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EVALUATION OF FLIGHT FIRE PROTECTION MEANS FOR INACCESSIBLE AIRCRAFT BAGGAGE COMPARTMENTS

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Civil Aeronautics Administration Technical Development and Evaluation Center
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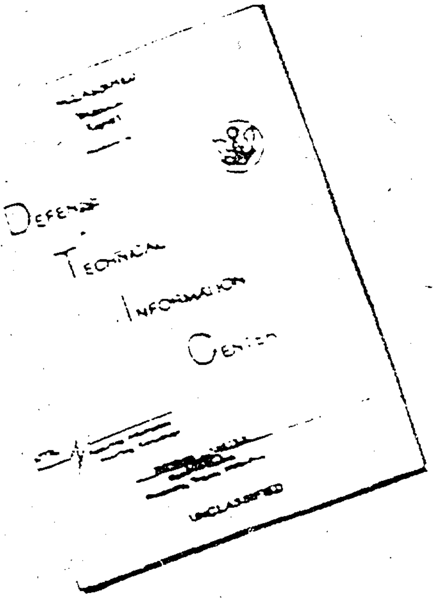

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By
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SUMMARY

The problem of providing adequate fire protection in flight for inaccessible aircraft baggage compartments was investigated in the laboratory. As the packaging, handling and shipping methods used for commercial cargo are subject to existing legislation, this program was confined to investigating those fires which could originate within personal baggage. The investigation was divided into four sections: (1) luggage-fire characteristics, (2) fire detection, (3) fire extinguishment and (4) fire control.

Investigation of luggage-fire characteristics showed that fire ignition within personal baggage is highly unlikely. Tests showed further that, even assuming ignition, self-sustaining fire in many instances would eventually be smothered by the generation of inert gases and by moisture within clothing and moisture produced by combustion. Many of the test fires smoldered internally for several hours, in some tests for 24 hours or more, before the internal fire penetrated the luggage wall. High altitudes, high humidity content and densely packed clothing had adverse effects on ignition possibilities and rate of fire spread. In general, these tests indicated that the occurrence of fire originating within personal luggage would be most remote.

In the detector tests conducted, luggage-compartment fires were rapidly and reliably detected by photoelectric-type smoke detectors, carbon monoxide detectors, visual smoke detectors and olfactory smoke detectors. As a result of the tests, it was evident that the existing sensitivity settings of both the photoelectric smoke and the CO detectors are much too high. In detecting fires of the type expected, dependability is more essential than speed. Hence, a reduction in sensitivity would greatly increase the dependability of the instruments.

The extinguishment tests showed that carbon dioxide will provide control for some baggage fires, and in a few instances may extinguish such fires. However, extinguishment of all baggage fires by carbon dioxide cannot be relied upon. The only agent which was found to be superior to CO_2 for extinguishing baggage fires was helium which, because of its low density and the ease with which it escapes, is limited to use in sealed compartments.

Carbon dioxide proved successful in extinguishing Class B fires and excelsior fires in baggage compartments.

Temperature surveys throughout baggage compartments during test fires indicated that Class A fires could attain flame temperatures of 2,000°F and that an aluminum alloy ceiling exposed to such flames could reach 1,000°F rapidly. Any insulation capable of withstanding such fire conditions would be satisfactory for confining fire and heat to the compartment. Several satisfactory insulations were revealed by the tests.

INTRODUCTION

Aircraft of the transport-category type used in scheduled air carrier operations were required by the Civil Air Regulations to have installed smoke-detecting means, as "fire detectors other than thermal type," and a suitable extinguishing means in the inaccessible C category cargo and baggage compartments as defined by the Civil Air Regulations. Subsequent operating experience with the types of detectors installed to comply with the Civil Air Regulations proved unsatisfactory due generally to the sensitivity settings being set too high, so that the hazard occasioned by the false alarming of the units was finally considered greater than the possible fire hazard. This resulted in the disconnection of the detectors in cargo compartments as authorized on April 29, 1948. Following this action, an immediate program of investigating the entire problem of cargo- and baggage-compartment fire protection was initiated at the Technical Development and Evaluation Center. The program included the evaluation of detection means and methods, and an investigation of baggage fires in compartments and the study of fire control.

Subsequent to the effective date for requiring smoke detectors by the Civil Air Regulations, performance requirements were established for these units and referenced in TSO-C1 and C1a covering the types of instruments installed. Resulting from the number of reports submitted by the operators who indicated false alarming of the units, the National Bureau of Standards was requested by the CAA to subject production instruments, manufactured by Walter Kidde, C-O-Two and Mine Safety Appliances Cos., to appropriate tests to determine conformance with the performance requirements outlined in the TSO. The National Bureau of Standards test results indicated that the photoelectric-type detectors manufactured by Walter Kidde and C-O-Two Cos. failed to meet the performance requirements, the carbon-monoxide-type detector manufactured by Mine Safety Appliance Co. conformed to all the performance requirements. However, alarming of the unit could be produced by "induced" interruption of the negative air flow through the unit by ice formation in the suction lines during extreme low-temperature tests. This condition is considered highly improbable during actual flight operations due to the location of the attendant installation components.

In addition to the requests made to the National Bureau of Standards regarding smoke-detector tests, they were requested to conduct an investigation of simulated baggage- and cargo-compartment fires.

The National Bureau of Standards during their investigation conducted a series of 19 fire tests which included varying conditions of ventilation and types of combustibles. The test results are indicated in the following quotations excerpted from the report submitted to the CAA:

"The relative tightness of the different suitcases used appeared to have an effect upon the relative rate with which a cigarette fire developed within, and consequently the amount of carbon monoxide and smoke produced. In the tighter suitcases, there was more carbon monoxide relative to smoke and a longer period of time was required for a fire to develop.

"The concentrations of carbon monoxide and smoke produced by the fires appeared to be related. Usually they were characterized by a slow rate of development, which lasted in some cases for a period of 20 minutes, followed by a rapid increase to concentrations sufficient to cause the ordinary smoke and carbon monoxide detectors to alarm.

"The rate and direction of ventilation within the compartment affected the concentrations of smoke and carbon monoxide at the different sampling locations, the highest concentrations being at the end toward which the air was moving."

The CAA conducted a survey of equipment manufacturers, insurance organizations and common carriers, in an effort to procure whatever background information might exist applicable to the problem of protecting aircraft cargo and baggage compartments against fire hazards. Although some information was procured which could be considered applicable to the hazard in that it dealt with Class A fire problems, no specific experimentation had apparently been directed toward the personal baggage and small cargo fire-protection problem. Statistically, the fire hazard involved in the carriage of personal and small baggage in passenger-carrying aircraft is not considered great; however, it was generally agreed that the hazard cannot be overlooked in spite of this lack of statistical support.

The few instances of baggage-compartment fire incidents known to the author are briefly described:

1. A piece of personal luggage being removed from an aircraft baggage compartment was found to be emitting a small quantity of smoke. The source of smoke was determined to be the ignition of a large box of foreign-made, strike-anywhere matches. There was no aircraft damage involved.
2. A small cotton bat in a B category compartment ignited and was extinguished by a steward using a tumbler of water. There was no aircraft damage involved.
3. A paper-wrapped blanket, in contact with an electric light bulb, produced a smoldering fire which sooted the interior of the baggage compartment. There was no aircraft damage involved.
4. A cotton webbing material treated with tung oil was improperly processed prior to shipment. While being unloaded, the container was found to be very warm. When opened on the ramp, flames resulted. There was no aircraft damage involved.

In general, the tests were limited to fires which would originate in personal luggage, because it was considered that only in such luggage could ignition sources and flammable materials be in close proximity. The contents of commercial cargo are known, and, when properly shipped in accordance with regulations, should represent no fire-ignition hazard, even though they could become involved in a fire ignited elsewhere. The contents of personal luggage, however, are unknown and can include ignition sources as well as highly flammable materials. Accordingly, the program was based upon fires originating in personal luggage. As a result of these preliminary investigations, it was determined that it would be desirable for the TDEC to consider the following:

1. Fire Characteristics — The objective being to determine the nature of a fire which might be expected to occur within typical aircraft baggage compartments and including the possibility of ignition, the rate of propagation and the effect of such fire on adjacent or associated materials.
2. Fire Detection — The evaluation of the existing photoelectric-cell- and carbon-monoxide-type smoke detectors under simulated flight conditions was of primary

interest. This information was desired for its possible bearing on the elimination of the serious false alarm problem. In addition, however, information was desired on other forms of Class A fire detection; e.g., the visual and olfactory methods.

3. Extinguishment — Primarily, carbon dioxide was to be evaluated as an extinguishing agent for the type of Class A fires which might be expected to occur in aircraft baggage compartments. In addition, other fire-extinguishing agents were to be considered.

4. Fire Control — It was considered desirable to determine the effects on fire control of compartmentation, controlling leakage rates and the use of fire-resistant and heat-insulating linings.

Control of compartment ventilation or of the oxygen supplied to any particular fire was assumed to be of fundamental importance from the very beginning of this program. Testing conducted on various models of transport-category aircraft indicated that compartment-ventilation rates varied widely; thus it was considered necessary to test the "standard" fire package over a wide range of compartment-air-change rates and within various size compartments. Preliminary analysis disclosed that there were many variables to be considered in any such program, and it was quite apparent that it would be difficult to effect precise results in all phases of the problem. The tests initiated therefore, were intended to determine as many fundamentals as possible, and to establish trends, at least, toward the best methods of providing adequate fire control for inaccessible baggage compartments.

BAGGAGE-FIRE CHARACTERISTICS

Purpose

The purpose of the tests on baggage-fire characteristics was to determine:

1. The probability and ease of ignition.
2. The rates of fire spread through various materials, and the effects on the fire characteristics of (a) density of materials within luggage, (b) altitude, (c) air temperature, (d) relative humidity, (e) flammable fluids and highly flammable solids contained within luggage and (f) air flow velocities.

Procedure

To effect ignition, paper and wooden matches, lighted cigars and cigarettes, electrically ignited gunpowder and electric heating elements were used in these tests.

The rates of fire spread were determined through silk, cotton, wool, nylon, cardboard, wood, excelsior, paper and other materials used in the construction of many grades of personal luggage.

In order to determine the effect of each of the materials in a minimum of time, a "standard fire" was established arbitrarily. This standard fire consisted of a corrugated cardboard box, 3 1/2 by 9 1/2 by 12 inches, filled with 2 pounds of excelsior, sealed with masking tape, ventilated by 6 holes, 3/8 inch in diameter and internally ignited by electrically sparking 70 grams of gunpowder. The external ambient conditions to which the standard fire was subjected were:

1. 150 ft/min surrounding air flow.
2. 29 inches Hg absolute pressure.
3. Room temperature (75°F).
4. 65 per cent relative humidity.

The time required for complete combustion of the standard fire was determined in a series of tests. The standard conditions were then varied, one at a time, in order to determine the effect on burning rate of:

1. Increasing the surrounding air velocity from the normal 150 ft/min to 800 ft/min.
2. Decreasing the absolute pressure to simulate increasing altitudes up to 20,000 feet.
3. Decreasing the ambient air temperature to 30°F.
4. Increasing the relative humidity to 95 per cent.

An altitude chamber, Fig. 1, capable of simulating altitudes up to 20,000 feet was used with arrangements to control the velocity of the air through the chamber. A balance between inlet needle valves permitted any desired air velocity for any required altitude. A deflector and wire wool baffle were incorporated in order to reduce high local air flows entering the chamber through the end inlet.

A steam generator unit was piped into an 8-cubic-foot compartment as shown in Fig. 2 to determine the effects of high humidity on Class A fires. Relative humidities as high as 95 per cent were effected in the air surrounding the standard fire.

Tests were conducted in which flammable liquids such as lacquer thinner and gasoline (contained in various size bottles, corked or screw capped) were imbedded in the clothing prior to ignition in order to evaluate the hazard resulting from carrying nail polish, alcohol and similar flammable fluids in personal luggage.

Approximately 175 individual tests were conducted in determining baggage-fire characteristics.

Results and Discussion

The probability of igniting self-sustaining cloth fires confined in suitcases by means of paper or wooden matches depended largely upon the quantity of matches involved. Only when 2 1/2 boxes of wooden (kitchen-type) matches were ignited simultaneously, would

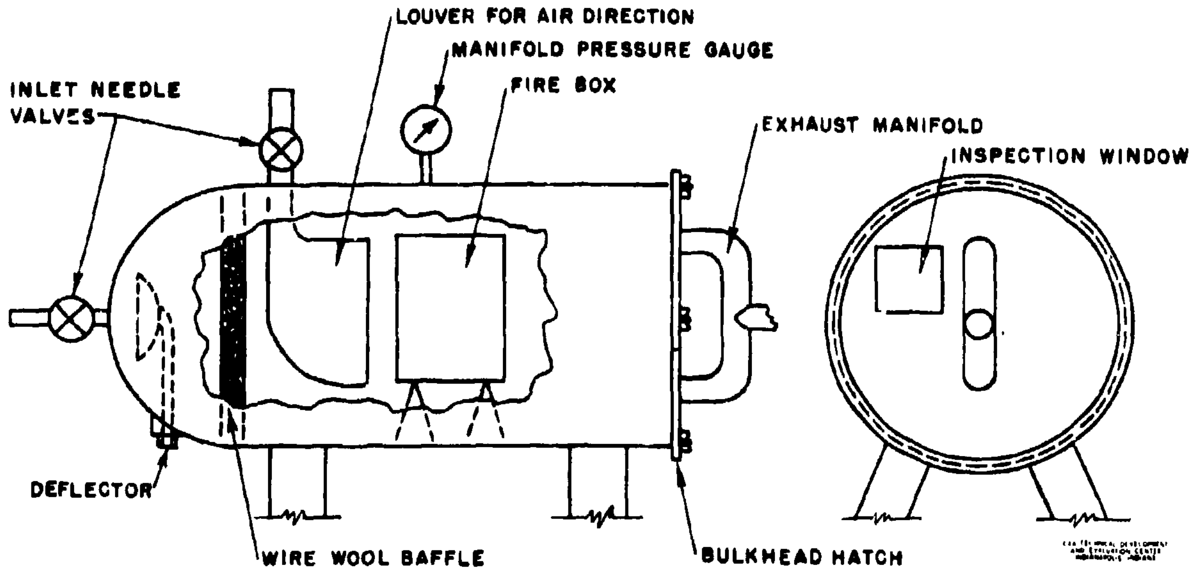

Fig. 1 Altitude Chamber

a suitcase filled with clothing ignite and continue to burn. Lighted cigars and cigarettes also were found to be poor sources of ignition. Very few fires resulted in luggage even though a lighted cigarette was carefully located in a clothing pocket or air space before the lid was closed. In later tests, in which ignition was assumed, in order to expedite the general test program, the clothing was ignited by an electric heating element (Calrod unit, 600-watt) or by igniting 70 grams of gunpowder.

Table I lists the effects of the several variables on the arbitrarily established standard fire.

The results of tests (Series 1 to 4) indicate that increased air flow over a burning piece of luggage will increase its burning rate.

The effect of altitude on the standard fire (Series 1, 5 and 6) indicated a gradual decrease in the burning rate from sea level to 20,000 feet. Not all fires were extinguished at 20,000 feet. Fires at any altitude were materially affected by surrounding air velocities in the same manner as the fires tested at sea level.

Low ambient air temperatures (Series 7) and high relative humidity conditions (Series 8) both tended to retard the luggage burning rate.

The density of the clothing within a given suitcase affected the burning time materially. For instance, small valises confined smoldering fires for 24 hours or more when the clothing density was 2 pounds per 100 cubic inches. The results given in Table I are of value chiefly because they indicate that the most severe fire conditions are those which exist at sea level in dry atmosphere.

From many attempts to effect ignition and continued burning in luggage, it is apparent that the following conditions (independently, or in combination) materially influenced fire probability.

1. The total heat output at the source of ignition is important because small quantities of paper or wooden matches would seldom ignite self-sustaining fires within luggage packed with reasonable quantities of clothing. A 300-watt electric light bulb lying on a pile of clothing caused fire after one minute of continuous contact. A 60-watt bulb did not cause a cloth fire after 1 1/2 hours of clothing contact.

2. The quantity of clothing and the kind of material contained within a suitcase had a marked effect on the ease of ignition and the probability of a self-sustaining fire. More densely packed clothing was much harder to ignite and much less susceptible to continued burning than lightly packed clothing. Silk was more susceptible to ignition and continued burning than was cotton, which, in turn, was more susceptible to ignition and continued burning than wool. Accordingly, a densely packed suitcase containing woolen clothing would be much less hazardous from the fire standpoint than a lightly packed suitcase containing silk.

3. Climatic conditions and resultant moisture content of the clothing affected the tendency of the clothing to ignite and con-

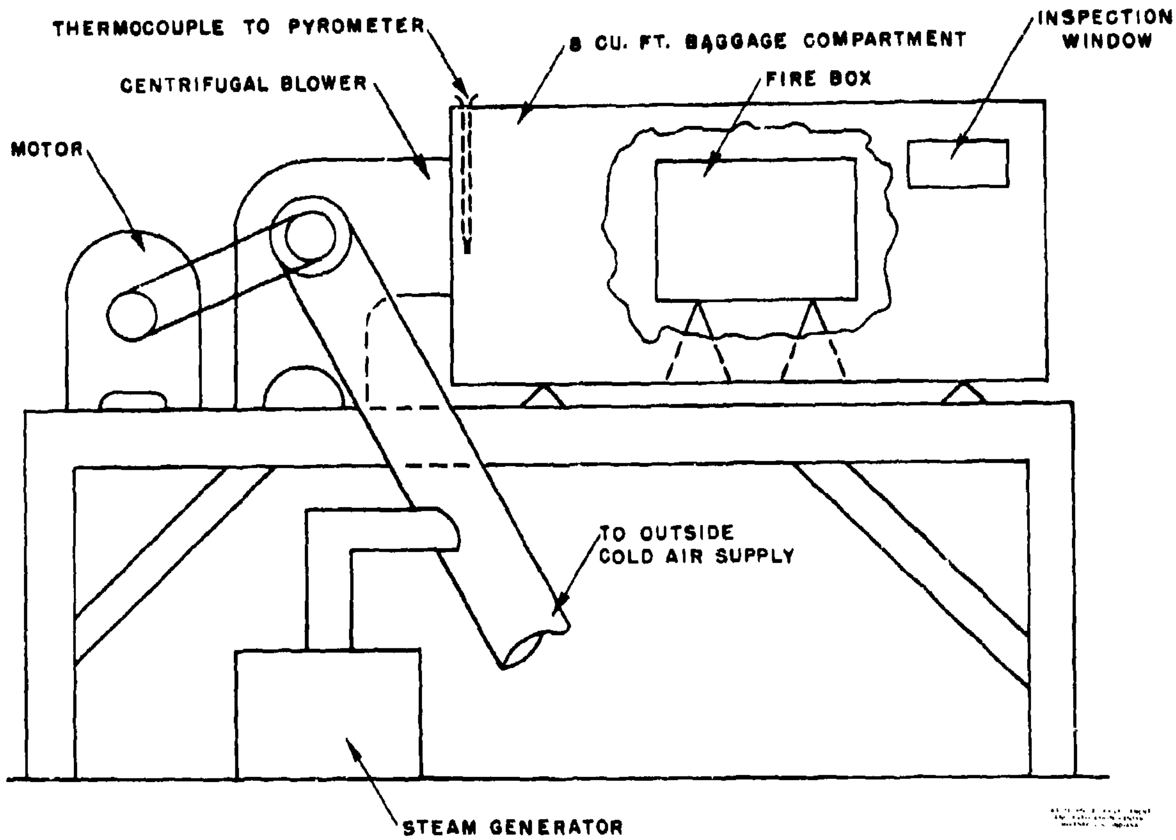

Fig. 2 Test Arrangement for Conducting High Humidity and Low Temperature Tests

tinue to burn. Ignition and/or continued burning of clothing were most difficult to produce on humid days.

4. Luggage construction and condition affected the ease of ignition and the probability of a self-sustaining fire. A poorly constructed piece of luggage with flaps which did not mate properly at the seams when closed was more hazardous from the standpoints of ignition and continued fire than a tight, new piece of luggage.

5. The location of the fire source within the luggage affected the time required before the internal fire broke through the luggage wall, after which an open fire existed. Many fires originating between the luggage walls and the contained clothing immediately attacked the wall. Fires originating deep within the clothing had to burn through that clothing before the wall was endangered.

6. Fires within luggage standing upright continued to burn, whereas fire ignited within a piece of luggage lying on its side would go out. This was due probably to the chimney action provided by the luggage joints when the luggage was in an upright position.

Although no violent explosions were encountered while conducting the test series involving flammable fluids contained within baggage, it is known from past experience in dealing with those fluids that a forceful and damaging explosion can result from even small quantities of flammable fluids. In most instances, the heat produced by the deep-seated fires either blew out the cork or cracked the bottle, allowing the contents to seep out into the clothing material. In some cases, the vapors were too rich to burn, and the liquid wetted the material and diminished the flame intensity. In other cases, the liquids volatilized and escaped without affecting the fires. When flammable fluid containers ruptured while in open fires, considerably larger fires resulted.

Small quantities of cellulose nitrate (0.4 pound), enclosed in the standard fire package, burned with near explosive force. The cardboard carton was ruptured at the time of the explosion, blowing the contents throughout the compartment. Fortunately, present ICC

TABLE I

Effect Of Variable Conditions On Standard Baggage Fire

Test Series*	Velocity Ft/Min	Altitude Feet	Temp. °F	Density of Pack Lb/100 Cu. In.	% Rel. Humid	Burn Time
1	150	sea level	Room	0.5	65-75	30 min.
2	200	sea level	Room	0.5	65-75	27 min.
3	400	sea level	Room	0.5	65-75	18 min.
4	800	sea level	Room	0.5	65-75	12 min.
5	150	10,000	Room	0.5	65-75	1 hr.
6	150	20,000	Room	0.5	65-75	No fire
7	150	sea level	35-40	0.5	65-75	40 min.
8	150	sea level	Room	0.5	85-90	45-50 min.

* Approximately 50 tests were conducted to obtain these data. Each test result shown is an average value of several tests.

regulations require special shipping containers for the shipment of nitrate substances (Ref. CAR 49).

In instances where enough heat was generated at the source of ignition to cause a self-sustained fire within a suitcase, the burning rate was so slow that the fire was far from being a threat to the structural integrity of an airplane. A typical test involved a suitcase of conventional size packed with a density of 1/2 pound of clothing per 100 cubic inches (total weight of rags equalled 17.3 pounds). After ignition, this fire burned for 7 1/4 hours, and was still burning at the time it was opened for inspection. Approximately 1/10 of the available material had been consumed during the entire burning period. The clothing material at the outer folds was found to be extremely damp. In spite of the very slow combustion process, substantial quantities of smoke and acrid fumes were emitted. The problem of asphyxiation due to smoke seepage into the passenger compartment could conceivably be more of a hazard than the fire itself.

Conclusions

From the tests which have been conducted it is concluded that:

1. The occurrence of ignition and sustained burning within luggage is very unlikely.
2. In the event that sustained burning should occur within luggage, the smoldering action may die out due to the generation of inert gas and moisture and many hours will probably pass before even a small, open flame results.
3. The probability of continued burning is reduced by increase of altitude, decrease in air temperature, increase in relative humidity and increased density of clothing pack.
4. The higher the velocity of air passing over luggage containing fire, the higher will be the burning rate (the degree of increase depending on the tightness of the luggage) and the greater will be the resulting fire severity.
5. Flammable liquids escaping within burning luggage can (a) wet the contents and extinguish a smoldering fire, (b) volatilize and escape without affecting the fire, (c) increase the burning rate and severity of the fire or (d) explode.
6. The presence of highly flammable solids will (a) increase the burning rate and severity of the fire or (b) depending on the nature of the material, explode.
7. Sustained burning is less likely to occur within luggage when lying on its side than when standing upright.
8. In the event that ignition, sustained burning and open fire should occur, the resultant fire will be far less hazardous (in severity and temperature) than those experienced in the power plants or aircraft-type combustion heaters.

DETECTORS

Purpose

The purpose of the tests on fire detectors was to:

1. Evaluate the abilities of existing photoelectric and carbon monoxide detectors to detect incipient fires, that may occur in aircraft baggage compartments, which are inaccessible during flight.
2. Investigate the possibilities of satisfactory operation of detectors that operate on more elementary principles, such as the visual detectors or the olfactory detector.

Description of Detectors

The detectors tested in this program

Fig. 3 Walter Kidde Photoelectric Smoke Detector Model A-4532-M1

were of four basic types, viz., photoelectric type, carbon monoxide gas-analyzer type, visual type and the olfactory type. A brief description of the operation of each of the detectors is given.

1. Photoelectric type:

a. The Walter Kidde Model A-4532-M1, illustrated in Fig. 3, operates on the principle of light interruption. An alarm is signaled when smoke passes between the light source and the photoelectric cell, thus diminishing the light intensity to which the cell is subjected when clear air is present.

b. The C-O-Two detectors, Types A-3 and A-4, illustrated in Figs. 4 and 5, operate on the principle of reflection of light; and an alarm is signaled when smoke particles reflect light into a photoelectric cell which is mounted outside the normal light beam.

2. The Mine Safety Appliances CO and fire-detector unit, illustrated in Fig. 6, is an electronic detector which will alarm when a predetermined percentage of CO is present in the air sample passing through it. The CO passing through the detector reacts with a catalyst causing it to oxidize. The heat thus

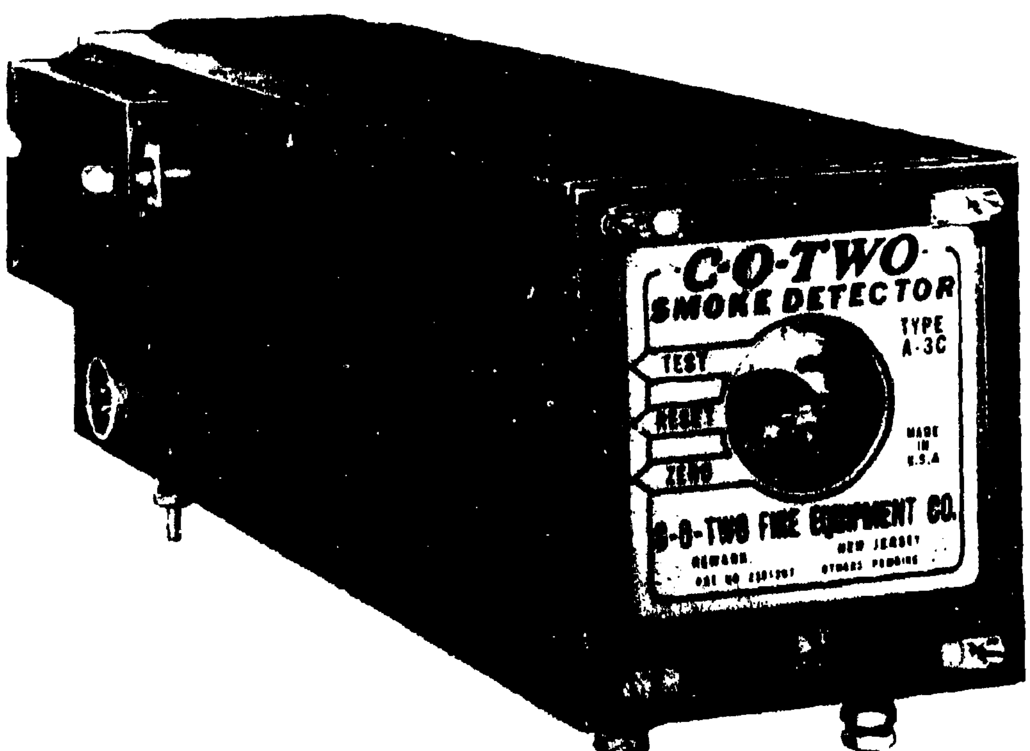

Fig. 4 C-O-Two Photoelectric Smoke Detector, Natural Convection Type

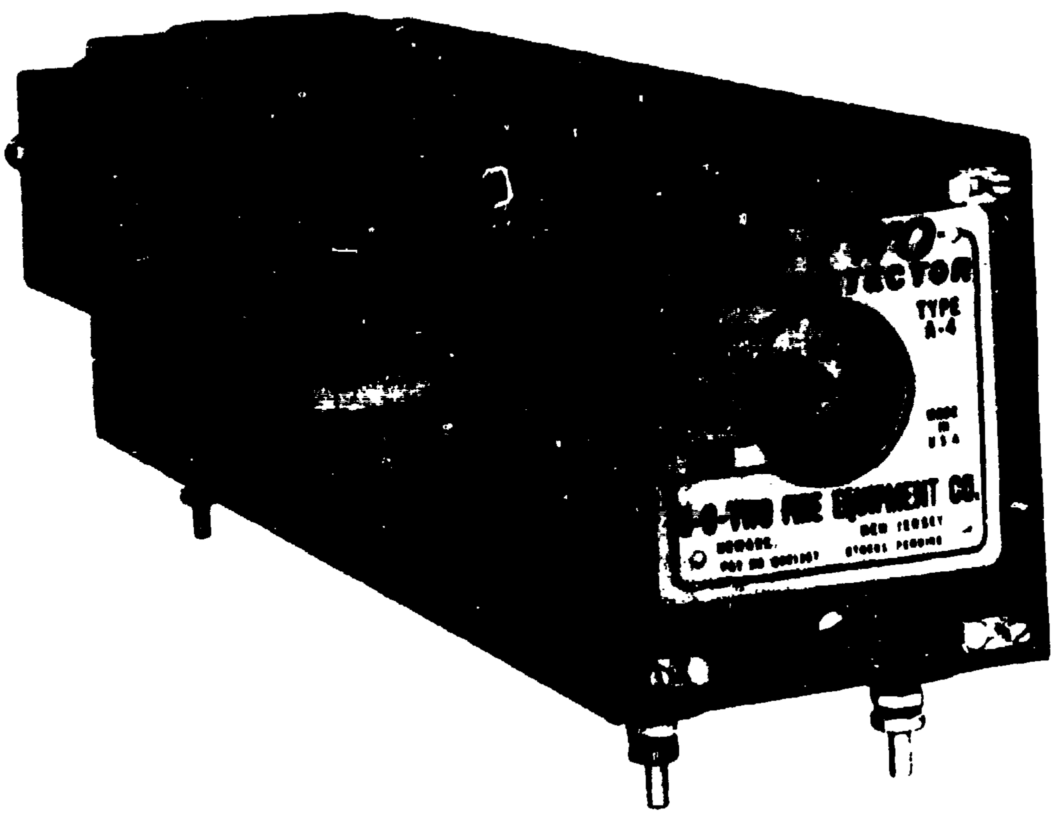

Fig. 5 C-O-Two Photoelectric Smoke Detector, Tube Type

released causes an emf to be induced in a thermopile which, in turn, triggers an alarm.

3. The visual-type detector, shown in Figs. 7A and 7B, includes a smoke chamber which is lined with a black material. A beam of light passing into the chamber is absorbed by the lining so that no visual light is noticeable when viewed from the inspection window. When air containing smoke particles passes through the black-lined chamber, the smoke particles reflect the light which is then visible in the inspection window.

4. The olfactory or sniffer-type detector discharges air samples from the cargo compartment directly into the pilot's compartment. The pilot's sense of smell acts as an alarm. See Fig. 8 for a schematic drawing of a typical olfactory system.

A smoke density meter, illustrated in Figs. 9A and 9B, similar in operation to the photoelectric type (1-a), was constructed and used to measure the per cent light transmission.

Procedure

A full-scale baggage compartment, Fig. 10, was constructed to simulate the aft belly compartment of the Lockheed Constellation. The general over-all dimensions were 27 feet long, 5 feet wide and 2 feet high. The framework consisted of 1 by 1 by 3/16 inch angle iron with 0.020-inch thick aluminum sheet mounted on the walls and ceilings. Aluminum sheets 0.040 inch thick were mounted on all of the floor area. Inspection windows, conveniently located along the length of the compartment, consisted of plexiglas. The compartment was sealed at all of the seams on the outside by means of masking tape and water glass. A plenum chamber 14 by 15 by 10 inches was mounted on the downstream wall of the compartment behind a thin plate orifice. Two aircraft vacuum pumps (Prescó 211), driven by a double V belt from a 10-horsepower motor, pumped air from the plenum chamber. This assembly was used to establish the compartment leakage rates desired for particular tests. One quarter of the compartment was lined with V board insulation which was 0.042 inch thick (2-ply fiberglas cloth impregnated with a bonding material). Loading hatches

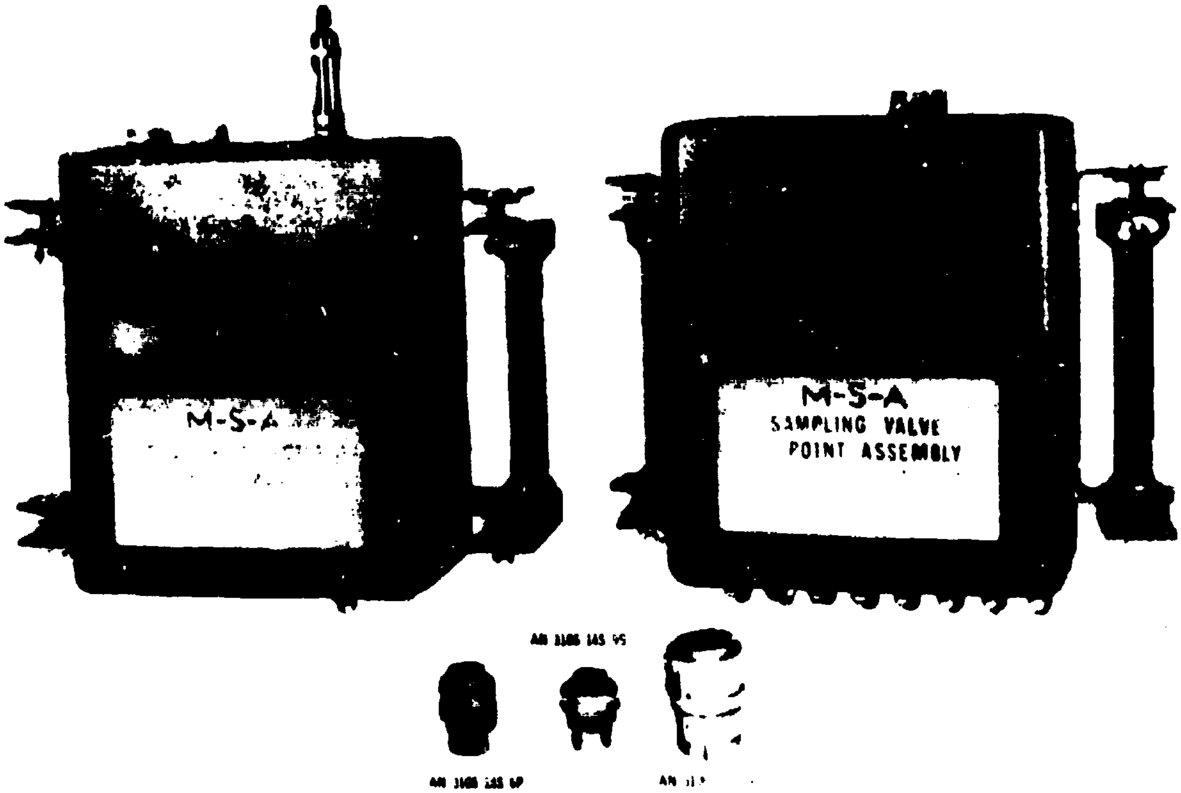

Fig. 6 MSA CO and Fire Detector and Multiple Sampling Valve Equipment

with sponge-rubber seals were located in the floor at each end of the compartment.

In order to illustrate the effect of various percentages of light transmission from 100 per cent to 0, six photographs were taken through a smoke-filled duct. See Fig. 11. The duct was 4 feet long and 6 inches square. The photographic target was lighted by a 60-watt bulb. Smoke was passed through the chamber, and the smoke density meter was mounted in series with it. For each photograph (A to F), the smoke supply was shut off at a predetermined range; and, after the smoke density meter had stabilized, the photograph was taken. It should be realized that the smoke density for a 1-foot depth would appear much lighter than those shown for the 4-foot depth.

A smoke generator rig (Fig. 12) was constructed with an internal volume of 64 cubic feet. The smoke emitted from the burning luggage passed into the plenum chamber A and to each of the smoke detectors B through parallel piping. The smoke from each of the smoke detectors was then passed through the plenum chamber C into the smoke density meter D and from there to a vacuum pump to exhaust. A pressure differential of 4 inches of water was maintained between plenum chambers A and C. The air-change rate within the entire system measured approximately 32 cubic feet per hour. Ignition in some tests was supplied by means of a 600-watt heating element (Calrod unit). Other tests, involving open fires, were ignited by match. The heating element locations varied for each test, so that in some cases it was placed between the luggage wall and the confined clothing, and in other cases entirely surrounded by clothing. The heating element, when used, was switched on for 5 seconds, then off for 10 seconds until the first trace of smoke was observed. The internal fire was then allowed to progress without further heating.

The Mine Safety Appliances unit incorporated an independent vacuum system which required a negative pressure of 4 inches Hg. Gas samples were, therefore, taken from chamber A and exhausted to atmosphere after passing through the detector. The C-O-Two convection-type detector was

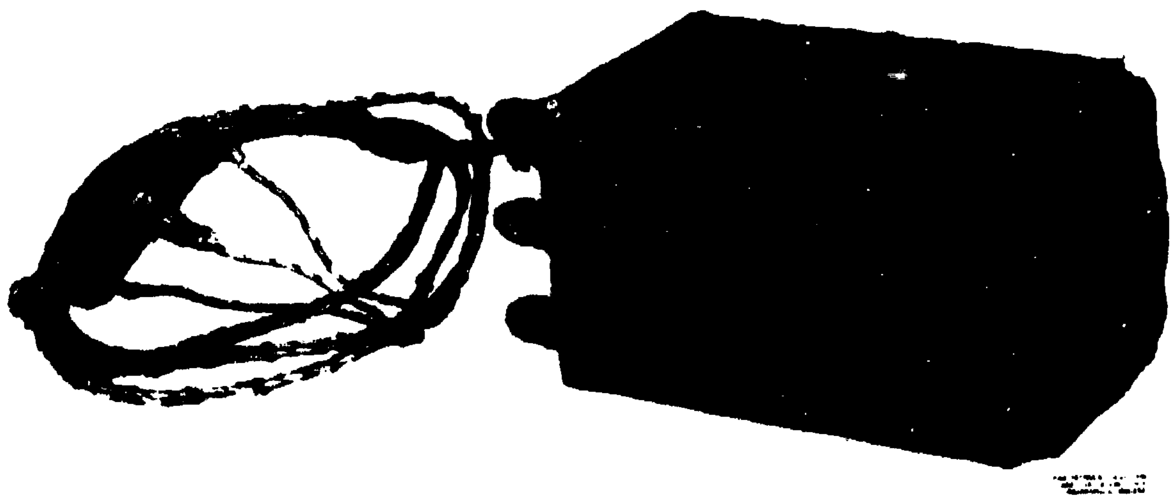

Fig. 7A C-O-Two Visual-Type Smoke Detector

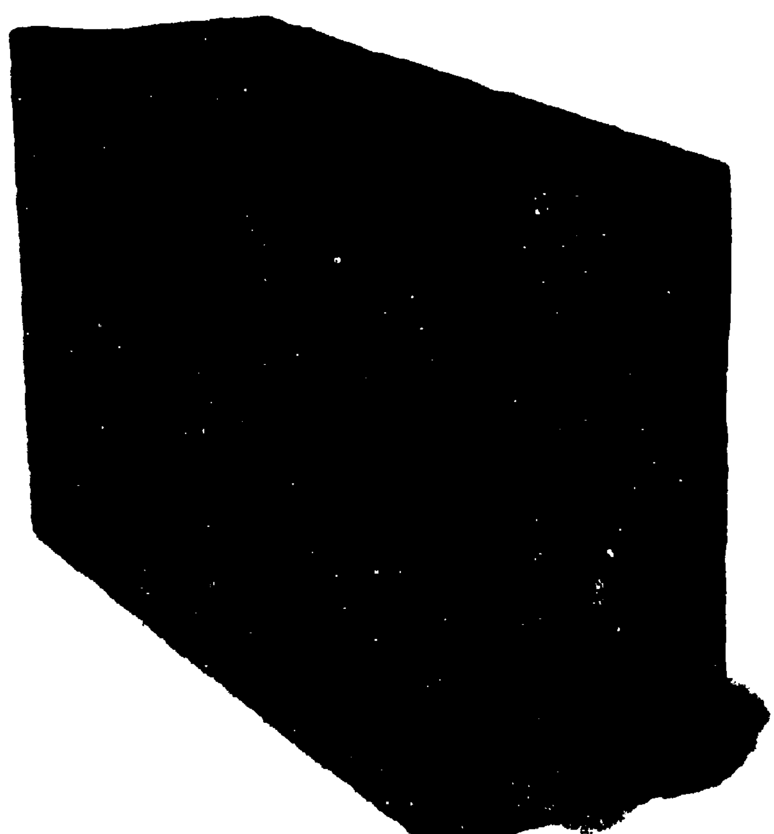

Fig. 7B Walter Kidde Visual Detector

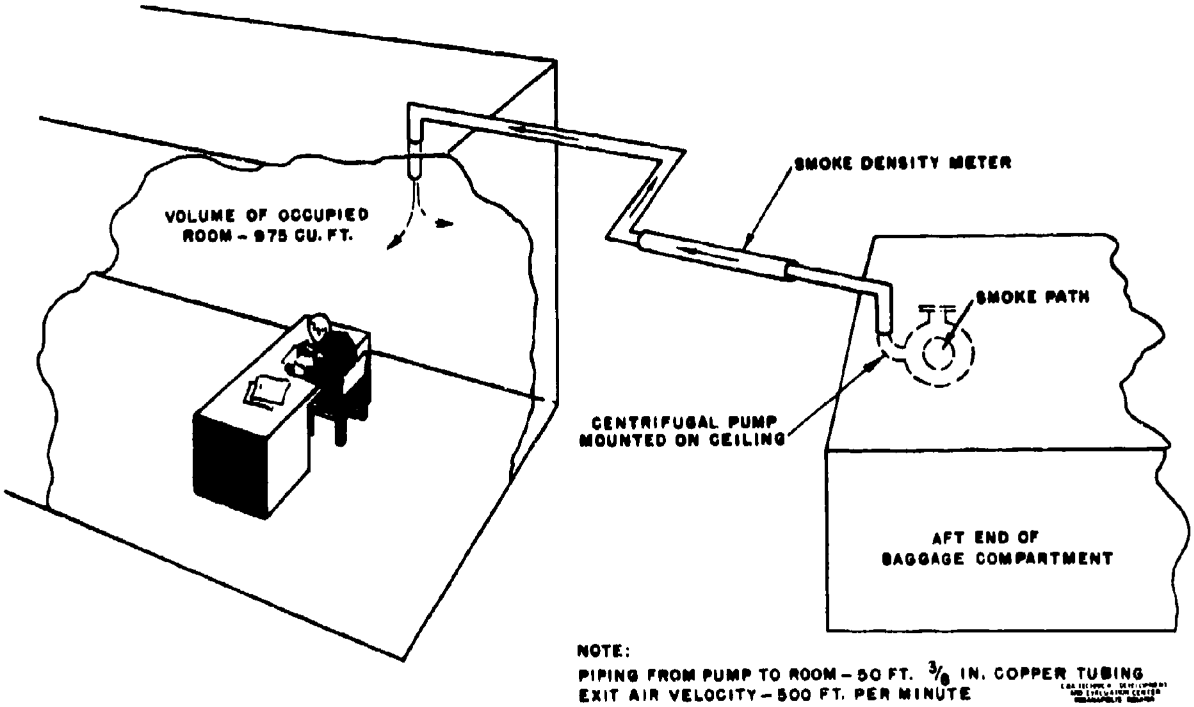

Fig. 8 Sniffer Test Rig Arrangement

tested while mounted inside of the full-scale compartment.

Ambient air temperatures within the cargo compartment were measured throughout many of these tests in order to evaluate the possible use and application of heat-type detectors (unit or continuous type).

In order to investigate the effects of sunlight on the visibility of smoke in the visual-type detector, a Constellation cockpit was obtained. See Fig. 13. An instrument panel was positioned in its normal location below the windshield. The visual smoke detector was mounted on a pivot arm, which allowed the detector to be positioned in any location in either the vertical or horizontal plane. Castered wheels made it possible to face the entire assembly directly into the sun, although the attitude of the cockpit section was always similar to normal flight. A battery of flood lamps shining directly into the cockpit also was used to simulate sunlight conditions. A centrifugal blower mounted within the compartment drew the air-smoke mixture through the detector. The smoke density to the detector was regulated by means of valves from a smoke generator unit. One valve permitted the flow of fresh air to a common manifold, and a second valve permitted the flow of smoke from the smoke chamber. Establishment of a balance between the two valves would maintain any desired smoke concentration for a reasonable length of time.

Some tests were conducted using the CO_2 discharge-system tubing as a means for sampling smoke or CO from within the full-scale compartment. The system consisted of two lengths of 3/8-inch copper tubing perforated by 3/32-inch drill holes, 1 foot apart. The two lengths of tubing ran the length of the compartment at the ceiling corners, and were manifolded at the upstream end to a smoke density meter or detector. In later tests, smoke densities were measured by sampling with a single pickup at the downstream end of the ceiling in the full-scale compartment.

Tests were conducted to determine the flow rates of smoke particles through various size tubes, which might be used for either the visual-type detector or in a sniffer (olfactory) system of detection. Fig. 14 is a diagram of the test apparatus. Three pieces of punk were ignited and placed under the smoke chamber. When the chamber became full of smoke, the copper tubing was coupled to the chamber and the time required for the smoke to pass through the tubing and past a beam of light at the exhaust end of the

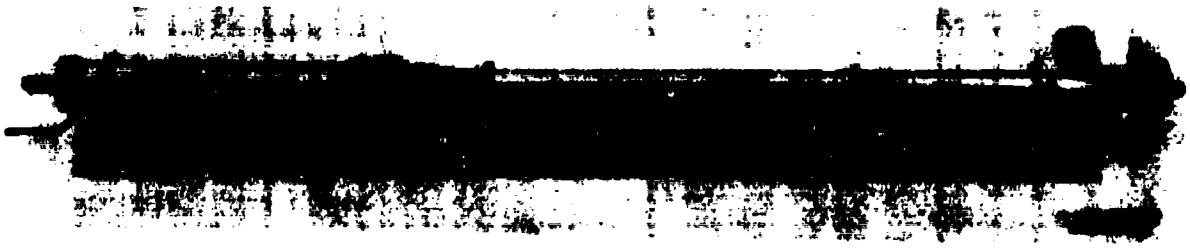

Fig. 9A CAA Smoke-Density Meter

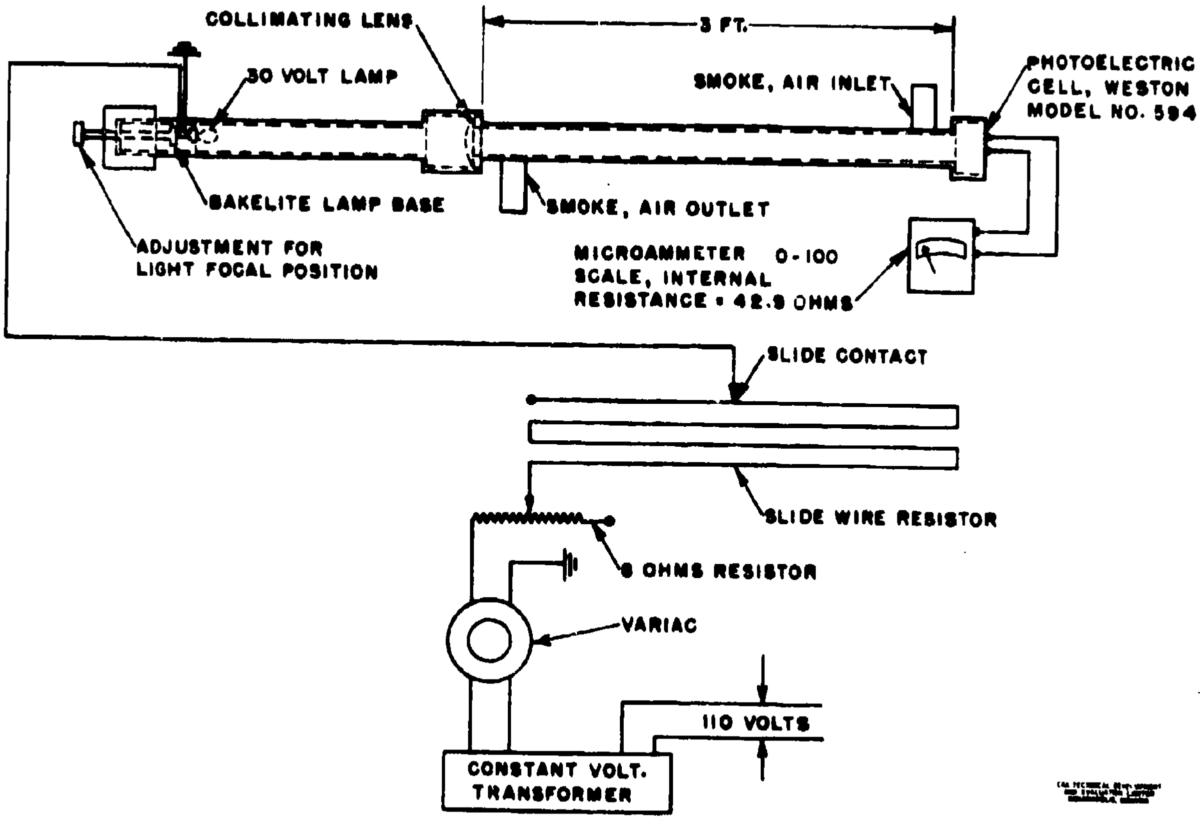

Fig. 9B Smoke Density Meter Wiring Diagram

pump was recorded. Variations in suction were controlled by regulation of the pump motor speed.

Detection by use of a sniffer tube also was attempted by piping a smoke-air mixture through a 50-foot length of 3/8-inch copper tubing from the full-scale compartment into an occupied office which had a volume of 975 cubic feet. The occupant in the room was not informed when samples of smoke-air mixture were being transmitted. The length of time required for the occupant to realize the presence of smoke in the room, through his sense of smell, was recorded and correlated with the smoke density in the baggage compartment. Immediately after detection, the smoke-air mixture to the office was reversed in direction and piped into the MSA unit to record CO concentrations within the room.

Results and Discussion

The smoke generation curves (Fig. 15) represent the outer extremities of the curves plotted after results were obtained using

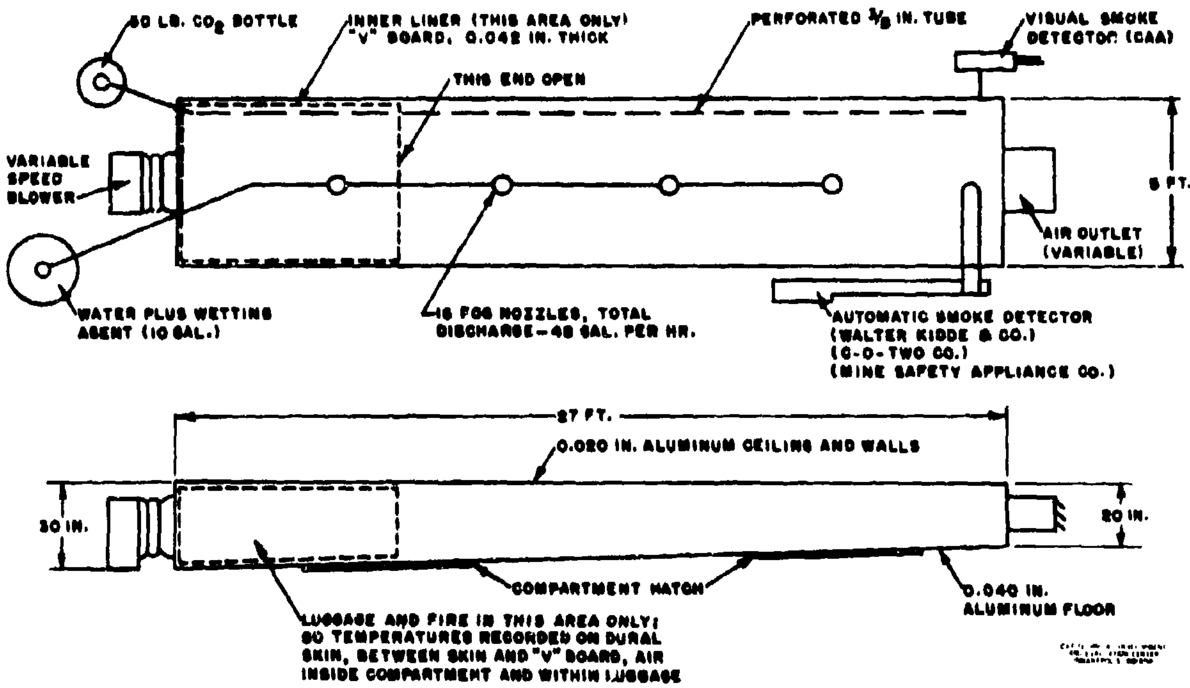

Fig. 10 Simulated Baggage Compartment

deep-seated fires with variations in the location of the heating element. The outer limits of these curves indicated that large quantities of smoke were emitted from burning luggage after the contained clothing began to burn of its own accord. Ignition times varied radically in the tests, so that zero time, as indicated in Fig. 15, was established when the internal fire within the luggage became self-sustaining. More severe fires and greater quantities of smoke occurred when the internal fires were located between the clothing and the luggage walls than in those fires which were deep-seated and located in the approximate center of the clothing contents.

The bar graph (Fig. 16) indicated that all the test detectors alarmed within the range prescribed in the TSO-C1 and TSO-C1a. The bar graph shows the variations in light transmission required for operation of each of the detectors, as well as the average light transmission reading at the time of operation. The convection-type C-O-Two detector (Model A-3) unit was comparable in sensitivity to the tube-type detector (Model A-4).

At present, smoke detectors are required to operate between 85 and 92 per cent light transmission. The approximate limits of this range are shown in Fig. 11C (84.5 per cent light transmission) and Fig. 11B (93 per cent light transmission). The recommended range would require detector operation between the limits shown in Fig. 11C (84.5 per cent light transmission) and Fig. 11E (58 per cent light transmission).

Luggage materials had a decided effect on the time required for an internal fire to burn through the luggage wall. In most of these tests, corrugated cardboard boxes were used, which afforded very little fire resistance; and, therefore, were assumed to be comparable to the poorest possible luggage materials. Open clothing fires generated more smoke in shorter periods of time than the submerged-type fires. The problem of smoke detection of an open-type clothing fire was not as difficult as was originally thought. It was noted, however, that open fires result in flame temperatures of 1,200° to 1,550°F, which should be considered in baggage-compartment design.

Class B (flammable liquids) fires generated large quantities of smoke. Hydraulic fluid and oil fires were burned by saturating cloth in the fluid bath and igniting the cloth by match, which produced a wick fire. Gasoline fires, of course, required no wick arrangement. Each of these fires generated large volumes of smoke. The smoke density meter indicated a smoke accumulation from

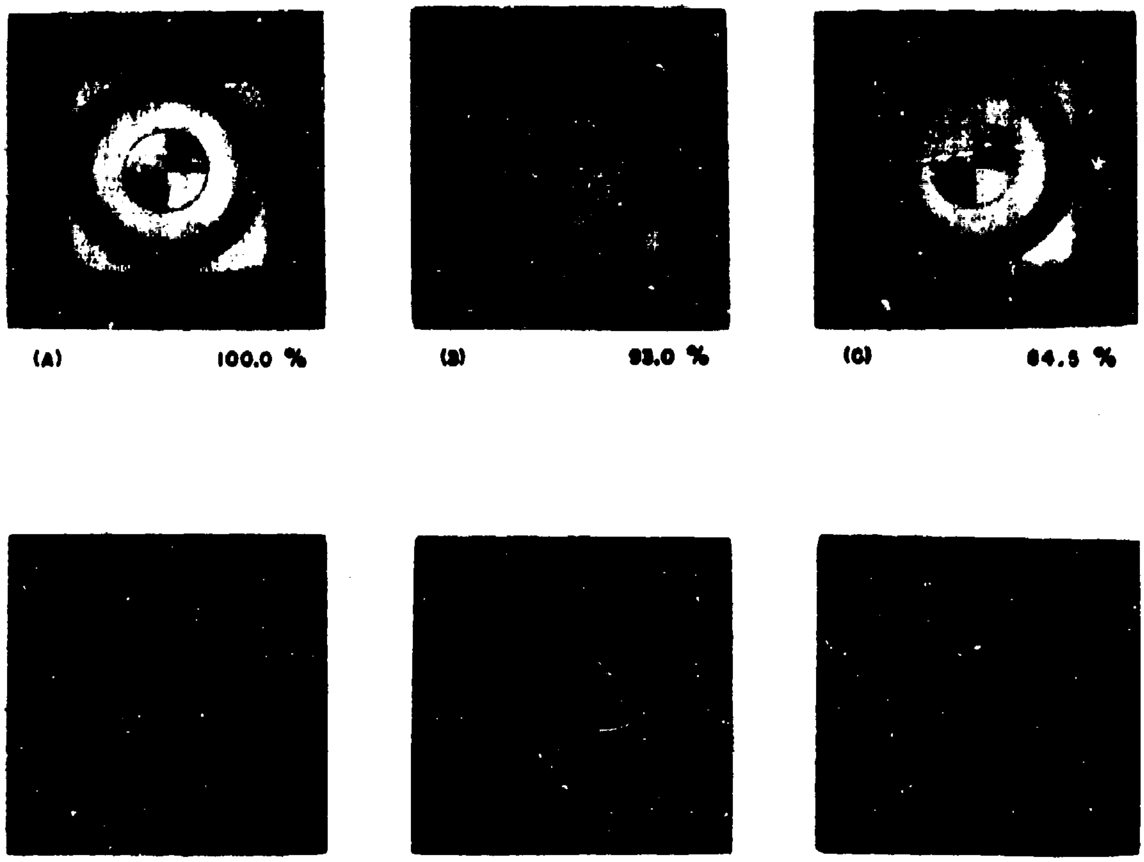

Fig. 11 Effect of Various Percentages of Light Transmission on Visibility (Percentage figures are given in terms of per cent light transmission per foot. Photographs show effect of visibility through four feet of smoke-air mixture.)

100 per cent light transmission to 0 per cent light transmission in a maximum of 6 minutes in the case of the oil and hydraulic fluid fires. Gasoline fires produced 0 per cent light transmission within 25 seconds after fire ignition. Tests conducted in various size compartments gave substantially the same smoke generation results over a wide range of air-leakage rates. The smoke produced by one small piece of luggage, burning in air-leakage rates as high as 3,300 cubic ft/hr, reduced the light transmission value to 0 in periods of 8 to 20 minutes.

Only one cause of false alarm for the detectors was investigated. Dust particles (dried ground earth) of undetermined size were discharged into the compartment through a jet of air under high pressure. The weight required for alarm was 300 grams.

Some applicable smoke generator, capable of emitting quantities of smoke equal to a baggage fire in its early stage of burning, was thought advantageous in order to check air-flow characteristics and ultimate locations of each type of detector. The present field test procedure makes use of a smoke bomb intended for an entirely different purpose. In the tests, the quantities of smoke emitted proved so great that little was learned because of obscuration. Fur-

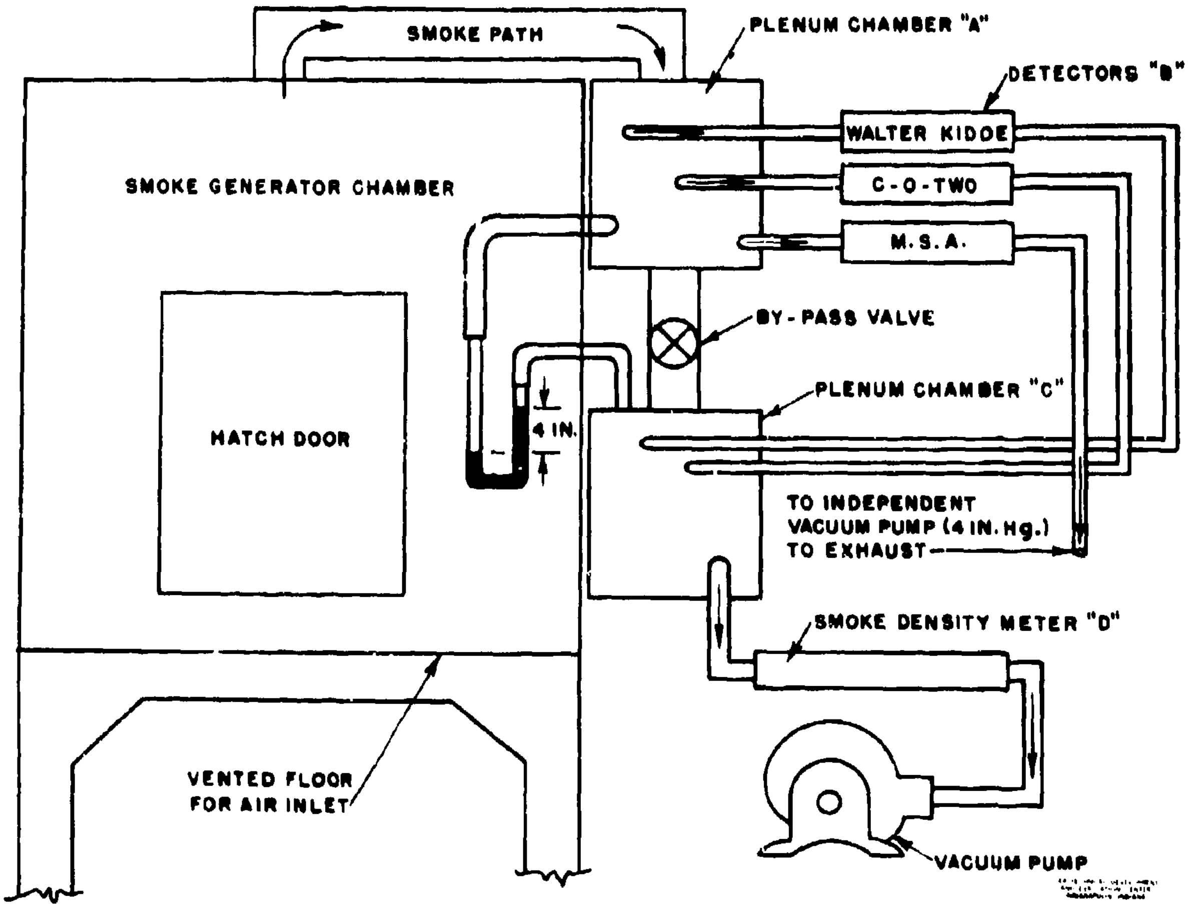

Fig. 12 Smoke and CO Detector Test Arrangement

ther tests indicated that 1/4-inch square, American-made punk of any desired length, when lighted, will generate a reasonably constant quantity of smoke. It was determined that nine such pieces would develop as much smoke as a burning piece of luggage at the instant the smoke density reached point A in Fig. 15. It should be noted that, in actual luggage fires, the increase in smoke density became relatively rapid after point A was reached, which was not the case when using punk. The quantity of smoke produced by the punk stabilized rapidly and remained constant for its entire burning time.

Both the C-O-Two and Walter Kidde Cos. designed and submitted smoke detectors of the visual type, as illustrated in Figs. 7A and 7B. The visual detectors proved very reliable from the standpoint of detection sensitivity. Smoke particles were obvious when passing through them, with light transmission values as high as 99 per cent. An intense reflection of light occurred when the light-transmission value was reduced to 95-90 per cent. There was no appreciable increase in the light intensity reflected from the visual detector at smoke densities below 90 per cent light transmission. There are three possible methods for using visual detectors for monitoring aircraft baggage compartments:

1. As a basic detector unit, independent of the more complicated photoelectric or CO units.

2. As a false-alarm indicator in conjunction with the photoelectric or CO units, or

3. As a basic instrument, but exhausting smoke-air samples into the pilot's compartment so that when smoke is emitted, the pilot's sense of smell acts as an attention caller.

All three smoke detection methods proved satisfactory when us. d in combination

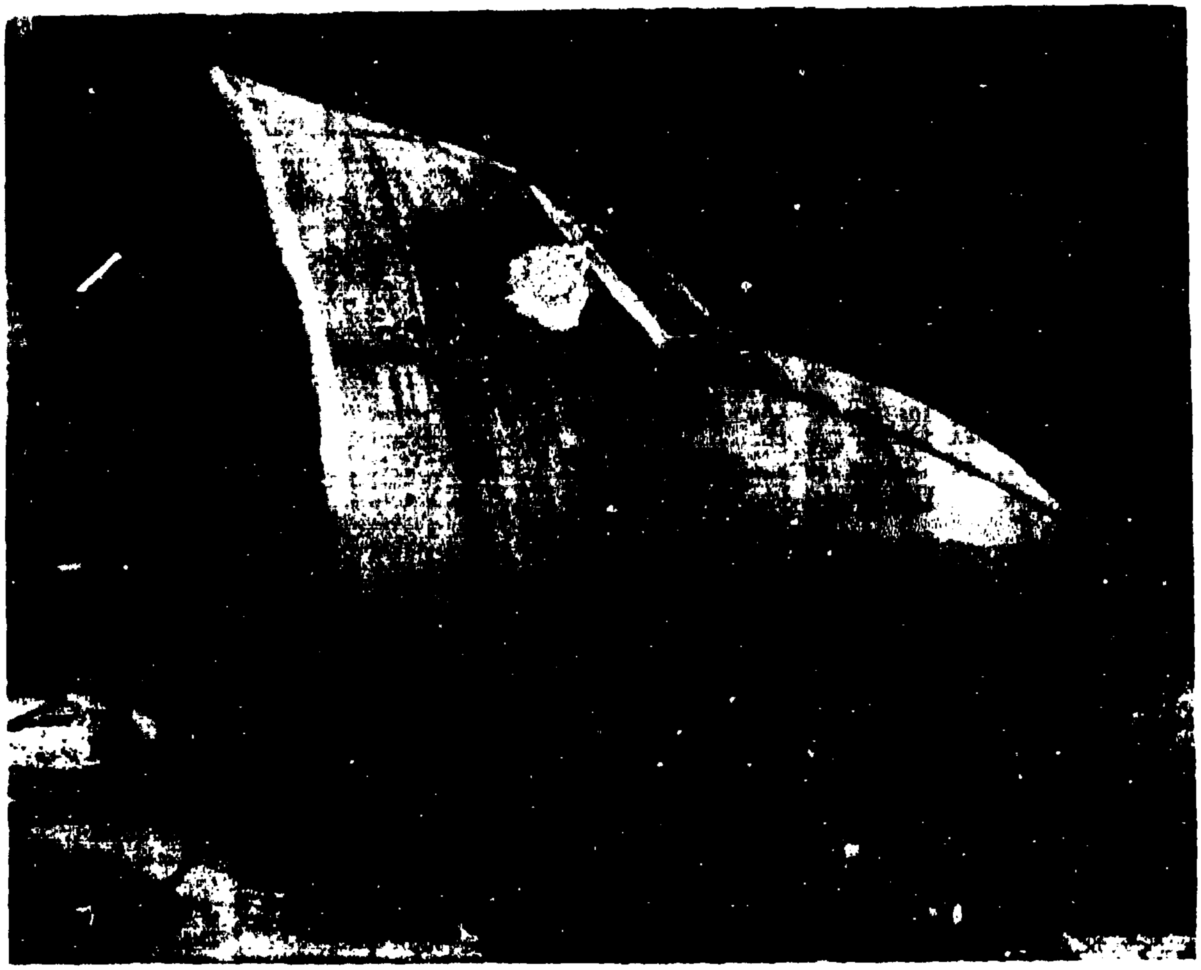

Fig. 13 Constellation Cockpit Compartment

with the full-scale cockpit shown in Fig. 13. The visual detector used in all three systems gave adequate warning at light transmission values from 99 to 90 per cent. If it is assumed that ambient light conditions are such as to interfere with the visibility of the visual detector, method (1) would give no signal, method (2) would signal within the range of 85-92 per cent light transmission and method (3) would provide an alarm at a light transmission value of approximately 40 per cent. The speed of the alarm provided by the olfactory system will depend on the pilot's sense of smell, the cockpit leakage rate, smoke density within the baggage compartment and the rate of smoke-air mixture being discharged into the cockpit.

The problem of conspicuity of the visual detectors during daytime flight was investigated. Although conspicuity basically is a physiological problem our observations of the visual detector indicated that it was as obvious at signal time as any of the other panel instruments after looking into the direction of the sun. However, this instrument problem can best be evaluated by actual test flight.

The olfactory-type detector, illustrated in Fig. 8, consisted of 50 feet of 3/8-inch o.d. copper tubing discharging air samples from the full-scale baggage compartment into an occupied room with a volume of 975 cubic feet. The air-sample discharge rate at the exhaust end was approximately 500 ft/min. Test results indicated that compartment smoke concentrations reached an average value of 40 per cent light transmission at the time smoke was detected by the occupant's sense of smell. Some concern was evidenced regarding the problem of toxicity

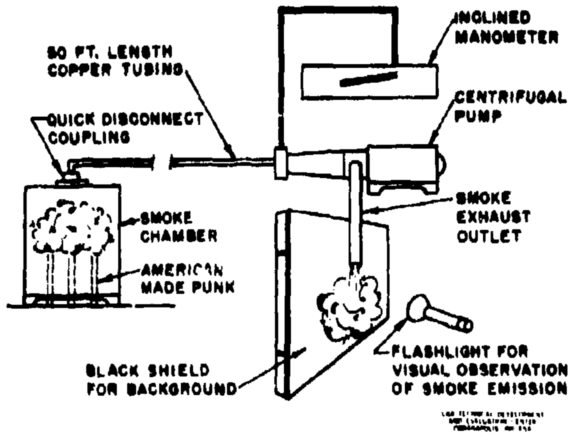

Fig. 14 Arrangement for Timing Smoke Transmission Through Tubing

introduced by this method of smoke detection. A careful analysis of the air in the occupied room immediately after detection, indicated that the percentage of CO present was well below the headache range. Because, in practice, so many electrical fires have been detected by the pilot's sense of smell, it was felt that this form of detection would be effective for the baggage compartment. Olfactory test systems made use of tubing as large as one inch in diameter. The larger diameter pipes (above 5/8 inch) were more effective timewise when higher values of light transmission existed within the cargo compartment, due to the greater volume of smoke-air mixture passed at any given pressure setting.

Detection of fire within baggage compartments by means of unit- or continuous-type heat detectors also was investigated. Ambient air temperatures within the compartment were recorded during various fires and compared with the quantities of smoke generated at various air-leakage rates as high as 2,700 cubic ft/hr. The generation of smoke, enough for detection, always preceded high ambient temperatures, except in the case of open flaming, which is not believed likely to occur during the earliest stage of a baggage fire. In tests commencing with open fires, ambient temperatures at the nearest thermocouple to the fire usually reached 250°F before the light transmission value dropped below 60 per cent. The difference in time, however, varied only by a maximum of 30 seconds. Induced deep-seated clothing fires alarmed smoke-type detectors 5 to 17 minutes before an open fire occurred, after which ambient temperatures reached 250°F.

The CO_2 discharge tubing, used as a means for sampling smoke or CO from within the baggage compartment, was not as effective, timewise, as a single point pickup located on the ceiling at the downstream end of the baggage compartment. This finding substantiated the Bureau of Standards statement that, "The rate and direction of ventilation within the compartment affected the concentrations of smoke and carbon monoxide at the different sampling locations, the highest concentrations being at the end toward which the air was moving."

The curves presented in Fig. 17 indicate the times required for smoke, under various pressures, to pass through 50-foot lengths of copper tubing of different diameters. In applying these curves to Olfactory detecting systems, an important consideration is that a larger diameter tubing can discharge a greater mass of smoke-air mixture, thereby decreasing the time required for detection.

Conclusions

From the tests which have been conducted, it is concluded that:

1. The existing automatic smoke- and carbon-monoxide-type detectors performed satisfactorily and operated in accordance with TSO-C1 and TSO-C1a with respect to that section which established sensitivity requirements.
2. The sensitivity settings as required by TSO-C1 and TSO-C1a are unnecessarily high and increase the probability of false alarms.
3. Photoelectric-type smoke detectors should alarm between a maximum value to 90 per cent light transmission and a minimum value of 60 per cent light transmission.
4. Sensitivity settings for carbon-monoxide-type detectors should be reduced from the present value of 50-150 parts of CO per million parts of air to a value no less than 250-300 parts CO per million parts of air.
5. Visual-type and olfactory-type smoke detectors performed satisfactorily. Tubing requirements for the best olfactory (sniffer) system indicated better results with increased volumes of smoke-air mixture through larger diameter tubing (3/4 - 1 inch) for any given pressure drop.
6. All types of smoke, olfactory and CO detectors gave warning of the presence of fire well in advance of fire conditions, which would be hazardous to aircraft structure, when the fire was deep-seated and confined within luggage.
7. Heat detectors could not be depended upon for detection of deep-seated baggage compartment fires in the incipient stages.
8. The conspicuity of the visual smoke

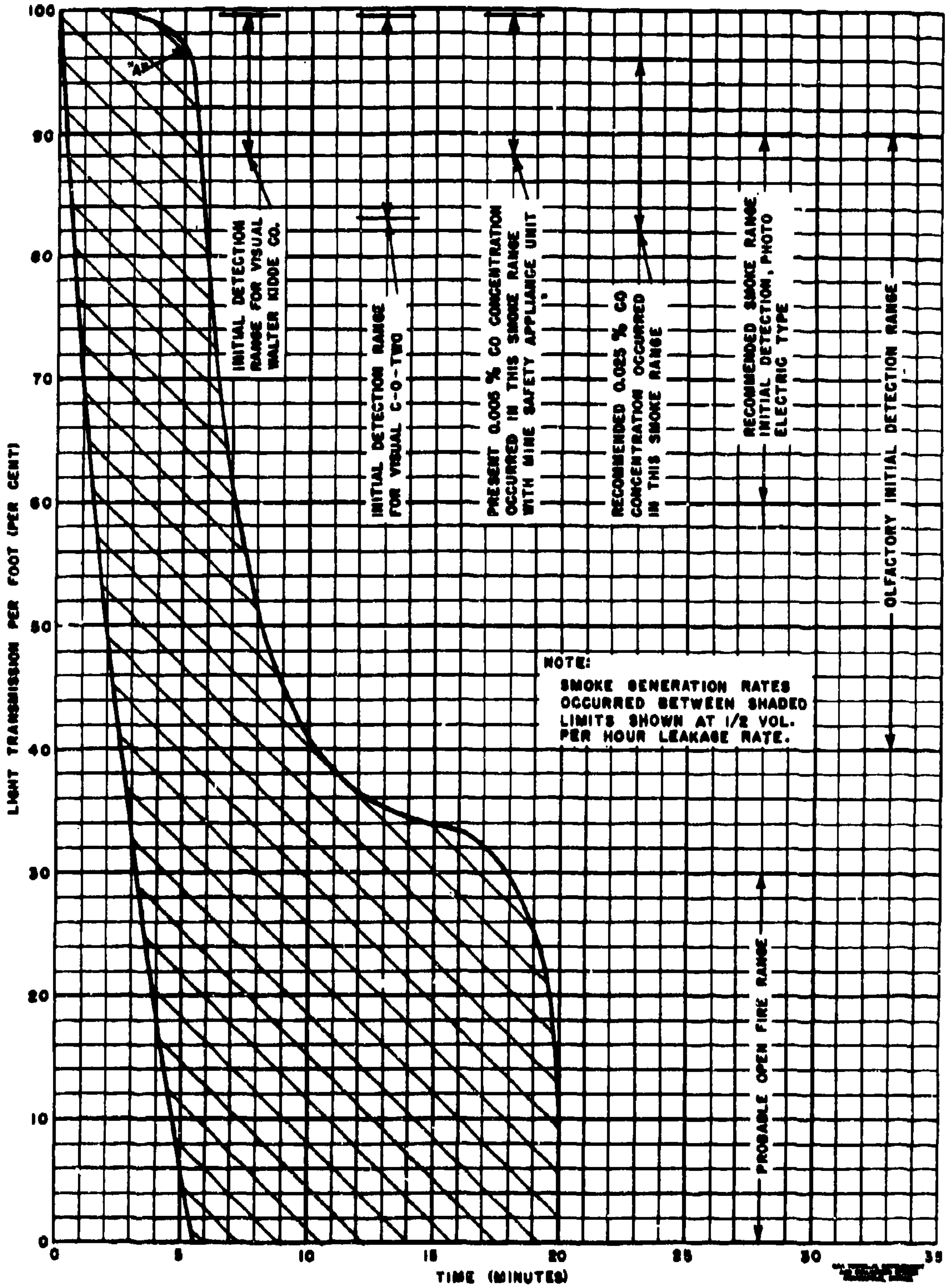

Fig. 15 Smoke Density vs. Time

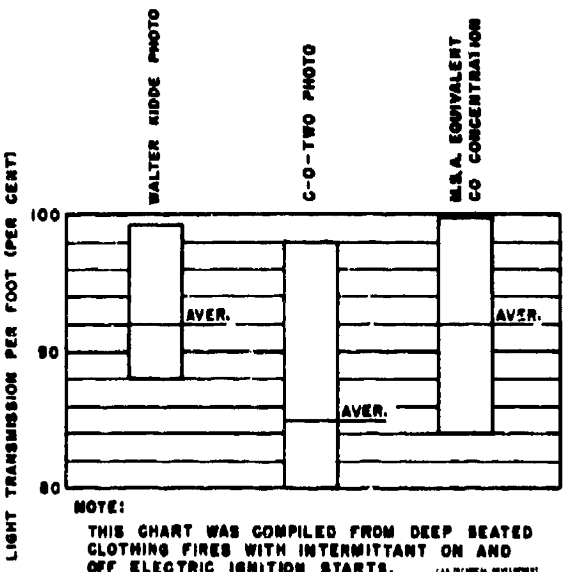

Fig. 16 Bar Graph Illustrating Detector Signal at Per Cent Light Transmission

detector, when signaling smoke signals in the range of 90 per cent light transmission, was similar to that of other cockpit instruments under equivalent ambient light conditions.

9. The concentration of CO carried into a cockpit by an olfactory-type smoke detecting system is negligible at the time smoke is detected.

EXTINGUISHMENT

Purpose

The purpose of the tests on fire extinguishment was to:

1. Determine the effectiveness of CO_2 on Class A fires with leakage rates normally present in aircraft cargo compartments.
2. Evaluate other presently known agents for use in extinguishment of baggage-compartment fires.

Procedure

Fires — The Class A test fires involved luggage and/or cardboard boxes packed with mixed types of clothing or with shredded wood (excelsior). In each such test, four thermocouples were placed around the fire source in a horizontal plane. A fifth thermocouple was located beneath the fire source.

Gunpowder and matches provided ignition in a few of the test fires. The source of ignition used for a majority of the test fires was an electric heating element. Heat was applied continuously until the internal temperatures had reached 1,600° to 1,800°F. The element was then disconnected and the temperatures within the suitcase were recorded. Stabilization of the temperatures followed by a temperature increase indicated a self-sustaining, deep-seated fire.

Compartments — Three compartments were used in this phase of the test program.

1. A 3.5-cubic-foot compartment which was well sealed and capable of withstanding internal pressures as low as 1 inch of Hg absolute.
2. A 48-cubic-foot compartment, built of aluminum alloy extrusions and 0.040-inch aluminum alloy skin.
3. The full-scale baggage compartment with a volume of 270 cubic feet, built of aluminum alloy extrusions and 0.020-inch aluminum alloy skin.

The leakage rates through the various compartments were varied during the tests from 0 to as high as 14 air-volume changes per hour. The leakage rates were produced both, by introducing air under slight pressure into the compartment, and by withdrawing air from the compartment. The leakage rates were determined by:

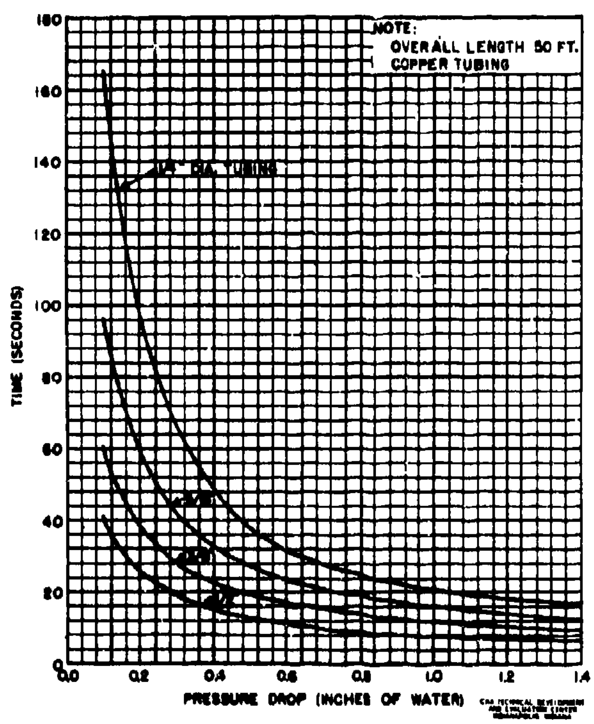

Fig. 17 Smoke Transmission Through Tubing. Time vs. Pressure Drop

Fig. 18A Positive Displacement Orifice Calibrating Rig

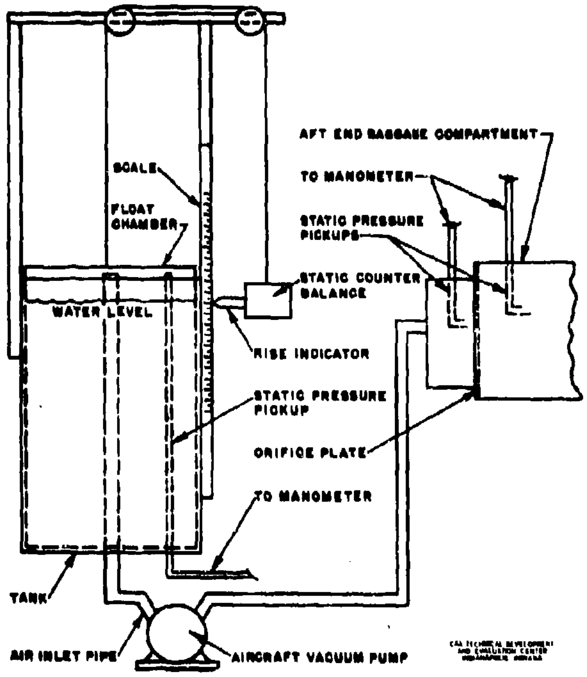

Fig. 18B Positive Displacement Meter Used to Calibrate Orifices

1. Measuring the exhaust air velocities through a thin plate orifice by means of a velometer.

2. Measuring the pressure drops across a thin plate orifice that had been calibrated using the positive displacement test rig illustrated in Fig. 18A. Details of the test rig are shown in Fig. 18B.

Extinguishing Agents — The extinguishing agents used in the tests included:

1. Carbon dioxide (CO_2).
2. Methyl bromide (MB).
3. Methylene chlorobromide (CB).
4. Carbon tetrachloride (CTC).
5. Helium.
6. Dry powder (sodium bicarbonate).
7. Water.
8. Water plus a wetting agent.

Carbon dioxide was discharged into the test compartments through tubing systems including perforated tubing, nozzles and single outlet test arrangements. Various discharge techniques included:

1. Single-shot, total quantity discharge.
2. Two-shot discharge, 1/2 total weight per shot.
3. One-shot discharge followed by CO_2 bleed at low rate.
4. One-shot discharge followed by intermittent burst discharges to maintain a minimum CO_2 concentration between 55-60 per

cent.

5. One-shot discharge followed by intermittent burst discharges to maintain a minimum CO_2 concentration between 70-80 per cent.

Methyl bromide, methylene chlorobromide and carbon tetrachloride were compared to carbon dioxide by releasing equivalent weights of those materials on identical test fires.

Helium was compared to CO_2 for fire extinguishing abilities on an equivalent free volume basis.

Only preliminary tests were conducted to determine the effects of dry-powder extinguishing agent on baggage-compartment fires.

The quantities of water and water plus a wetting agent used in the tests varied between 10-50 gallons, and were discharged by pressures from the equivalent of a static head of 10 feet (gravity feed) to as high as 200 psi.

For all of the liquid extinguishing agents, various spray nozzles were tested using different discharge rates and spray patterns.

TEST INSTRUMENTATION

The instruments used in the tests included a velometer, pressure pickups, manometers, thermocouples, recording pyrometers and gas analyzers (Orsat and Ranarex).

Tests — During the many extinguishment tests using CO_2 in the 48-cubic-foot compartment and in the 270-cubic-foot compartment, four pickup tubes were used in each compartment. The four tubes were spaced equally along the length of the compartment. The lowest pickup was located one inch above the floor line, and the highest pickup was located flush with the compartment ceiling.

Six series of tests were conducted to determine:

1. The efficacy of CO_2 used in quantities presently carried in civil aircraft, on both open and deep-seated fires. Those quantities generally fall within the range of 1 pound of CO_2 for every 7 or 8 cubic feet of compartment volume.
2. The effectiveness of excessive quantities of CO_2 up to quantities as high as 1 pound of CO_2 for every 4.8 cubic feet of compartment volume.
3. The differences between CO_2 concentrations within the baggage compartment and within individual pieces of luggage, with and without contained fire.
4. The effectiveness of other common extinguishing agents, as compared to that of CO_2, by using equivalent volumes on similar test fires and under similar conditions.
5. The effect of load factor on carbon dioxide dilution rates.
6. A method for accurately establishing the air-volume change rate of any baggage compartment in flight by determining the CO_2 concentration decreases with time. As this phase of the work does not involve extinguishment, but results in a recommended technique for establishing baggage-compartment leakage rates, the procedure is detailed in Appendix I.

Results and Discussion

The tests proved that carbon dioxide in the quantities carried aboard civil aircraft could not extinguish deep-seated clothing fires. In such quantities, CO_2 did extinguish excelsior fires. The major hazard existing in aircraft baggage compartments is, of course, cloth fires originating within pieces of personal luggage, and it was on this type fire that carbon dioxide proved most ineffective. A review of all of the extinguishment tests conducted shows that very few test fires involving cloth were extinguished by carbon dioxide under any circumstances, and that only when the air-change rates through the baggage compartments were extremely low, of the order of one-half volume air change per hour, could CO_2 even provide significant "fire control" time. See Table II. The term "fire control" means the time that the fire is actually subdued or reduced in intensity by the presence of CO_2 in the surrounding atmosphere.

When the air-volume change rates exceeded one-half change per hour, the degree of fire control provided by CO_2 was generally so slight as to be, for all practical purposes, useless. The tests showed that the extinguishment of deep-seated clothing fires required extremely high concentrations of CO_2 (of the order of 90-100 per cent) for periods of hours. To maintain such concentrations for long periods of time in anything other than a completely sealed compartment is impossible with the quantities of CO_2 that can be carried in an airplane.

Of the six techniques for discharging CO_2, described previously, the best results were obtained by discharging the total quantity of CO_2 available in a single discharge. The superiority of this technique was undoubtedly due to the initial high concentrations of CO_2 which were produced. This condition, in turn, produced the highest possible CO_2 concentrations within the individual pieces of luggage.

Tests in which excessive quantities of CO_2 were discharged did provide more instances of extinguishment and generally in-

TABLE II

Carbon Dioxide Fire Extinguishment Test Data

Type Ignition	Type Container	Contents	Air Vol. Changes Per Hr.	Type of Fire	Weight of CO_2 (Lbs/Ft^3 of Vol.)	Type* Discharge	Fire Results	Control Time (Min.)
Gunpowder	Cardboard Box	Excelsior	11.20	Open	1:6.0	One Shot	Ext.	-
Gunpowder	Cardboard Box	Excelsior	5.60	Open	1:7.0	One Shot	Ext.	-
Gunpowder	Cardboard Box	Excelsior	2.80	Open	1:8.0	One Shot	Ext.	-
Gunpowder	Cardboard Box	Excelsior	2.80	Submerged	1:9.6	One Shot	Ext.	-
Gunpowder	Cardboard Box	Excelsior	0.56	Submerged	1:6.0	One Shot	Ext.	-
Gunpowder	Valise	Cloth	0.56	Submerged	1:6.0	One Shot	Not Ext.	120
Calrod	Valise	Cloth	0.56	Submerged	1:4.8	One Shot	Not Ext.	20
Calrod	Valise	Cloth	0.56	Submerged	1:4.8	Bleed	Not Ext.	30
Calrod	Valise	Cloth	0.0	Submerged	1:4.8	Bleed	Ext.	-
Calrod	Valise	Cloth	0.0	Submerged	1:5.6	Bleed	Not Ext.	20
Calrod	Valise	Cloth	0.56	Submerged	1:6.0	Bleed	Not Ext.	37
Calrod	Valise	Cloth	0.56	Submerged	1:6.0	Bleed	Not Ext.	35
Calrod	Cardboard Box	Cloth	0.56	Open	1:6.0	One Shot	Ext.	-
Calrod	Cardboard Box	Cloth	0.0	Open	1:8.0	Bleed	Ext.	-
Calrod	Cardboard Box	Cloth	0.0	Submerged	1:8.0	Bleed	Ext.	-
Calrod	Cardboard Box	Cloth	1.0	Submerged	1:6.0	One Shot	Not Ext.	10
Calrod	Cardboard Box	Cloth	1.0	Submerged	1:8.0	One Shot	Not Ext.	26
Calrod	Cardboard Box	Cloth	2.0	Submerged	1:8.0	One Shot	Not Ext.	No Control
Calrod	Cardboard Box	Cloth	2.0	Submerged	1:6.0	One Shot	Not Ext.	30
Calrod	Cardboard Box	Cloth	1.0	Open	1:7.4	One Shot	Not Ext.	5
Calrod	Cardboard Box	Cloth	0.5	Open	1:7.4	One Shot	Ext.	-
Calrod	Cardboard Box	Cloth	0.5	Open	1:7.4	One Shot	Ext.	-
Match	Cardboard Box	Cloth	0.25	Open	1:7.4	One Shot	Not Ext.	11
Match	Cardboard Box	Cloth	0.25	Open	1:7.4	One Shot	Not Ext.	5

* One shot required approximately 15 seconds for total CO_2 discharge.
Bleed arrangement required 45-60 seconds for total CO_2 discharge.

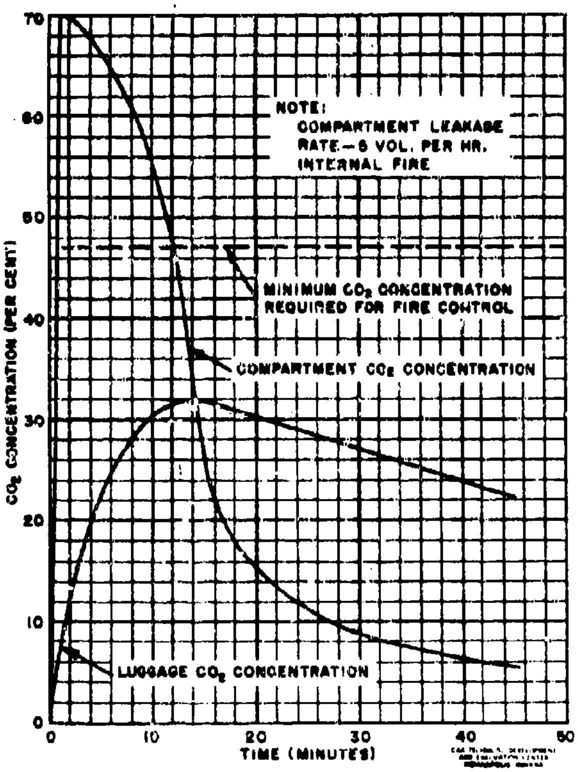

Fig. 19 CO_2 Concentrations Inside Luggage Pack vs. Compartment CO_2 Concentrations

creased fire control times. However, to illustrate the difficulties of providing fire extinguishment by the use of carbon dioxide, a typical test will be described. The small test chamber (3.5 cubic feet) was evacuated of air, and CO_2 was discharged into it to bring the internal pressure of the compartment back to atmospheric. A cardboard box with an internal clothing fire, introduced into the compartment just prior to the evacuation, was kept in the compartment until the fire was extinguished. Extinguishment required 1 1/2 hours, and the CO_2 concentration at the time of extinguishment was 98.4 per cent. Although such a test could be conducted in a laboratory, it is obviously unreasonable to expect to encounter such conditions in an aircraft baggage compartment.

The major reason for the failure of any of the extinguishing agents tested to provide adequate fire extinguishment was found to be the inability of the agents to penetrate through the luggage and into the burning cloth. The curves, Figs. 19 and 20, compare the CO_2 concentrations within the baggage compartment with the concentrations within individual pieces of luggage (with and without fire). In both instances, it can be seen that the mere provision of a high concentration of extinguishing agent in the baggage compartment does not prove that the required concentration of CO_2 exists within the luggage where the fire occurs. The quantity of CO_2 which affected the fire within the luggage depended upon the tightness of luggage construction and the mass of clothing which was packed into the luggage. In one particular test where a reasonably tight suitcase densely packed with cloth was provided, the maximum CO_2 concentration contained within the luggage was 11 per cent at the time the CO_2 concentration within the baggage compartment was 70 per cent. While the CO_2 concentration in the compartment dropped from 70 per cent to 64 per cent, the CO_2 concentration within the luggage never exceeded the 11 per cent figure, which was obviously incapable of extinguishing the clothing fire.

Of all the agents tested, carbon dioxide proved to be the most practical, and generally was the best agent for this purpose. Only in instances where completely sealed compartments were used, did helium prove superior to carbon dioxide. In such instances, helium was found to be much more capable of diffusing through packed clothing than carbon dioxide. Conversely, however, helium was found to be far more difficult to confine within a baggage compartment than carbon

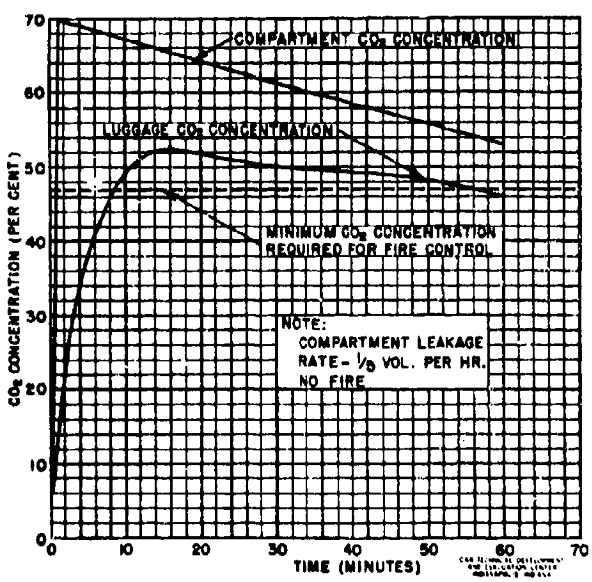

Fig. 20 CO_2 Concentrations Inside Luggage Pack vs. Compartment CO_2 Concentrations dioxide. The liquid chemical agents such as methyl bromide, methylene chlorobromide and carbon tetrachloride proved to be inferior to carbon dioxide pound for pound; therefore, the tests of these agents were abandoned. Preliminary tests indicated that the heat provided in the initial stages of a baggage fire was not sufficient to break down appreciable quantities of the dry-powder agent (sodium bicarbonate) so that this agent also was abandoned.

In the quantities used, water and water plus a wetting agent proved incapable of extinguishing deep-seated clothing fires. Associated wick tests were conducted to determine the relative abilities of water and water plus a wetting agent to penetrate into massed clothing. These tests proved the obvious superiority of the wetted water to penetrate masses of clothing over that of water. However, the limited quantities of either liquid which could be used in these tests reduced this superiority to the point of insignificance. The advantages of either water or wetted water demonstrated by these tests were:

1. Water discharge was capable of reducing luggage fires to a smoldering condition.
2. Water discharge did wet down surrounding luggage with a consequent reduction in the rate of fire spread.
3. The water discharge tended to cool the metal surfaces of the baggage compartment, thereby preventing or minimizing damage to the surfaces.
4. In baggage compartments that are subject to high air-volume change rates, the water tended to remain within the compartment under circumstances in which the gaseous agents would be rapidly dispersed.

Investigation as to the effect of compartment load factor (by volume) on carbon dioxide dilution rates indicated that the effect of volume change rate in a loaded compartment is appreciably higher than might be expected as a result of the loading. In a typical test, the actual air-volume change rate was 1.8 per hour. A cargo load equal to 41 per cent of the compartment volume was added. Theoretically, the air-volume rate within the loaded compartment would equal 1.8/0.59, or 3 volume changes per hour. The effective air-volume change rate, however, as determined by theoretical CO_2 concentration drop versus air-dilution curves, Fig. 21, indicated an air-volume change rate of 3.8 per hour. In this particular test, an internal fan was used to reduce the stratification of CO_2. Actually, the stratification of CO_2 within a cargo compartment (without the fan) could make this condition even more severe.

Conclusions

1. With CO_2 in the quantities carried on aircraft today and with the leakage rates normally present in aircraft today, (a) all Class A fires cannot be extinguished, (b) open flames can be eliminated initially, but smoldering will continue and open flame will again occur when CO_2 concentrations are reduced but (c) open liquid fires can be extinguished.
2. The CO_2 concentration in any compartment is higher than that within a burning piece of luggage and, for that reason, the degree of fire control will depend largely upon the density and quantity or mass of clothing and the construction of the luggage involved.
3. The rate of reduction of a CO_2 concentration for any given volume change rate is affected by cargo load factors, and varies approximately inversely as the remaining free space. Stratification of CO_2 gas can further reduce the desired concentration nearest the ceiling by 200 per cent.
4. Helium is a better extinguishant than CO_2 for Class A fires, but is effective only in a completely sealed compartment.
5. While the wetting of baggage by water slowed up the spread of fire, in no test did water completely extinguish the fire with fixed-type discharge systems and with the quantities used (10-50 gallons)
6. The addition of a wetting agent to the discharge water did not produce any significant improvement in the extinguishing ability of water in the quantities used.
7. None of the agents tested, in reasonable presently carried aircraft quantities, are adequate extinguishants when used in fixed extinguishing systems for combating Class A fires with leakage rates existing in C category baggage compartments.
8. Existing agents in reasonable quantities will become progressively better in ability to control a Class A fire as the leakage rate of a cargo compartment is reduced. The control time for any given leakage rate, is, however, materially affected by the type of fire experienced. For this reason, no specific duration of fire control can be established for any known leakage rate.

FIRE CONTROL

Purpose

To determine the extent to which luggage fires, confined within inaccessible cargo compartments, may be controlled in flight by:

1. Limiting the original volume of compartments, the leakage rates through compartments and/or

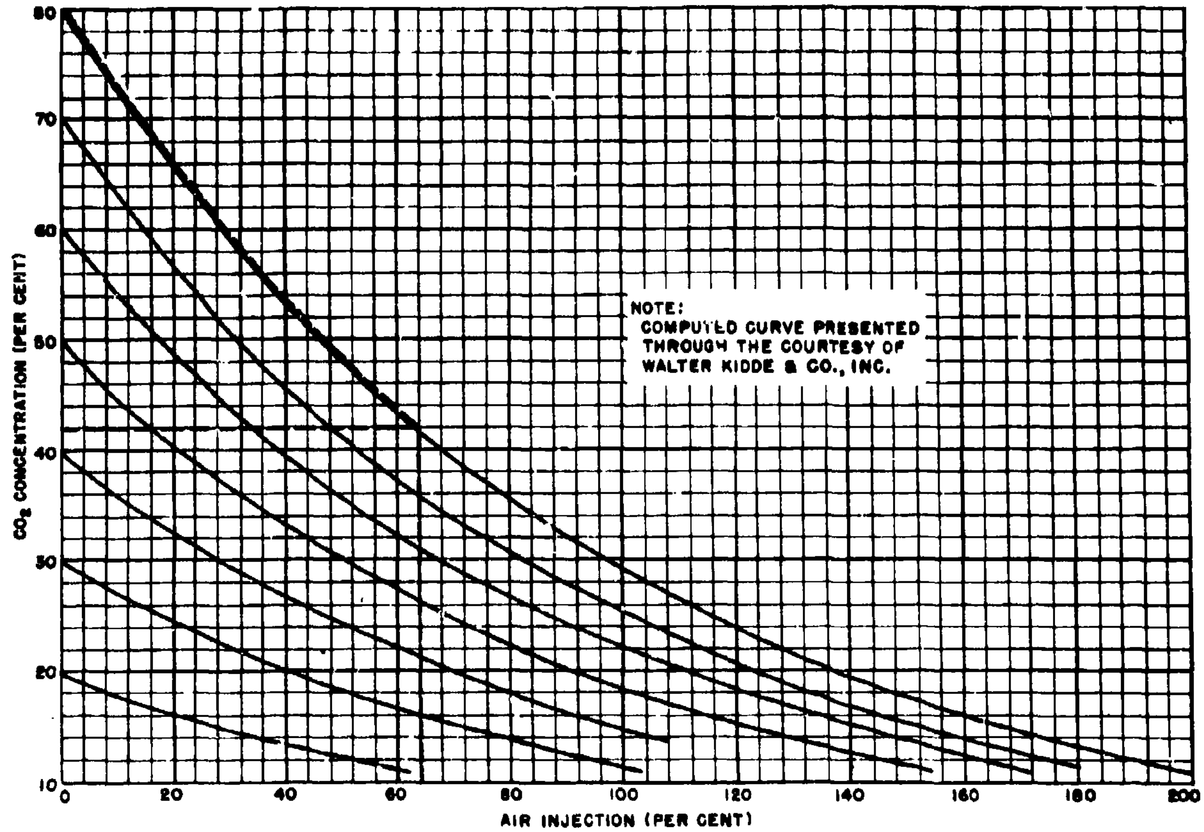

Fig. 21 Resultant Carbon Dioxide Concentration Secured by Injecting Air Into a Closed Space Having Various Initial Carbon Dioxide Concentrations

2. Using heat insulating materials in the construction of, or as a lining for, compartments.

Procedure

The tests were conducted using cotton cloth, excelsior and oil fires. The excelsior and the cotton cloth fires were produced by igniting the material contained in a 12- by 12- by 12-inch cardboard box open at the top. These fires were open fires, since deep-seated or smoldering fires in previous tests produced insignificant amounts of heat. The rates of burning and, consequently, the sizes of these fires, were random. The oil fires were produced by a small gun-type conversion burner. The sizes of these fires were quite closely controlled by the nozzles used and produced from approximately 100,000 to 500,000 Btu per hour. It was estimated that this more than covered the range of the open-type Class A fires used in these tests.

The effect of volume on the severity of fire was determined by igniting the various fires within compartments ranging in size from 48 cubic feet to 270 cubic feet. The times required for the disappearance of visible flames due to oxygen deficiency were noted, and, in the case of the Class A fires, skin temperatures were recorded at locations of flame impingement.

The effect of leakage rates through compartments on the severity of fire was determined by igniting various fires within compartments which were subjected to leakage rates up to 10,000 cubic feet per hour. The times required for disappearance of the visible flames due to oxygen deficiency were noted, and, in the case of Class A fires, skin temperatures were recorded at locations of flame impingement. These tests were conducted using the 48-, 110- and the 270-cubic-foot compartments.

Tests were conducted to determine the amount of protection that would be afforded the 0.020-inch-thick aluminum alloy ceiling and wall panels by insulating materials. A 12- by 12- by 12-inch cardboard box, open at the top and filled with wood excelsior, was used as the fire source, because it produced the most severe, probable fire.

An insulation material commonly known as V board, 0.042 inch thick, manufactured by the U. S. Rubber Co., was applied to the walls and ceiling of 1/4 of the 270-cubic-foot compartment. The fire source was placed in this quarter of the compartment, and ceiling skin temperatures above the fire were recorded.

Albi RX, a heat insulating paint manufactured by the Albi Chemical Co., was applied to panels 2 feet square, and mounted in the ceiling above the fire source. Temperatures of these aluminum panels were recorded. The amount of insulation afforded the panels was determined for both the oil base and water base Albi RX paints. From one to four coats of these paints were applied to the test panels.

A severe fire test was devised using a conversion-type oil burner producing a 2,000°F flame for comparing heat insulating materials in order to evaluate their characteristics. These tests involved such materials as Refrasil (H. I. Thompson Co.), V board (U. S. Rubber Co.), fiberglas wool (Dow Chemical Co.) and Silicone PC XL-33 (Dow Corning Co.). A 1-foot square of the material was impinged normally by the flame, and the time for penetration of the flame was noted.

Results and Discussion

The cotton cloth and excelsior fires, burning in a sealed compartment with a volume of 270 cubic feet, continued to produce open flames for an average of 3 to 5 minutes, at which time the fire reverted to a glowing mass. Similar fires in the 48- and 110-cubic-foot sealed compartments gave similar results, except that the time that open flames persisted was somewhat less. The maximum ceiling skin temperature recorded for both cotton cloth and excelsior fires was 950°F in each of the three compartments. This temperature was reached in about 1 1/2 minutes after ignition. In the 270-cubic-foot compartment, this maximum temperature was maintained for about three minutes; while, in the 48-cubic-foot compartment, it was maintained for less than one minute. The size of fire or rate of burning of the Class A fires was not easily controllable. Generally, the excelsior produced larger, quicker fires than the cotton cloth. With this variable being so great, it was difficult to determine what effect other variables, such as original size of compartment, had on controlling a fire. For this reason, a small gun-type conversion oil burner was used for producing a test flame. The rate of burning or size of fire was controlled by the burner nozzle used. The test conditions used in the cotton cloth and excelsior fire tests were then repeated, using various oil fire sizes that ranged from the smallest to greater than the largest fire produced in the previous Class A fire tests. The results indicated that identical test fires, burning at nearly a constant rate, would persist considerably longer in the 270-cubic-foot compartment than in the 48-cubic-foot compartment. The "no air flow" curve in Fig. 22 shows the effect of volume for several different oil fire sizes expressed in Btu per hour output.

The cotton cloth and excelsior fires, in the various sized compartments ventilated at various rates, continued to burn at reduced rates for greater durations than oil-type fires; some continuing until all of the combustible material had been consumed. However, the maximum ceiling skin temperature did not exceed 950°F, which was the same as the value determined in the sealed-compartment fire tests. Ceiling skin temperature versus time after ignition curves for several of the Class A fire conditions are shown in Fig. 23.

Again, in order to determine accurately the effect on the fire caused by variations in compartment volume and air flow, the oil-burner fires were used. Fig. 22 shows the effects of air flows up to 10,000 cubic ft/hr on duration of visible flames in the 48-cubic-foot compartment and in the 270-cubic-foot compartment. From these curves, it can be seen that the maximum size fire that burned continuously for any one leakage rate was the same for the large and the small compartments. For any fire larger than this, the time that visual flames persisted, as shown by this curve, was greater for the larger compartment than for the smaller compartment.

From the large number of fires observed in this test series of both the Class A and Class B fires, it was evident that:

1. Class B fires produced by the oil burner would continue burning at nearly a constant rate until approximately 12 to 14 per cent oxygen remained, at which time the flames disappeared.

2. Class A open-type fires would decrease in size as the oxygen concentration decreased, and, provided the air-leakage rate was above 1,800 cubic ft/hr, would continue to burn until all combustible material was consumed.

3. Class A open-type fires would flame until the oxygen concentration was reduced to 12-14 per cent, at which time the fire be-

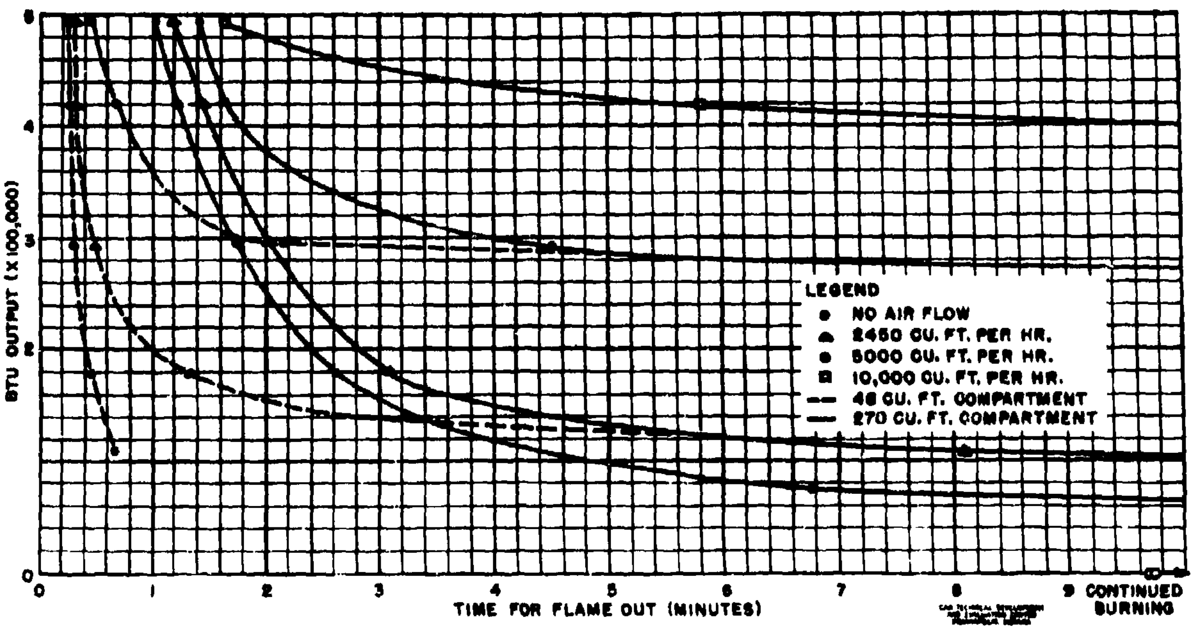

Fig. 22 Effect of Fire Size on Flame Duration

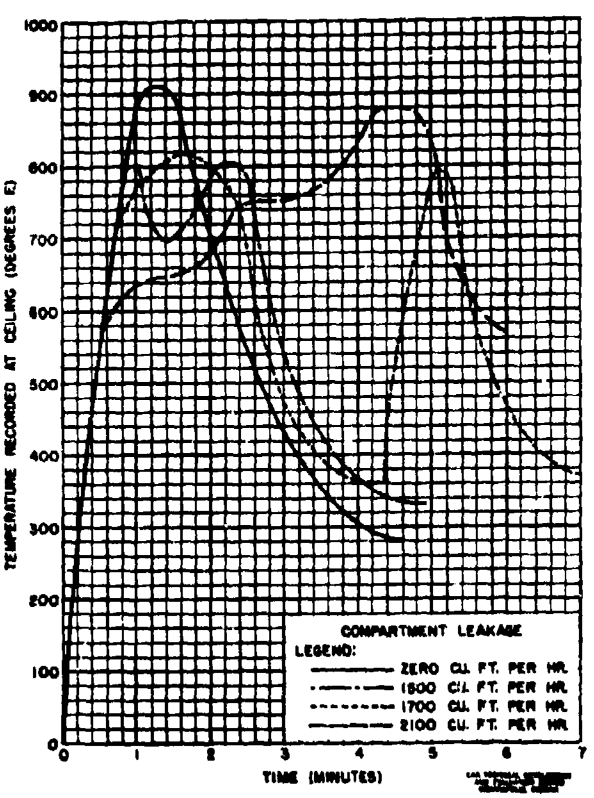

Fig. 23 Ceiling Skin (0.020 Al.) Temperatures vs. Time

came a smoldering mass. This smoldering condition persisted if the air-leakage rate was 1,500 cubic feet per hour or less.

Table III briefs the results of 40 tests conducted using a 12- by 12- by 12-inch cardboard box filled with excelsior and match ignited. This arbitrary selected fire was assumed to be the most dangerous or severe condition which could exist within an aircraft baggage compartment. Such a fire simulates the end condition of any deep-seated clothing fire that had smoldered for a long period of time prior to breaking through the luggage surface and producing an open flame. The size of the arbitrary test fire affects the values as presented in Table III. If a larger fire had been selected, the results would have indicated that higher air-leakage rates would have proved safe. Conversely, if the test fire had been smaller, the results would have shown that lower air-leakage rates would be required for safety. Obviously, an extremely small fire could flame for a very long period even with low air-leakage rates. It is believed, however, that fires of such small size could not be considered as hazardous. Review of Table III will indicate that definite fire control is attained up to air-leakage rates of 1,500 cubic feet per hour. Between 1,500 and 1,800 cubic feet per hour air-leakage rates, the flaming of the fire alternates with the smoldering condition. Above 1,800 cubic feet per hour air-leakage rate, most fires will continue flaming.

TABLE III

Effect Of Air-Leakage Rate On Open-Type Baggage Fires

Test Series	Compartment Volume Cu. Ft.	Leakage Rate Cu. Ft/Hr	Open Flame			Time for Flame Suppression (min.)
			Suppressed	Intermittent	Continuous	
1	48	0	X			1
2	110	0	X			2 1/2
3	270	0	X			1 1/2
4	48	1500	X			2
5	110	1500	X			3
6	110	1500	X			2 1/2
7	110	1500	X			3
8	110	1500		X		
9	48	1680		X		
10	48	1900			X	
11	48	1900			X	
12	110	1900			X	
13	110	2100			X	
14	110	3600			X	
15	110	3600			X	

During the first few tests conducted on the V board lining mounted in the quarter of the 270-cubic-foot compartment, extremely large quantities of pungent gases and smoke were emitted. This was due to the disintegrating of the bonding material used in the V board. However, the remaining glass cloth continued to afford protection to the aluminum ceiling and prevented its temperature from exceeding 550°F during any of the fire tests which included various air-change rates from 0 to 3,700 cubic feet per hour.

Tests on the fire-retardant, paint-covered ceiling panels gave results which indicated that Albi RX paints give approximately the same protection against severe excelsior fires as the V board. The results of the tests on the Albi RX coated panels are given in Table IV.

These results indicate that the water base Albi RX provides considerably more protection against heat than the oil base; however, the water base paint must be coated with a fire-retardant paint with good weathering qualities if similar resistance to weathering is desired.

The tests conducted on insulating materials to estimate their fire resistance indicated that Refrasil is capable of preventing penetration by any fire originating from aircraft fluids for a period of over one hour. Other materials such as V board, fiberglas wool or Silicone PC XL-33 were penetrated by the 2,000°F oil-burner fire within approximately one minute or less.

Conclusions

From the tests which have been conducted, it is concluded that:

1. A completely sealed compartment will prevent any large or dangerous flame from existing for more than a few minutes.
2. The maximum ceiling skin temperature is not materially affected by the volume of the compartment.
3. The volume of a compartment, with no leakage, directly affects the time required to reduce the open fire to a smoldering condition.
4. The quantity of air injected into a compartment, regardless of the compartment size, determines the maximum size of the fire that can continue to burn.

TABLE IV

Fire Insulating Properties Of Albi RX Coatings

No. of Coats of Albi RX (oil base)	Leakage Rate Cu. Ft/Hr	Maximum Skin Temperatures
none	0	900
1	0	800
2	0	600
4	0	525
none	3700	900
2	3700	690
4	3700	600
4 (water base)	3700	295

5. A compartment lined with Refrasil, or its equivalent, will prevent spread of any Class A fire to other parts of the aircraft, regardless of the air flow through the compartment.

6. A compartment lined with V board or Albi RX (water base) insulating paint can protect airframe structures from overheat due to any Class A compartment fire if the air flow through the compartment does not exceed 1,500 cubic ft/hr.

7. Class A fires in a smoldering condition (not producing visible flame) can burn for an indefinite period of time, even if the leakage rate approaches zero.

APPENDIX I

Recommended Method for Measuring Baggage Compartment Leakage Rates

Early in the test program, it was determined that actual air-leakage rates, as established by air-flow measurements through a calibrated thin plate orifice, differed markedly from those determined by means of the carbon-dioxide dilution rate curves shown in Fig. 21. The explanation for this difference can be illustrated by a review of Figs. 24, 25 and 26.

The curves shown in Fig. 24 were obtained when the compartment air-leakage rate was produced by withdrawing air in measured quantities from the compartment. The curves shown in Fig. 25 were obtained when the air-leakage rate was produced by measured quantities of air being pumped into the compartment. The curves in Fig. 26 were obtained when air and carbon dioxide were being withdrawn from the compartment, but with a 1/3-horsepower fan operating within the compartment so that the carbon dioxide and air were continually mixed, thus eliminating the stratification normally present.

Examination of the three sets of curves indicates that, when air-volume changes are produced by withdrawing air-carbon-dioxide mixtures from the compartment, extremely erratic carbon dioxide concentration curves can result. This is due to the stratification of the air and carbon dioxide within the compartment. The same condition exists when air is pumped into the compartment, but to a lesser degree, due to the increased turbulence of the air flow. Only when a mixing device, such as a fan, is used in conjunction with the measurement of air-leakage rates within a compartment can a reasonably homogeneous mixture be obtained such that the theoretical carbon dioxide concentration curves can be relied upon for determining the actual air-leakage rates. Therefore, it is recommended that the following method be used for determining baggage compartment air-leakage rates:

1. Prepare the empty compartment for test by installing the largest possible fan or blower and air-carbon-dioxide pickups in the compartment. The fan should be installed so as to provide maximum mixing of the air and carbon dioxide. Tests have indicated that a single air-carbon-dioxide pickup at the center of a compartment volume is adequate, but more pickups may be used for purposes of corroboration. The pickup leads should be connected to a gas analyser, preferably a continuous reading type, such as the Ranarex or Englehardt instruments.

2. Inject, at a reasonable discharge rate, sufficient carbon dioxide to provide a carbon dioxide concentration within the compartment of 70 to 80 per cent. The quantity of CO_2 required can be calculated as in the following example, making use of the curves shown in Fig. 27.

Assuming that the baggage-compartment volume is equal to 270 cubic feet, and knowing that 1 pound of carbon dioxide equals 8.1 cubic feet free volume: Find the weight of carbon dioxide required to attain an 80 per cent carbon dioxide concentration immediately after discharge.

From the abscissa of Fig. 27, read "required percentage CO_2 remaining in space" — 80 per cent. Follow the vertical line from 80 per cent until it intersects Curve A. From the point of intersection with Curve A, move across to the ordinate on the left and read "per cent CO_2 injected into the space" = 160 per cent.

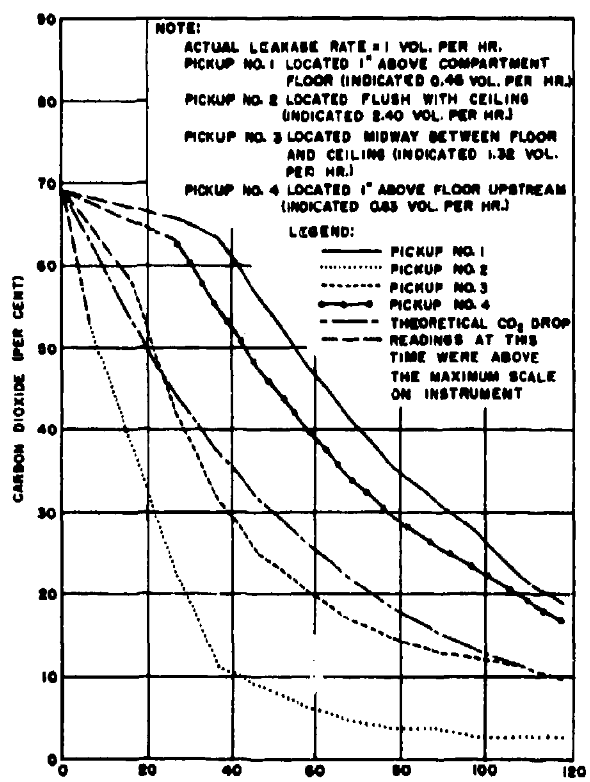

Fig. 24 CO_2 Concentration Drop vs. Time (Volume Change Rate Due to Withdrawing Air Samples From the Compartment)

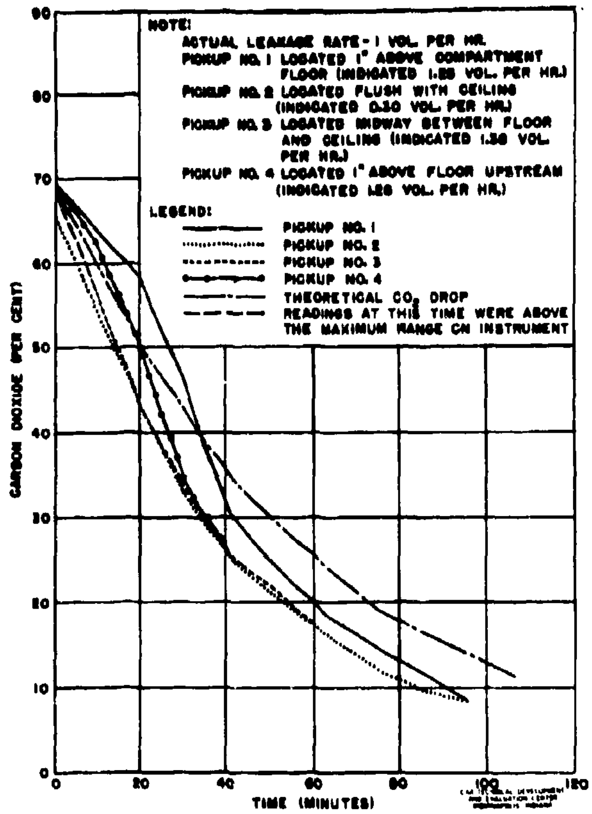

Fig. 25 CO_2 Concentration Drop vs. Time (Volume Change Rate Due to Injecting Air into the Compartment)

Then

$$\frac{1.6 \times 270}{8.1} = 53.4 \text{ pounds } CO_2$$

The ordinate on the right indicates the remaining oxygen percentage for any known CO_2 concentration. For example, with an 80 per cent CO_2 concentration (the abscissa), determine the intersection of the vertical line through 80 per cent with Curve B. Reading horizontally to the ordinate on the right will indicate an oxygen concentration of approximately 4 per cent.

Note: The continuous reading gas analyzer should not be operated at the time the CO_2 is discharged, because the agent pressures involved may indicate higher than true carbon dioxide concentration readings. The instruments should be operated only after the carbon dioxide has been completely discharged.

3. Determine the CO_2 concentration changes by recording the maximum CO_2 concentration shortly after the CO_2 discharge (zero time) and record the decreasing CO_2 concentrations at reasonable time intervals, until a minimum CO_2 concentration of 40 per cent is attained or record the CO_2 concentration after one hour, whichever is first. Recordings made at CO_2 concentrations below 40 per cent are unnecessary for determining the air-volume change rate; and can be inaccurate, due to the fact that the CO_2 concentration curve becomes asymptotic to the time scale as the CO_2 concentrations approach zero.

4. Calculate the air-leakage rate, as illustrated in the following example, making use of the curves shown in Fig. 21.

Assume that an initial CO_2 concentration of 80 per cent was attained immediately after discharge, and that 30 minutes later the baggage compartment CO_2 concentration has been diluted to 42 per cent CO_2. Using Fig. 21, locate 80 per cent on the ordinate and follow the curve down to the point where it

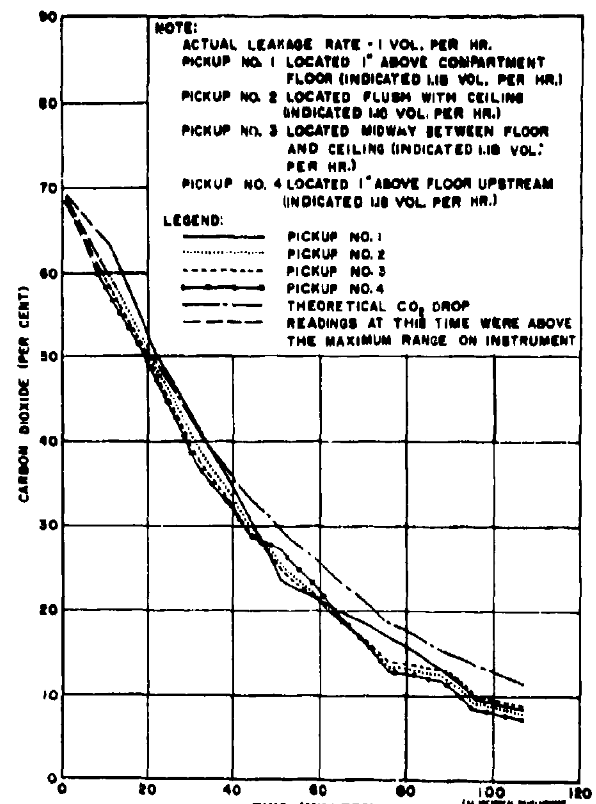

Fig. 26 CO_2 Concentration Drop vs. Time (Volume Change Rate Due to Withdrawing Air Samples From the Compartment with Internal Fan Action)

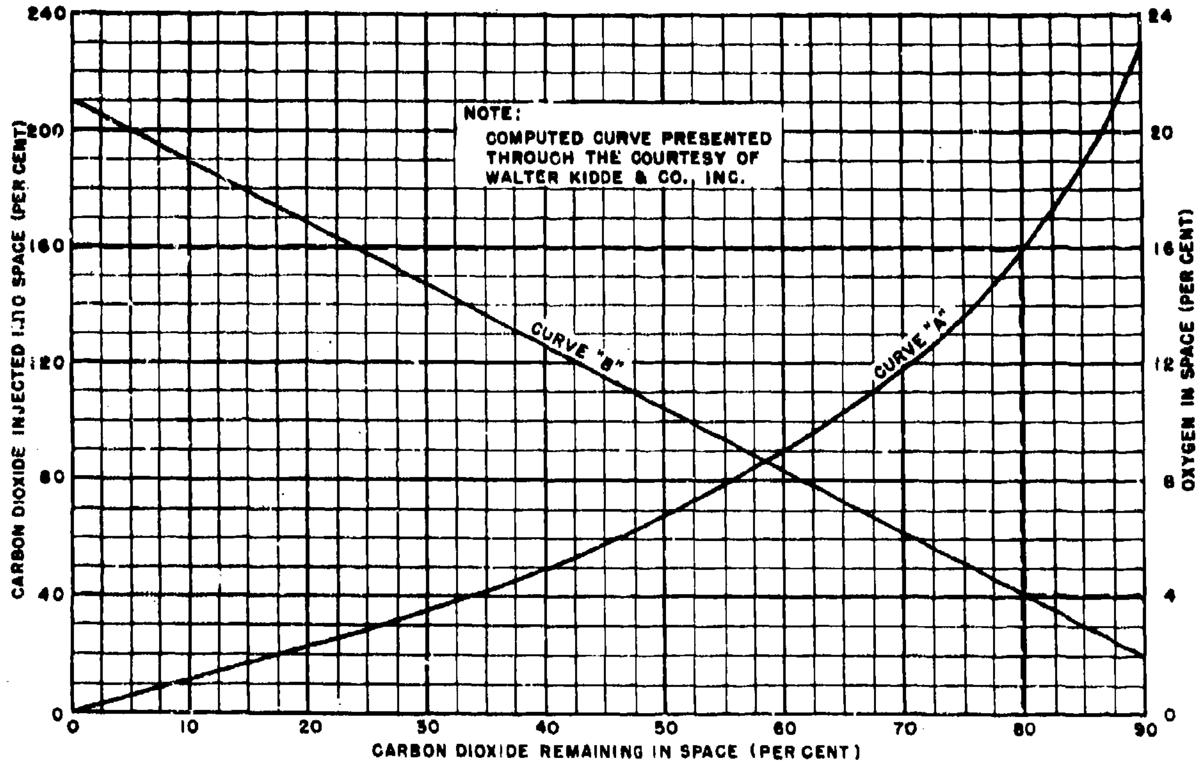

Fig. 27 Computed Curve

intersects a horizontal line through 42 per cent CO_2, as shown on the same scale. From the point of intersection, drop a vertical line down to the abscissa, which in this instance, would read 64 per cent air injection.

Then

$$\frac{0.64 \times 60}{30} = 1.28 \text{ air-volume changes per hour.}$$

The air-leakage rate = 1.28 x 270 = 346 cubic feet of air per hour.