA 800 flight, to assess the significance of carrying extra fuel in the center wing tank, and to assess the impact of running different numbers of heat packs at different amounts of time while on the ground. While temperatures were measured at more than 100 locations in the center wing tank and at more than 30 under the tank of a B747-100 series aircraft, the measurements represent very limited flight conditions and only one airplane. In spite of these limitations, these measurements do provide a wealth of data that can be used in the validation of a computational thermal model of the tank and its environment. However, it will take many months before any model can be validated to the point the scientific community has faith in the output of the model. In addition, it is clear that additional ground and/or flight testing will need to be carried out to provide additional data for the validation process. Of particular importance is the need for heat flux measurements between the ECS and the tank bottom.

2.5 FUEL TANK VULNERABILITY ANALYSIS METHODOLOGY.

2.5.1 Methodology Development.

In the interest of simplifying the ignition probability calculation described in section 2.2.4, the probabilistic aspects of the spark ignition energies can be replaced by a deterministic representation. With this approach, the conditional ignition probability is now given by

$$P\left(E_{ign} < E_{spark}\right) = 1 - FE_{spark}\left(E_{ign}\right) \tag{5}$$

where FE_{spark} is the cumulative distribution function for the spark energy, and E_{ign} is the spark energy required for ignition.

The deterministic form of E_{ign} is represented functionally as

$$E_{ign} = E_{ign}\left(T_{fuel}, T_{FP}, Z\right) \tag{6}$$

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The specific equation for E_{ign} requires a correlation of the available experimental information. While the curves shown in figure 5, originally developed by British Aerospace, have been used for many years by industry for design purposes, their relationship to experimental data has not been clearly documented. A new correlation will, therefore, be introduced here based on the data already presented in figures 10 to 12 and on information available in the literature.

The first component of the correlation concerns the variation of the minimum value of E_{ign} as a function of altitude, Z. This is written as

$$Ln\,(E_{ign})_{min} = \frac{0.063Z - 1.395}{(1 - Z/67)^{0.5}} \qquad (7)$$

where E_{ign} is entered in mJ and Z in 1,000 ft. Equation 7 is based on values for the minimum of E_{ign} as a function of pressure reported for ethane in reference 38, taking into account the fact that there is a value of pressure below which a mixture is no longer flammable. This limit pressure is reported in reference 39 as being equal to 50-, 90-, and 120-mm Hg (67, 120, and 160 mbar) for methyl alcohol, ethylene, and methane, respectively. The same reference reports a value from an earlier study [40] for gasoline of 35-mm Hg (47 mbar) obtained with a strong ignition source (guncotton). This last data point, which is equivalent to an altitude of 67,000 ft (20,400 m), was used in equation 7. A comparison of this equation with available data is shown in figure 14. It shows good agreement with the points extracted from the British Aerospace curves, indicating that they were probably obtained using a procedure analogous to the one followed here.
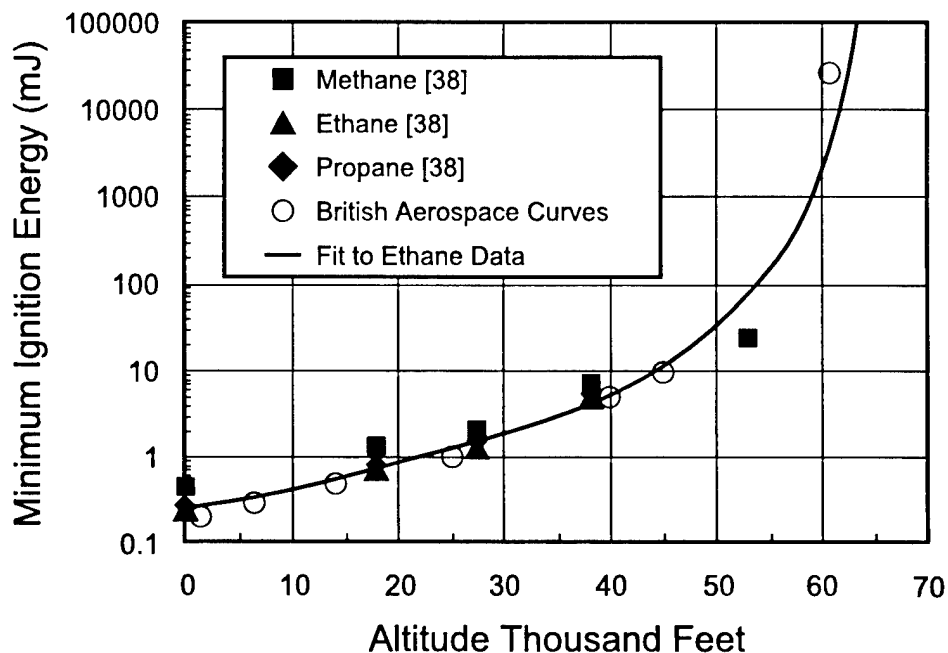
FIGURE 14. COMPARISON OF THE CORRELATION FORMULA WITH DATA FOR VARIATION OF MINIMUM IGNITION ENERGY WITH ALTITUDE

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Additional expressions are needed to describe the variation of E_{ign} with fuel temperature, T_{fuel}. A parabolic dependence has been assumed according to the following equation:

$$Ln\,(E_{ign}) = Ln(E_{ign})_{min} + a\,(T_{fuel} - T_{min})^2$$

(8)

The variation of the constant, a, with altitude is written by matching to the 20-Joule ignition curves in Nestor's work [22]:

$$a = 8.66\,10^{-5}\,Z + 6.73\,10^{-3}$$

(9)

and the temperature, T_{min}, of the minimum of the parabola is calculated as a function of the flash point of the fuel, T_{FP}, and altitude according to

$$T_{min} = T_{FP} + 22 - 1.5\,Z$$

(10)

A comparison between the values for E_{ign} provided by equations 7-10 and data reported in references 17, 22, and 23 is shown in figures 15-17. In general, the analytical representation provides a conservative approximation (lower bound) to the data. The implications of equations 7-10 in terms of ignition energy contours in the temperature-altitude plane are shown in figure 18. As can be seen by reference to figure 5, these contours are very similar to those developed by British Aerospace. The proposed correlation is believed to be applicable for altitudes up to about 55,000 ft.

FIGURE 15. COMPARISON OF CORRELATION WITH MIE DATA FOR JET A FUEL AT SEA LEVEL
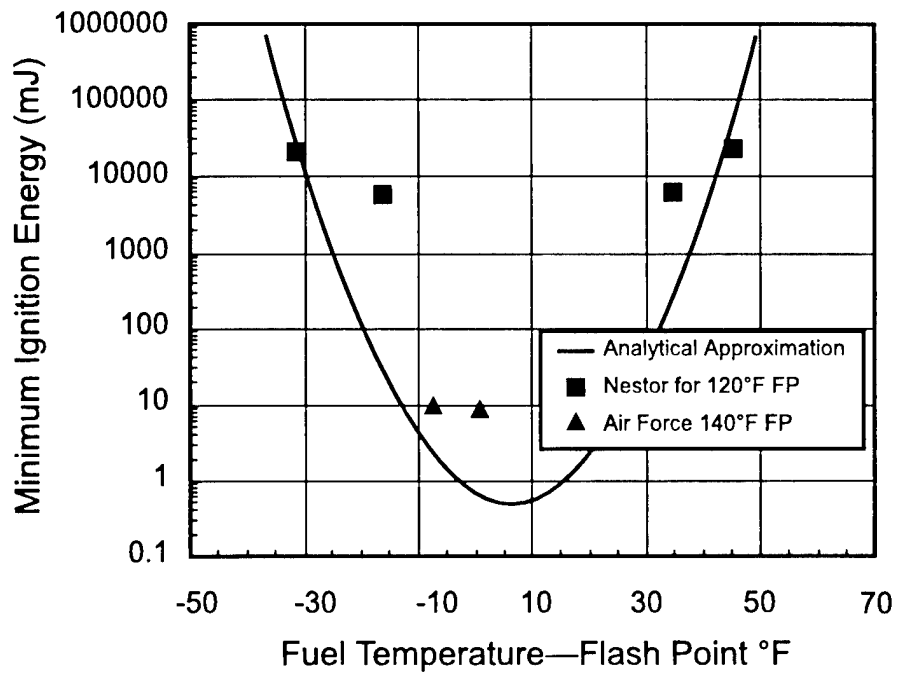
FIGURE 16. COMPARISON OF CORRELATION WITH MIE DATA FOR JET A FUEL AT
10,000 FT ALTITUDE
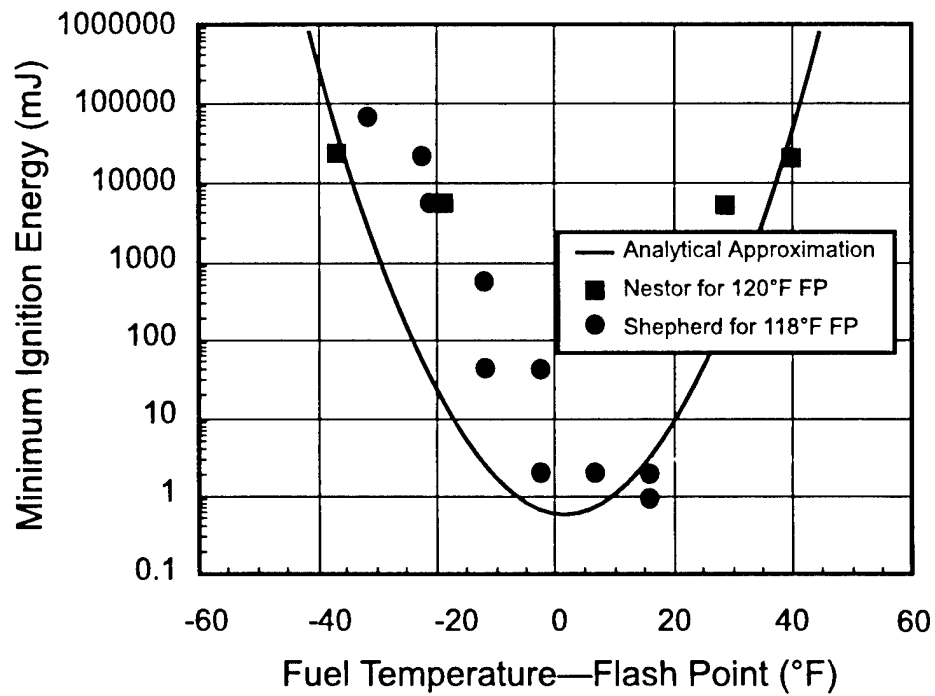
FIGURE 17. COMPARISON OF CORRELATION WITH MIE DATA FOR JET A FUEL AT
14,000 FT ALTITUDE

Calculated Ignition Energy Contours for Different MIEs
(Parabolic Variation of Ln(MIE) with Temperature)

Legend:
- — — — 20000 (mJ)
- — · — · 1000 (mJ)
- ········ 10 (mJ)
- — — — 1 (mJ)
- ———— 0.3 (mJ)

Y-axis: Altitude (thousand feet)
X-axis: Fuel Temperature (°F)

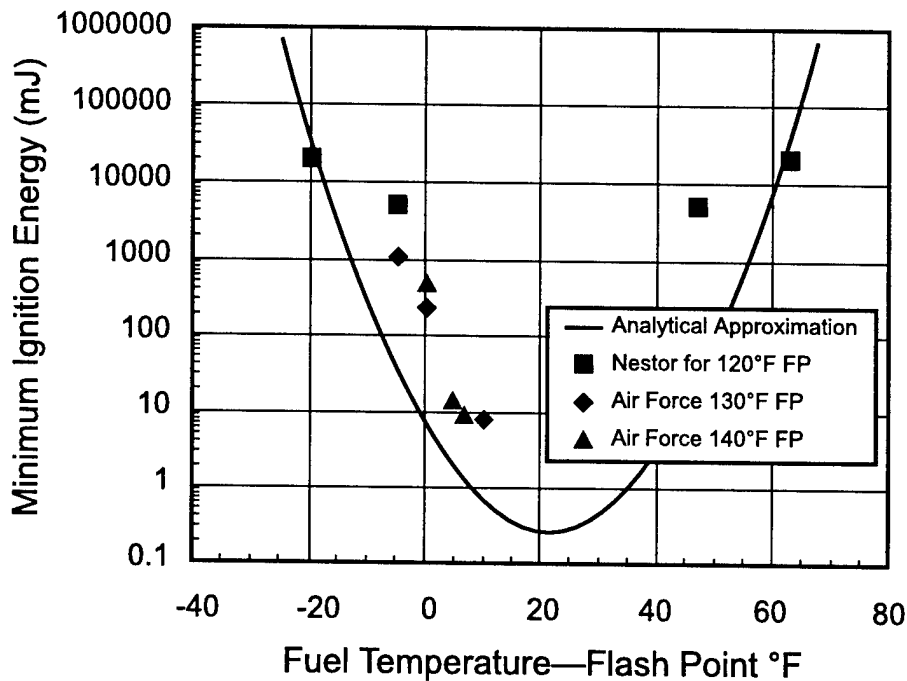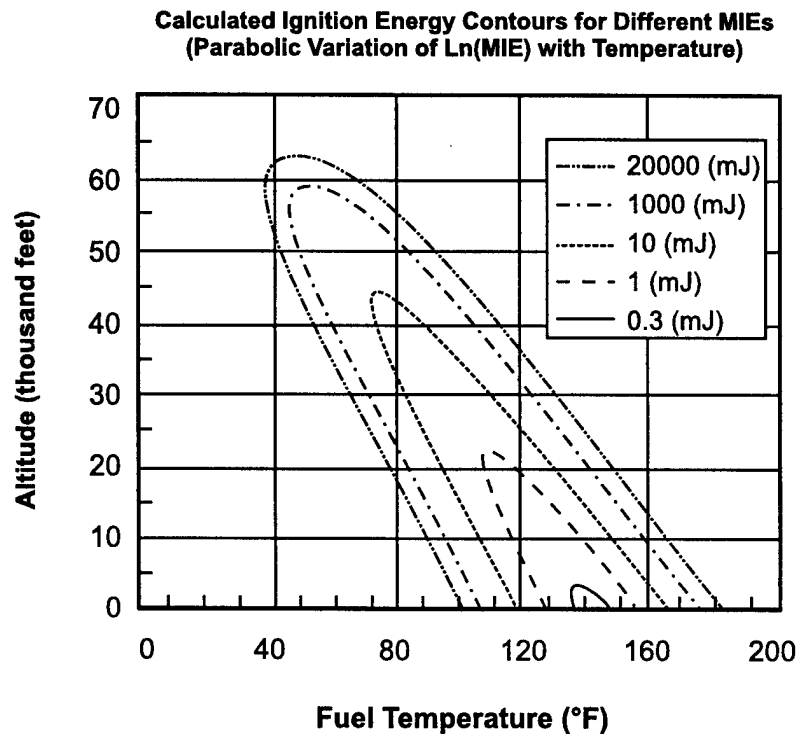FIGURE 18. CONSTANT IGNITION ENERGY CONTOURS PREDICTED BY THE RECOMMENDED CORRELATION FOR A FUEL WITH A FLASH POINT OF 120°F (49°C)

While adequate for the fuel tank safety analyses to be carried out in the near term, it should be recognized that the correlation formulas introduced here are based on several assumptions and, therefore, have serious limitations. For example, the shift of the MIE profiles with the fuel flash point implied by equation 10 has no fundamental backing and can be, at best, expected to be applicable over a relatively narrow range of jet fuel volatility (say about a ±20°F range in flash point). The altitude cutoff of 67,000 ft, inferred from the gasoline data, is also approximate and may have to be modified when more experimental information becomes available. In summary, this methodology should be taken as a best effort at capturing the current incomplete knowledge of the ignition characteristics of Jet A fuel. It represents only an interim solution to a complex problem. Accordingly, it is strongly recommended that it be replaced with an improved approach incorporating the new data to be developed.

Using equations 7-10, the required spark ignition energy can be determined for any combination of fuel temperature, fuel flash point, and aircraft elevation. If the spark energy cumulative distribution function FE_{spark} (E) can also be estimated, equation 5 can be used to determine the resulting conditional probability of ignition. Since fuel temperature and elevation vary with flight time, this procedure would have to be carried out as a function of time. A sample calculation is provided below for illustrative purposes.

2.5.2 Example Application.

The cumulative distribution function FE_{spark} (E) should be determined from considerations of electrical circuit faults and electrostatic discharges. In lieu of the detailed design and operational information required for such considerations, two arbitrary forms of FE_{spark} (E) will be used for illustrative purposes. An exponential distribution with a median spark energy of 0.47 J and a step function with two spark energies of 5 mj and 5 j, each with a probability of .5, are shown in figure 15.

The example selected for application is the typical B747 flight elevation and temperature profile provided by Teresa Fornia of Boeing at the 1997 Fuel Flammability Conference [41]. Table 3 lists fuel temperatures and elevations reported at ½ hr increments in the flight profile. Assuming a fuel flash point of 120°F, the calculated spark ignition energies are shown along with the conditional ignition probabilities computed with the exponential and step function spark energy distribution functions cited previously.

TABLE 3. SAMPLE CALCULATION: CONDITIONAL SPARK IGNITION PROBABILITIES

Time (hr)	T_{fuel} (°F)	Elevation (1,000 ft)	T_{FP} (F) = T_{fuel} - T_{FP} (°F)	120 $\ln(E_{ign})$	E_{ign} (J)	F_{spark} Exponential	Probability ($E_{ign} < F_{spark}$)	F_{spark} Step Function	Probability ($E_{ign} < E_{spark}$)
0	80	0	-40	24.475	4.26E+10	1.0000	0	1.000	0.000
0.5	105	0	-15	7.818	2485	0.981	0.019	.5	.5
1	120	0	0	1.86	6.44	0.010	0.990	.5	.5
1.5	115	20	-5	.085	.9185	0.0015	0.9985	0	1
2	95	34	-25	1.22	3.38	0.0054	0.9946	0	1
2.5	80	34	-40	2.23	9.35	0.0148	0.9852	.5	.5
3	77	34	-43	2.96	19.3	0.0304	0.9696	.5	.5
3.5	74	36	-46	3.21	24.87	0.0390	0.9610	.5	.5
4	71	36	-49	4.13	62.14	0.0946	0.9054	.5	.5
4.5	69	38	-51	4.08	59.37	0.0906	0.9094	.5	.5
5	65	38	-55	5.53	251.33	0.3311	0.6689	.5	.5
5.5	60	38	-60	7.78	2395	0.9784	0.0216	1.000	0
6	70	0	-50	33.49	2.5E+14	1.000	0	1.000	0.000

In carrying out these calculations, the reader is reminded that there is considerable uncertainty in the conditional ignition probabilities because of the limited spark ignition data, the inaccuracies and limitations associated with the particular correlations used here (including the neglect of any slosh or vibration effects such as those shown in figure 12), and the treatment of E_{ign} as a deterministic rather than probabilistic variable. Furthermore, only arbitrary spark energy distributions have been used so far. Further development of this methodology is needed for more reliable evaluations.

2.5.3 Computer Code [43].

A probability software model was developed to assess the hazard at discrete points in time. In order to assess the hazard during an entire flight and evaluate the effect of changes to the fuel

temperature and/or fuel flash point, it is necessary to sum the total of $E_{ign} < E_{spark}$ from time equal to zero till the time corresponding to the end of flight. Dividing by the total flight time in minutes would determine the norm of $E_{ign} < E_{spark}$.

<u>2.5.3.1 Input.</u>

A probability input screen provides the user the ability to specify flash point(s) of the fuel (T_{FP}) in °F and assign a distribution to T_{FP} (if desired). Spark probability (F_{spark}) distribution can be selected using a curve that is resident in the program or inputted by the user.

The flight scenario screen allows the user to develop the flight profile. Here, an altitude (Z) vs. time profile is entered. Altitude is entered in thousands of feet and time in minutes. A rectilinear line is assumed between points.

Also entered in the flight scenario screen is the temperature of the fuel (T_{fuel}) vs. time profile. Fuel temperature is input as °F and time is entered in minutes. Once again, a rectilinear line is assumed between points. It should be noted that the temperature being entered (T_{fuel}) should be the hottest measured or calculated fuel temperature in the tank at that time, with the following exception. When the fuel temperature starts to decrease in flight and the hottest measured or calculated ullage temperature at a specific time is hotter than the fuel temperature at that same time, one should use the maximum fuel temperature recorded <u>up</u> to that time or the ullage temperature at that <u>specific</u> time, whichever is less.

<u>2.5.3.2 Calculations.</u>

From the above input, the model will extrapolate T_{fuel} and altitude (Z) and calculate the probability of an explosion, given that a spark occurs, for each minute of the flight profile (P). These probabilities will then be weighted (based on the flash point distribution), totaled, and divided by the total flight time of the flight profile. This yields the average probability of an explosion over the entire flight, given a spark occurs (P_f).

<u>2.5.3.3 Output.</u>

The primary output of the model is as follows:

- Graphical representation of the flight profile

- Altitude (1,000 feet) vs. time (minutes)

- Fuel temperature (°F) vs. time (minutes)

- Color-coded potential hazard range based on the altitude and flash point that show when T_{fuel} vs. time crosses into the range of a potential hazard.

- Average probability of an explosion over the entire flight, given a spark occurs (P_f).

- Maximum probability of an explosion over the entire flight, at time (t) into flight, given that a spark occurs (P_{max}).

2.5.3.4 Limitations.

The results are estimates based on a limited amount of available data. Although it was felt that for most cases to be analyzed that both off gassing of O_2 from the fuel and misting or sprays of fuel can be ignored, that may not always be the case. For large quantities of fuel and small ullage spaces, the off gassing of O_2 from the fuel may raise the O_2 level in the ullage significantly (3% to 5%) thus reducing the spark energy needed for ignition. Should fuel be sprayed into a tank during flight the lower flammability limit would be greatly decreased, making the above calculation invalid.

3. CONCLUSIONS.

Jet fuels are complex mixtures, quite variable in composition, and the current delivery specifications are not designed to establish control values for fire safety. Aircraft fuel systems and system operations are similarly complex in their geometry and environmental exposure. Thus an exact prediction of when an aircraft fuel tank has an explosive vapor mixture is not to be expected. It is possible, however, using presently available data, to develop a methodology for assessing various approaches to reduce or minimize the fuel tank explosion hazard. The methodology would also allow the identification of research needed to either support or refute these approaches. On this basis, the information and discussions in this report can be summarized in the following conclusions:

- Although Jet A fuel flammability conditions in an aircraft fuel tank are best described in terms of the distribution of the fuel vapor/air ratio in the tank, there are no existing mathematical models or empirical methods for calculating these ratios during flight. Furthermore, since existing flammability data are presented in terms of fuel temperature and tank pressure, tank flammability evaluations will continue to be formulated in terms of these parameters, assuming equilibrium conditions between the gas space and the liquid.

- Existing data for spark ignition energy, although not extensive, has been used to develop a method for calculating the probability of a spark-ignited fuel tank explosion during flight. Implementation of this method requires (1) probability distributions for spark energies and (2) fuel temperatures as a function of time and altitude during flight. The method does not account for the modifying affects of fuel sprays or possible oxygen enrichment of the tank ullage nor variable probabilities of sparks occurring in the tank during flight.

- Existing models for calculating fuel temperature during flight need to be improved and validated in order to provide reliable estimates of fuel tank flammability. Provisions for nonuniform temperature distributions and for puddling of thin fuel layers need to be incorporated into the models, and additional comparisons with test data are needed.

- Jet fuel flammability is also dependent on ignition energies, but minimum spark ignition energy data are very limited, especially for conditions of low fuel temperatures and high altitudes and for a range of jet fuel flash points.

- At the present time, there are neither flight data nor thermal models or calculations that are adequate to determine the extent of the fuel temperature variation over typical flight profiles for various fuel loading scenarios, hence, the times of exposure and probabilities of experiencing potentially hazardous conditions cannot be determined. Therefore, the effectiveness of additional fuel being added to a fuel tank cannot be determined.

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Department of Energy Hydrogen Technical Advisory Panel: 1992 –
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National Research Council, Building Research Board, Committee on Risk Appraisal in the Development of Facilities Design Criteria, 1989 – 1991.
Fire Technology, Editorial Review Board, 1992-.
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1969-1970   Politecnico of Torino, Italy: Assistant Professor.
               Experimental and theoretical investigation of unsteady flows in manifolds of
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1970-1971   California Institute of Technology, Pasadena, California: Fulbright Fellow.
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In a 46-year career with NASA and its predecessor agency , the National Advisory Committee for Aeronautics, Friedman has conducted research and managed projects in jet- and alternative-fuel properties, turbojet and ramjet-engine combustion, cryogenic heat transfer, nozzle flow, and jet-noise reduction. He has authored 55 technical reports and journal articles on results in these fields.

Friedman has a BS degree from the University of Illinois and an MS degree from the Carnegie Institute of Technology (now Carnagie-Mellon University), both in chemical engineering. He is a member of the American Institute of Aeronautics and Astronautics, the American Institute of Chemical Engineers, and committees D-2 on petroleum products and lubricants and E-5 on fire standards of the ASTM. He is a registered professional engineer in the state of Ohio.

Friedman has represented NASA on many international and national groups and committees, including the NATO Advisory Group for Aerospace Research and Development (AGARD) Working Group on Supply and Demand Scenarios for Aviation Turbine Fuel, the Coordinating Council, Inc., Low-Temperature Flow Performance of Aviation Fuels Group, the US Interagency Working Group on Fire and Materials, and the NASA Lewis Independent Assessment Team for the Fire Detection and Suppression Subsystem of the Space Station. In 1997, he was awarded the NASA Exceptional Service Medal for the activities in spacecraft fire safety.

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1985-1995	Program Manager, Fire Safety, Federal Aviation Administration All aspects of in-flight and post crash aircraft fire protection.
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1980-1994	Associate Staff – Transportation Safety Institute, Aviation Safety Program
1987-Present	Adjunct Instructor – Masters Program – Embry Riddle Aeronautical University.

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Dr. Lee was the first researcher in the world to obtain continuous flow combustion/emissions data under extreme high inlet pressure (60 atmospheres) and inlet temperature (1300 F) gas turbine engine operating conditions. Dr. Chi-Ming Lee is a senior research engineer specializing in combustion and gas turbine fuel system integration for the Turbomachinery and Propulsion Systems Division of the National Aeronautics and Space Administration (NASA) Lewis Research Center. Currently he is the program manager and lead engineer for the NASA Advanced Subsonic Technology (AST) Low Emissions Combustor Program.

Dr. Lee has 5 years experience in the petroleum industry and 15 years with NASA Lewis. Dr. Lee has conducted research and managed programs in aviation and jet fuels properties, intermittent engine and gas turbine combustion, advanced materials and laser diagnostics. Dr. Lee has authored more than 20 technical reports and journal articles on results in these fields.

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1970   Transferred to British Aerospace at Bristol as Head of Fire Precautions Engineering with responsibilities that included definition and conformance of fire safety standards for Concorde.

1986   Appointed Fire Engineering Design Leader for the whole British Aerospace Civil Aircraft Division on the Executive Staff. Now retired.

Other experience includes on-site crash wreckage investigations in America and Australia, fire specialist witness at courts of inquiry, publication of technical articles in international magazines, lecturing at various seminars including NATO Specialist Lecture Series on Aircraft Fire Safety in various countries, annual guest lecturer in Fire Safety Engineering at Cranfield University. Consultant Referee for papers submitted to the Forensic Science Society.

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Dr. Merritt Birky has participated in the investigation of some of the nation's major aviation accidents, including the downing of Pan Am 103, the space shuttle Challenger, the U.S. Air Force Titan 34 D, and the 1996 ValuJet crash in the Everglades. Dr. Birky has also participated in the investigation of major railroad, pipeline, and marine accidents, including the grounding of the Exxon Valdez in Alaska in 1989. Prior to joining the Safety Board, Dr. Birky worked for more than 20 years at the National Bureau of Standards and then served as Director of Research at the Foundation for Fire Safety.

Education

Bachelor of Arts degree (1958) from Goshen College and Doctorate (1961) from the University of Virginia. Dr. Birky attended N.I.H. Graduate School in Toxicology from 1971 to 1972, and was Adjunct Professor at the University of Utah from 1972 to 1976.

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Prior to joining SwRI, Mr. Wright was on active duty in the U.S. army as a commissioned artillery officer. His duties included establishing fire direction centers and controlling weapon firing in both conventional artillery and missiles in the Nike family. At SwRI, he initially worked in the development and analysis of lubricant additives in the Department of Chemistry and Chemical Engineering and has done work on engine sludge analysis. He later transferred to the Belvoir Fuels and Lubricants Research Facility (BFLRF) where his work has included instrumental analysis (infrared, flame photometry, and gas chromatography of fuels and lubricants); low-temperature diesel fuel crystallization studies; and studies of engine emission formation related to fuel composition, utilizing both petroleum and alternative fuels. Since joining BFLRF, Mr. Wright has managed numerous research programs, including the Fire-Resistant Fuel Program, Obscuration Smoke Program, and the multi-million dollar David Taylor naval Fuels and Lubricants Program.

Mr. Wright is an internationally recognized expert in fuels and fluid flammability, combustion, and flammability mitigation. He is also well-known as a leading scientist in fuel tank flammability and explosivity. Among other responsibilities, he established and supervised experimental laboratory, bench-scale, and ballistic techniques used for characterizing fluid flammability and explosion hazards. He has spent over 30 years in direct support of the U.S. army Tank-Automotive Command's Mobility Technology Center-Belvoir (MTCB), Ft. Belvoir, Virginia, and is currently responsible for fluid flammability and hazard elimination programs funded by the Federal Aviation Administration (FAA) and all branches of the Department of Defense 9DOD). Mr. Wright has extensive experience in the development of specialized flammability tests from laboratory-scale to full-scale vehicular ballistic testing. He has authored numerous publications and managed programs evaluating fluid flammability mitigation concepts, including fire-resistant diesel fuel emulsions, antimisting agents, and halon-fluid blending. Mr. Wright is chairman of the Coordinating Research Council (CRC) Aviation System Safety Group, which acts as the interface between industry and the FAA on subjects relating to aircraft safety. This forum addresses such subjects as flammability and flame mitigation. Recent relevant programs that Mr. Wright is managing at TFLRF include the following:

- Nonflammable Hydraulic Fluid Development for MTCB
- Development of fuel fire suppressant for post-impact aircraft fuel pool-burning (funding for this research is provided by the FAA)
- U.S. Army Materiel Command Test Integration Working Group on Halon 1301 alternate agent program plan
- Laboratory evaluations of current U.S. Air Force candidate agents for engine nacelle fire-suppression systems (funding for this research is SBIR with U.S. Air Force to Dr. Dennis Zallen, ZIA)

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