DETERMINATION OF MEANS TO SAFEGUARD AIRCRAFT FROM POWER PLANT FIRES IN FLIGHT

PART V
THE LOCKHEED CONSTITUTION (NAVY XR60-1)

By

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SUMMARY

A full-scale operating XR60-1 Navy Constitution combination of a power plant, nacelle, and wing was subjected to fire tests under simulated flight conditions Five separate investigations were conducted concerning (1) fire detection, (2) fire extinguishment, (3) crew procedure, (4) materials and design, and (5) ignition sources

The detection tests indicated that the system with which the power plant was equipped at the time of delivery, although not adequate, was relatively well designed when it is considered that there was no previous fire testing on power plants of this size and configuration prior to the design The tests showed many ways in which the original system could be improved and also showed that the use of newly developed detectors could result in better and simpler detecting systems

The extinguishing systems in all zones with the exception of Zone 1 proved to be effective A simple and effective system was developed for the power zone, and simpler systems were developed for some of the other zones of the XR60-1 The newer ones involved the use of conventional as well as newly developed extinguishing agents

The essential operations involved in quickly shutting down an engine were determined in order that a simple crew procedure could be formulated for use in time of emergency The procedure recommended in conjunction with the semiautomatic emergency system with which the test power plant was equipped was found to be very effective and was used throughout the test program

From the standpoint of materials and design, the test power plant was superior to those of other existing aircraft Although many shortcomings concerning the use of fire-resistant materials and design were revealed by the tests, the basic and important components of the power plant and nacelle proved to be rugged and highly fire-resistant

The power plant was not particularly susceptible to fire, but the tests showed that under certain air-flow conditions the hot engine exhaust stacks were possible ignition sources and that backfiring could start fires in Zones 1 and 2

In co-operation with the Department of the Navy and the Cornell Aeronautical Laboratory, a short series of tests was conducted to determine the feasibility of using cooled, dried exhaust gases to produce an inert atmosphere in some of the aircraft power-plant zones and thus prevent fires from starting in those zones

INTRODUCTION

The testing of the XR60-1 power plant, as reported herein, is a continuation of the fire studies of representative aircraft power-plant types made by the Technical Development and Evaluation Center of the Civil Aeronautics Administration The last previously published report concerned with these studies was Technical Development Report No 107 [1]

This particular type of aircraft power plant was selected for study because

1 The nacelle was designed with a stainless steel monocoque accessory section
2 The extinguishing system was designed for methyl bromide and included protection for the power section, Zone 1
3 This was one of the first aircraft in which the problem of fire was given detailed consideration during the design stage
4 The power plant is representative of installations incorporating the Pratt & Whitney R-4360 engine which is used in the Boeing 377 and the B-50, as well as in the Lockheed XR60-1

Testing was started in June 1948 and completed in May 1952 The test program included a study of the design and materials used in this power plant, the evaluation of the original fire-detecting system, the development of an improved fire-detector system, the full-scale evaluations of several newly developed fire detectors, the evaluation of the original fire-extinguishing system, the development of an improved fire-extinguishing

[1] Lyle E Tarbell and H R Keeler, "Determination of Means to Safeguard Aircraft from Power-Plant Fires in Flight, Part IV, The Boeing B-29," CAA Technical Development Report No 107, April 1950

system, and studies of proper crew procedure in the event of fire in flight

Supplementary programs were also conducted One such program was concerned with the control of landing-gear fires on the ground by the continued rotation of the propeller directly ahead of a burning landing-gear wheel until outside apparatus could be brought in to extinguish the fire [2] The purpose of the second supplementary program was to make specific recommendations for improving the fire safety of the B-50 airplane The results were contained in a report for limited distribution to the military services A third such program was conducted in collaboration with the Cornell Aeronautical Laboratory, Inc , Buffalo, New York, to determine the feasibility of using cooled, dried engine exhaust gases to render inert the various zones of aircraft power plants [3]

TEST EQUIPMENT AND PROCEDURE

The aircraft nacelle in which the fire tests were performed was the original mock-up of the left outboard power plant for the Constitution XR60-1 It was built and tested by the Lockheed Aircraft Corporation, and later it was used for further tests in the altitude wind tunnel at the laboratory of the National Advisory Committee for Aeronautics at Cleveland, Ohio

The engine was a Pratt & Whitney 28-cylinder R-4360-P183 modified from a -18 series to a -22W and was capable of developing 3000 horsepower (hp) at 2700 revolutions per minute (rpm) It was equipped with a Stromberg PR-100B3 injection carburetor and an exhaust-driven General Electric Type BH3 turbosupercharger The propeller was a Curtiss Electric Type C644S-A24, having four blades cut off to a diameter of 16 feet 8 inches Aft of the engine was a large accessory section having a gross volume of 190 cubic feet Wing stubs extended on either side of the nacelle for a total span of 19 feet

Many improvements had been incorporated in the R-60 aircraft power plants by the time the fire testing began The improvements believed to have a bearing on the fire problem were made in the test article Included among these was the installation of an auxiliary fire wall located midway between the diaphragm and the main fire wall It contained a folding door which permitted personnel access to the rear of the engine via a passageway through the wing The installation of this fire wall divided the original accessory section into two parts, Zones 2 and 3

The nacelle consisted of several zones The power section, Zone 1, extended from the propeller to the air-seal diaphragm just aft of the cowl flaps Zone 2 extended from the diaphragm to the auxiliary fire wall Its gross volume was approximately 80 cubic feet, but because it contained many accessories, its net volume was approximately 60 cubic feet Zone 3 extended from the auxiliary fire wall to the main one Its net volume was approximately 48 cubic feet Zone 4, located beneath Zones 2 and 3, contained a turbosupercharger and several ducts Its gross volume was approximately 62 cubic feet

The nacelle was mounted on structural members at the ends of the wing stubs so that its center line coincided with that of the wind tunnel and air from the wind tunnel provided simulated flight conditions A view of the installation in the wind tunnel is shown in Fig 1

All fire procedures for the tests depended on the operating conditions which were to be simulated, such as taxiing, flight with emergency action, and flight without emergency action Starting operation was simulated by opening the cowl flaps wide and running the engine at 1450 rpm with no air supplied by the wind tunnel Adding a small flow of air from the tunnel changed the starting operation to simulated taxiing During simulated flight the tunnel was operated at higher air speeds, and the cowl flaps were maintained in nearly closed position while the engine was operated at 1800 rpm or higher at 150 brake mean effective pressure (bmep) to produce 1480 brake horsepower (bhp) or more Usually, when extinguishment of fires was to be attempted, emergency crew action was initiated This involved stopping the engine, feathering the propeller, turning off flammable-fluid valves, and opening the cowl flaps In some tests, the emergency action was not initiated in order to determine the relative importance of the action in extinguishing fires

Fires were repeated at various points of origin to ascertain that the fire-detecting and extinguishing systems were adequate to

[2] Lyle E Tarbell and Burnett C Street, "Determination of the Air Speed Required to Control Landing-Gear Fires," CAA Technical Development Report No 100, December 1949

[3] H W Naulty, "The Elimination of Aircraft Fuel Tank Fire Hazards (Nacelle Inerting)," Cornell Aeronautical Laboratory, Inc , Buffalo, N Y , Report No V-449-D-3, June 25, 1949

cope with any emergency likely to occur The systems were constantly revised to obtain a maximum of effectiveness Only by studying a large number of fires under a wide variety of conditions could dependable answers be obtained, with so many variables present

To establish the location of detector systems or other equipment in Zone 1, a reference line for radial or longitudinal measurements was adopted, namely, the outside forward edge of the cowl support ring Circumferential locations were designated by cowl-flap numbers or by cylinder numbers The cowl flaps were numbered from one to eight starting at the lower left side of the nacelle (viewed from the rear) and continuing in order over the top of the nacelle to the lower right side The cylinders were designated by numbered rows in a clockwise direction and by lettered banks from rear to front Cylinder 1A is at the top rear of the engine The rows of cylinders are not in a straight line, they twist in a clockwise direction from back to front. This characteristic is evident in any of the illustrations showing the bare engine

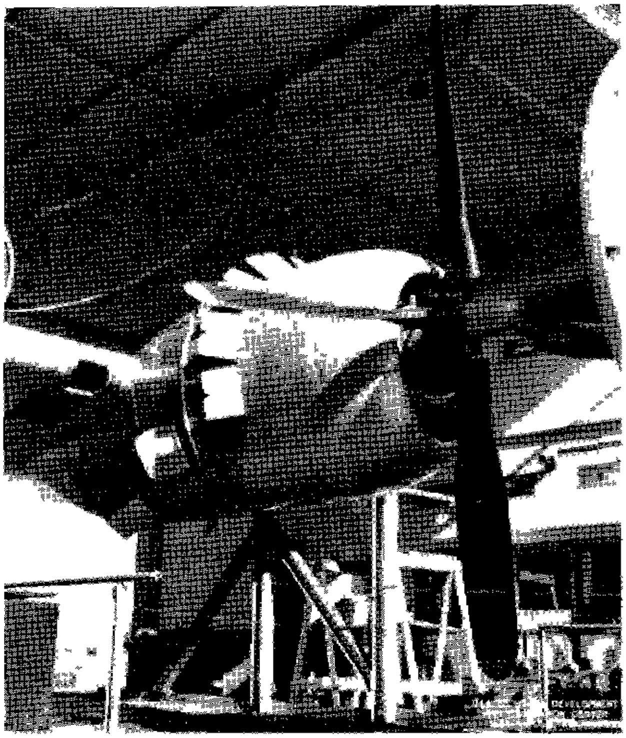


Fig 1 The XR60-1 Constitution Test Nacelle

DETECTORS

Purpose

The three main objectives of the fire-detector program were (1) to evaluate the detector system installed in the test installation, (2) to find the optimum locations for fire detectors, and (3) to test new types of fire detectors under full-scale conditions

Test Procedure

Before any fire tests were conducted in the nacelle, a temperature survey was made of all zones to determine the normal ambient temperatures and the maximum ones to be expected from engine operation alone Such information is useful both as data for the design of fire detectors and as a guide for presetting certain types of fixed temperature detectors

A later survey was conducted using small fires to trace the path of flames from the point of origin in a zone to the point of exit from it Thermocouples, arranged in gridlike patterns, were placed in the regions through which the flames appeared to pass Study of the temperatures on the grid pattern revealed where fire was concentrated and indicated optimum detector locations

The test nacelle (as received) incorporated a Thomas A Edison, Incorporated, Type A fire-detector system which was similar to that used in the R-60 aircraft The system was evaluated immediately so that the test results might be used to improve the R-60 aircraft After first consideration had been given to the evaluation of the original Edison system, newly developed detectors were evaluated and optimum locations for each new system were determined

Test fires were started in the nacelle by igniting gasoline or oil piped to any selected point through flexible lines As the fire fuels left the ends of the lines, they were ignited by a spark-plug ignitor Solenoid valves located near the ends of the fluid lines provided positive control of the fluid flow

Small gasoline fires, called standard detector fires, were used in Zone 1 These were not large enough to be immediately damaging, but they were large enough so that they should have been detected promptly The size of these fires was arbitrarily established by burning 100-octane gasoline discharged at a rate of 0 28 gallons per minute (gpm) Hydraulic fluid was burned at rates of 1/4 to 1/2 gpm, and oil was burned at rates of 2 to 4 1/2 gpm To facilitate ignition, a small gasoline fire usually was ignited first, then either gasoline, hydraulic fluid, or oil was introduced in the quantity desired Oil for test fires was preheated to approximately 200° F

In preparation for fire tests, the detectors were arranged in the nacelle in

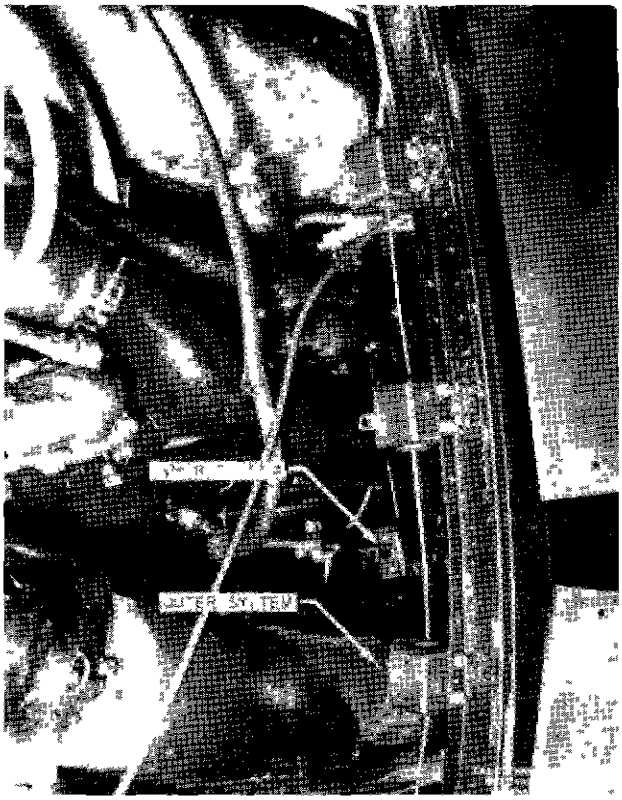


Fig 2 View of Inner and Outer Systems of Edison units

accordance with observed data on flame paths Then standard fires were started at selected locations within the zones where detectors were located During each test, every important occurrence was recorded the activation of the ignitor, the release of the gasoline, and the detection of the fire by each system of fire detectors At the conclusion, a complete record was available showing both the sequence in which the operations occurred and their duration Records of the maximum temperature and rates of temperature rise at selected points were used in interpreting the results

Detectors Tested

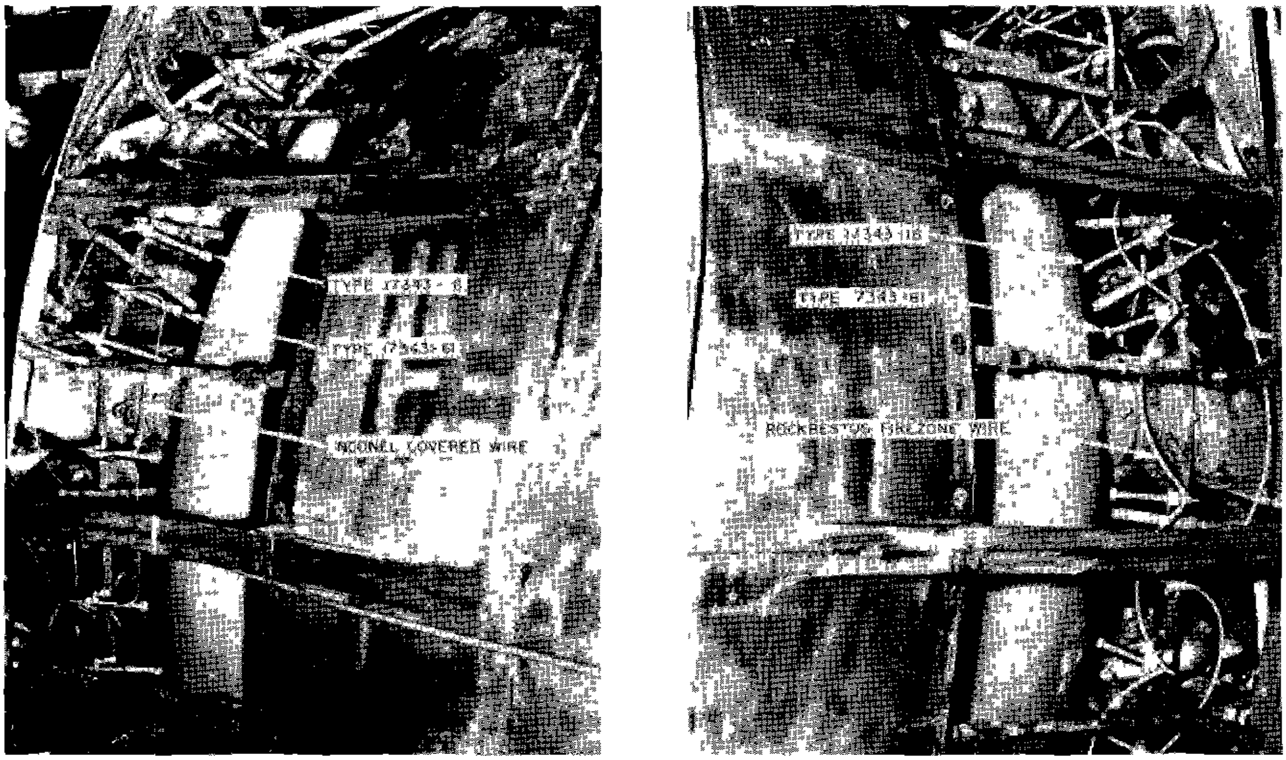
The Edison Type A aircraft fire-detection system consists essentially of thermocouples connected in series and a relay-panel unit Each thermocouple comprises a pair of dissimilar metal wires with the external ends twisted and welded together to form the hot junction and the internal ends the cold junction confined within a hollow plastic, steel-covered base At the cold junction the wires of the element are attached to terminal screws which extend outside the base for the purpose of making electrical connections The relay-panel unit contains the sensitive relays, thermal test units, resistors, and slave relays required to transform the tiny electrical current generated by a rise in temperature at a detector unit (or units) into a warning signal The system operates only when subjected to an abnormal rate of rise of temperature Fig 2 shows Edison units mounted around the engine for one series of tests

The Fenwal fire-detecting system, manufactured by Fenwal Incorporated, is composed of individual detecting units connected in parallel The power supply and the alarm light, or warning device, are connected in series The detecting unit consists of a stainless steel tube with closed ends inside of which two metal struts with a low expansion coefficient are bowed apart by compression Each strut carries a silver contact, but one of the contacts is insulated from its strut and is connected by means of insulated wire to the terminal Where the wire passes through the sealing head, a hermetic seal is made The other contact is grounded through its strut and through the outer shell and mounting flange

A rise in temperature causes the outer shell to expand and to reduce the compression on the metal struts allowing the contacts to meet when the preset temperature is reached Two types of Fenwal detectors, both of which are shown in Fig 3, were used in the tests These were the Model 17343-61 which is currently used as a fire detector and the Model 17343-16 which was designed to be used as an overheat detector For the tests, all of the former units were preset at the factory to alarm at 450° F and all of the latter type which incorporate an adjustable feature were preset in the laboratory to alarm at 425° F

The Dittmann fire-detecting system, Fig 4, is a heat-actuated, continuous type of system based on a liquid and vapor expansion principle It consists of a liquid-filled tube of any reasonable predetermined length and a control box containing compensators, bellows, accumulator, and switches The tube tested was 20 feet long, but tube lengths can be varied When exposed to high temperatures or when the test button is actuated the liquid in the element vaporizes rapidly, expands, and actuates the fire alarm signal When the temperature is reduced or when the test button is released, the fluid returns to its liquid state and the device automatically resets itself The normal operating voltage is 28 volts direct current (d-c), although any voltage within the switch rating may be used

Another type of heat-actuated, continuous, resetting fire detector (Fig 5) is manufactured by the Walter Kidde & Company, Inc



(A) VIEW OF LEFT SIDE — DETECTORS CONNECTED BY INCONEL-COVERED WIRE (UNIFORM TUBES)

(B) VIEW OF RIGHT SIDE — DETECTORS CONNECTED BY ROCKBESTOS FIREZONE WIRE

Fig 3 View of Fenwal 17343-16 and 17343-61 Types Mounted on the XR60-1 for Tests

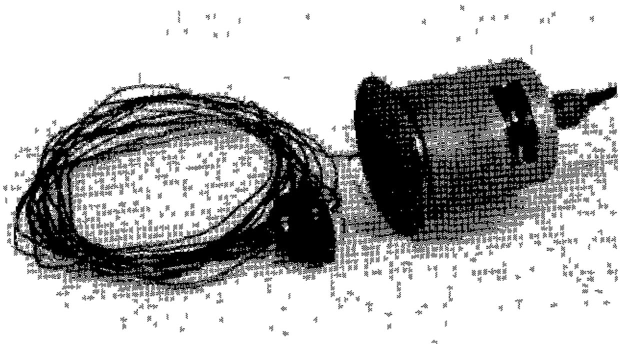


Fig 4 The Dittmann Continuous Fire Detector

A complete fire-detecting system of this type for an average installation consists of one or more detecting elements and an electronic control unit, a signal lamp, and a test switch The sensing element consists of a pair of wires separated and surrounded by a ceramic insulator, which in turn is encased in a thin-walled Inconel tube of 0 065-inch outside diameter (OD) The insulator, which is physically and chemically bonded to the wires, is in the form of tiny beads which permit bending of the tube When the sensing element is subjected to normal temperatures, the insulator offers high resistance to the flow of current between the two conductors As the temperature increases, the resistance of the insulator drops rapidly and permits a flow of current between the two wires This flow increases with a rise of temperature, and the alarms are actuated when a predetermined temperature is attained When the temperature returns to normal, the resistance of the insulator is restored and the alarms automatically shut off The sensing element comes in lengths up to 20 feet, however, coupled elements can be used in conjunction with each control unit in lengths up to 100 feet

The power required to operate the detector is 115 volts, 400 cycles per second (cps), single-phase alternating current (a-c) Normal operating consumption is approximately 8 watts, but during a fire alarm the consumption increases to approximately 30 watts

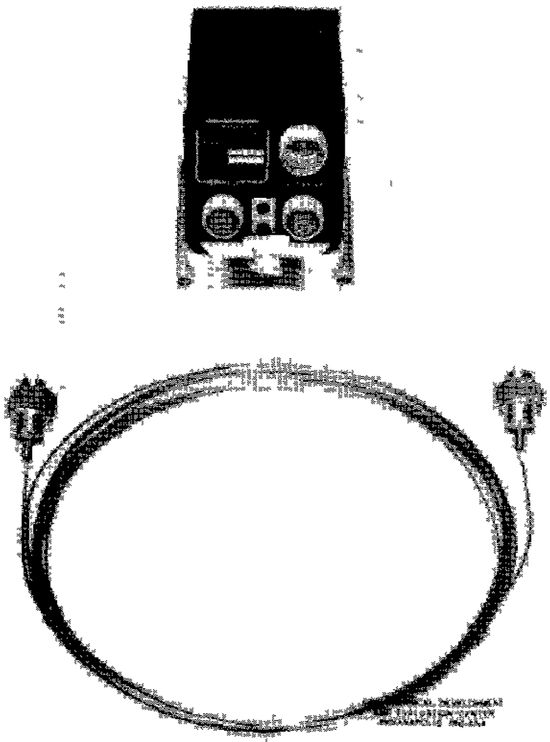


Fig 5 The Kidde Continuous Fire Detector

The test switch consists of a single-pole, single-throw (SPST) switch, normally open with spring return When the switch is operated, it makes an electrical connection between the two conductors at their extreme ends thus testing the entire detector system

The ATMO fire detector, Fig 6, is a product of J H Scharff, Incorporated It is a continuous, heat-actuated, resetting detector which operates on a different principle than the Kidde or the Dittmann detectors The detecting element consists of a length of

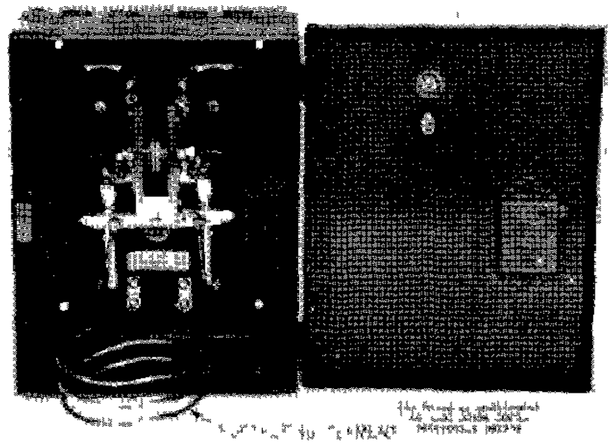


Fig 6 The ATMO Fire Detector

Inconel tubing filled with air at atmospheric pressure Both ends of the tubing are connected to a receiver When heat is applied to the tubing, the air in the tube expands through the compensator, breathers, and diaphragms A moderate rate of expansion is absorbed, but excessive rates of expansion are used to close two contact points and complete an electrical circuit When the sensing element is cooled, the air in the tube returns to normal pressure and the device resets

The Adams detector, Fig 7, designed and fabricated in a limited quantity by Mr Charles J Adams is, in effect, a combination unit and continuous type detector This detector consists of a small metal case with two tubes projecting from opposite sides The case is 1 3/4 inches in diameter and 5/8 inch deep The tubes are 2 feet long and 3/32 inch in diameter Each of the tubes contains a solid metal rod having a coefficient of heat expansion less than that of the tube The rods are attached to the outer ends of the tubes and extend through the tubes into the

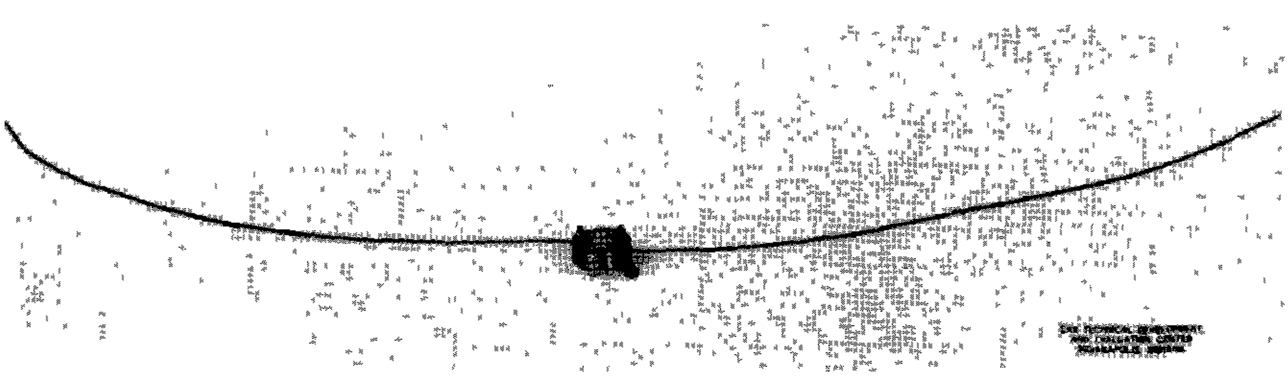


Fig 7 The Adams Fire Detector

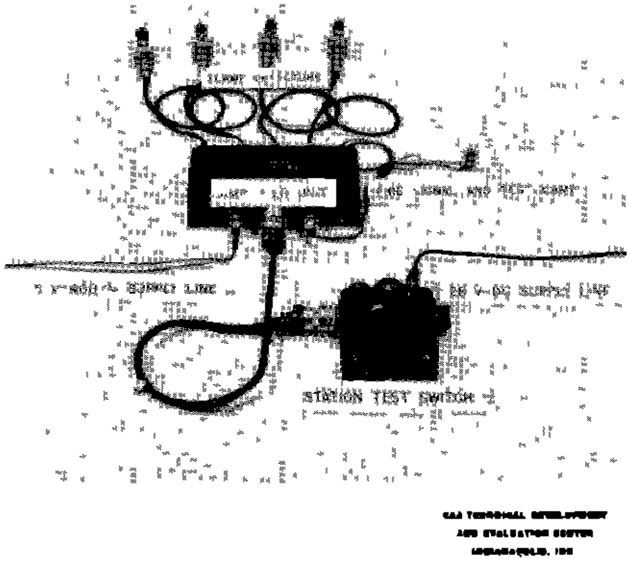


Fig 8 The FD-2 Fireye Detector System

case Inside the case, the two rod ends are attached to the periphery of a disc at points 180 degrees apart, so that equal-and-opposite movement of the rods produces rotation about the center of the disc, while unequal movement displaces the disc laterally Lateral displacement depresses a metal ball located at the center of the disc A predetermined amount of depression causes a contact to close and complete an electrical circuit

Equal heating of each tube produces equal expansion and causes the disc to rotate without effect Unequal heating of the tubes produces unequal expansion, and if the differential is sufficient, the resulting action of the disc and ball closes an electrical circuit and energizes a warning signal To assure complete coverage of a hazardous space the prescribed method of installation is to overlap the tubes of adjacent units

The Fireye aircraft fire-detector system, Fig 8, is a development of Photoswitch Incorporated, now known as Fireye Corporation An early model of this detector, known as Type P, used a cesium phototube enclosed in a cadmium-plated steel shell as the detecting unit A window in the shell allowed light to enter and impinge on the phototube after being filtered through infrared transmitting glass in order to discriminate against daylight While the unit was only moderately affected by daylight, it could not tolerate direct sunlight As a result, units had to be installed in aircraft in such a manner that sunlight or other strong light could not shine directly on them

Some improvements are incorporated in the later Model FD-2 which is designed to operate on a different principle than its predecessor Instead of being sensitive to steady light, it is sensitive only to the flicker inherent in a flame, which is modulated light of low frequency

The detector of the FD-2 system is essentially a lead sulfide layer type of photoelectric cell sensitive to both the infrared and visible range of the light spectrum An electrical signal generated in the cell is amplified by an amplifier whose peak response is at approximately 10 cps The output of the amplifier is fed into a limiter circuit which limits strong signals to a value that is comparable to the voltage from a weak one

A discriminator circuit operates from a series of pulses which must be fed into it at a rate corresponding to the flickering frequency of a flame in order to operate the amplifier which in turn operates the fire signal

The system incorporates a test switch to provide properly modulated electrical impulses to the test lamps in each Fireye unit, thus making it possible to check the entire system operation at any time

According to the design specifications, the unit is suitable for operating in ambient temperatures up to 220° F Temperatures in excess of this resulted in reduced sensitivity of the unit and made it difficult to obtain operational checks of the system by means of the test switch Although the design specifications limit the voltage variation for successful operation to 110 to 120 volts, it was capable of operating between 100 and 130 volts

Test Results and Discussion

A temperature survey was made prior to the initiation of detector tests while the engine was operated at 1200 bhp at 1450 rpm, 150 bmep and while the wind tunnel supplied air to the installation at 90 miles per hour (mph) The significant temperatures and the rates of temperature rise measured on an 87° F day are given in Table I During the period when the engine was being warmed up, the temperatures increased at a moderate rate at all points where detectors would be mounted

After operating conditions had reached a steady state, they were changed by the use of the propeller to simulate stopping and backing of the airplane These conditions were produced by reversing the engine propeller and simultaneously stopping the air blast from the tunnel The temperature rose

TABLE I

MAXIMUM TEMPERATURES AND RATES OF TEMPERATURE RISE IN XR60-1 POWER PLANT

Simulated Ground Maneuvers with Ambient Air Temperature 87° F

Region	Maximum Temperature		Maximum Rate of Temperature Rise	
	Simulated Taxiing (degrees F)	Propeller Reversal (degrees F)	Reverse (degrees F per minute)	Forward (degrees F per minute)
Lower left cowl flap	225	250	-	750
Top cowl flaps	190	280	450	1100
Lower right cowl flap	240	250	-	975
Zone 2	155	190	-	-
Zone 3	145	145	-	-

at a rate of 450° F per minute near the top cowl flaps and continued at this rate for eight seconds Changing the propeller from reverse to positive thrust (forward) caused the temperature to rise again at a rate of 1100 degrees per minute for at least five seconds These rates and durations of temperature rise did not cause the Edison system to alarm

The temperature survey was followed by tests of the Edison system A wiring diagram of the original system is shown in Fig 9 It was divided into three parts one was used exclusively for the protection of Zones 2 and 3, and each of the others was used for the protection of one-half of Zone 1 and one-half of Zone 4 The units located around the exhaust collector were attached to the cowl support ring One hundred ninety-seven fires were started at eight different places around the engine while flight and ground operating conditions were simulated Most of the fires were detected during normal flight conditions Very few were detected when the flaps were wide open, a condition which might occur in ground operations Fire detection improved as the cowl-flap opening decreased

The poorest detection occurred when fires originated near the rear row of cylinders on the left side of the engine This may have been due to the fact that the air flow carried the flames close to the crankcase as they passed under the cowl support ring or to the fact that the flames passed between detector units which were spaced eight inches apart Closer spacing of the detectors around the engine might have improved the detection of cylinder-head fires

Crankcase fires were more difficult to detect than cylinder-head fires Fig 10 shows that the cylinder-head fires pass very close to the cowl support ring where the Edison detectors were attached, but crankcase fires tend to stay close to the engine crankcase until the cowl support ring is passed It was obvious in these and later tests that the cowl support ring was not the optimum detector location

Fires which started under the middle or forward part of the engine were sensed by the detectors located on the cowl support ring rather than by those mounted on the lower part of the diaphragm This fact is attributed to the configuration of this particular power plant which has cowl flaps extending around the upper portion of the nacelle only Because fires cannot escape from the bottom of the nacelle, they emerge through the existing cowl-flap openings

After further study of the fire paths through the zone, an attempt was made to improve detection by modifications and additions to the original system Two systems of Edison units were installed one was composed of 16 units mounted on the cowl support ring in a similar manner to the original system except that the units were

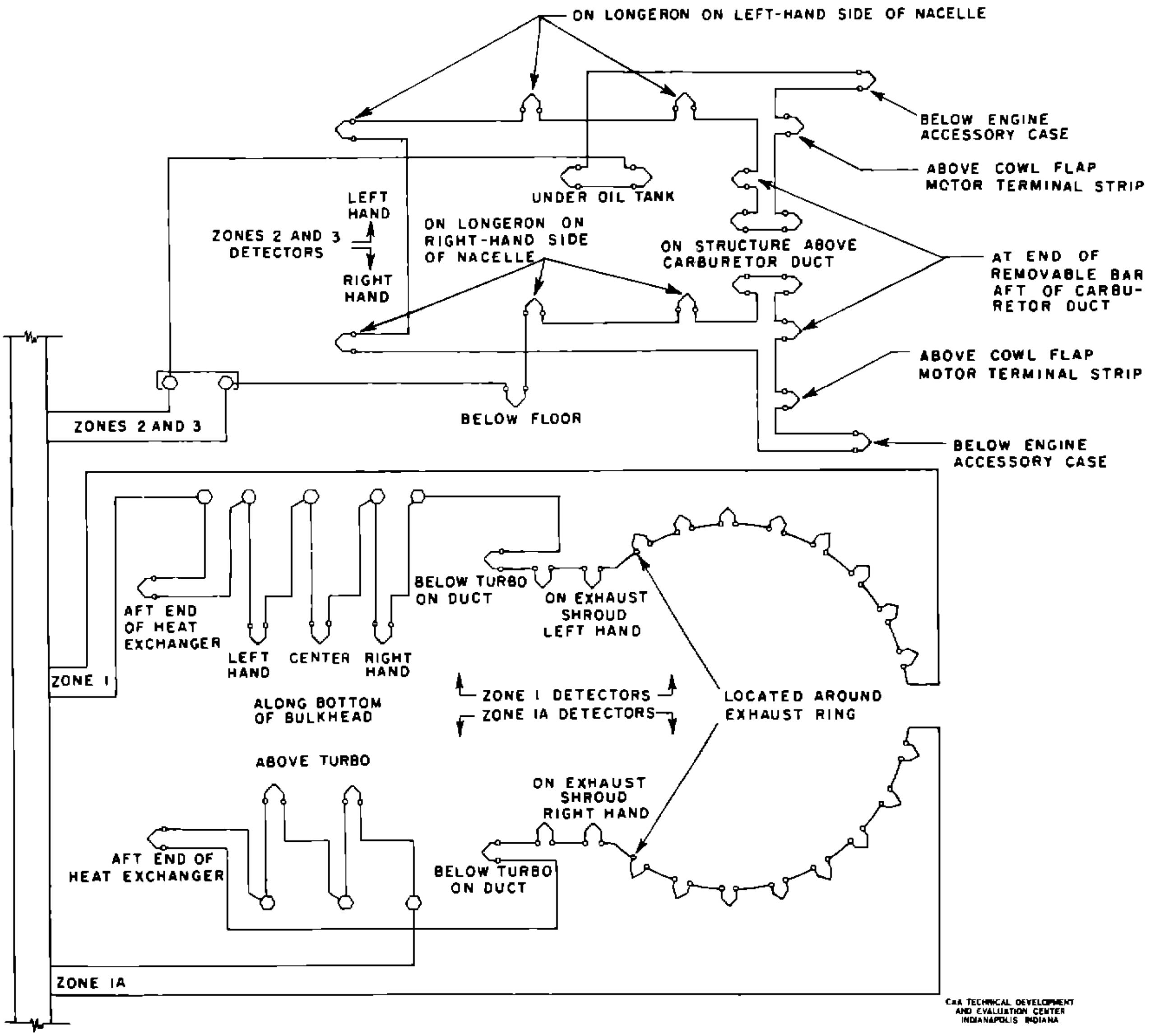


Fig 9 Wiring Diagram of Original Edison System in XR60-1

about 1 1/2 inches closer to the engine, the other was composed of 14 units attached to the engine-mount shields, one on each side of each exhaust stack The latter system was located radially inward about eleven inches and aft about six inches from the reference line established for the location of test equipment The outer system was intended to intercept cylinder-head fires, and the inner one was intended to intercept crankcase fires A few of the units of each system can be seen in Fig 2 Eighty-one tests were conducted with this configuration of Edison units The fires which originated on the crankcase or near the forward three rows of cylinders were detected satisfactorily by either the inner or outer systems However, it was found that fires originating at the rear row of cylinders could escape detection, presumably by passing between the inner and outer systems This led to studies of a more suitable detector location in the cowl-flap area

A detector system mounted on the air-seal diaphragm radially outward from, but concentric with, the exhaust collector ring was subjected to 16 fire tests These tests revealed that the flow of air through the nacelle forces the flames originating anywhere in the power section to move toward the rear

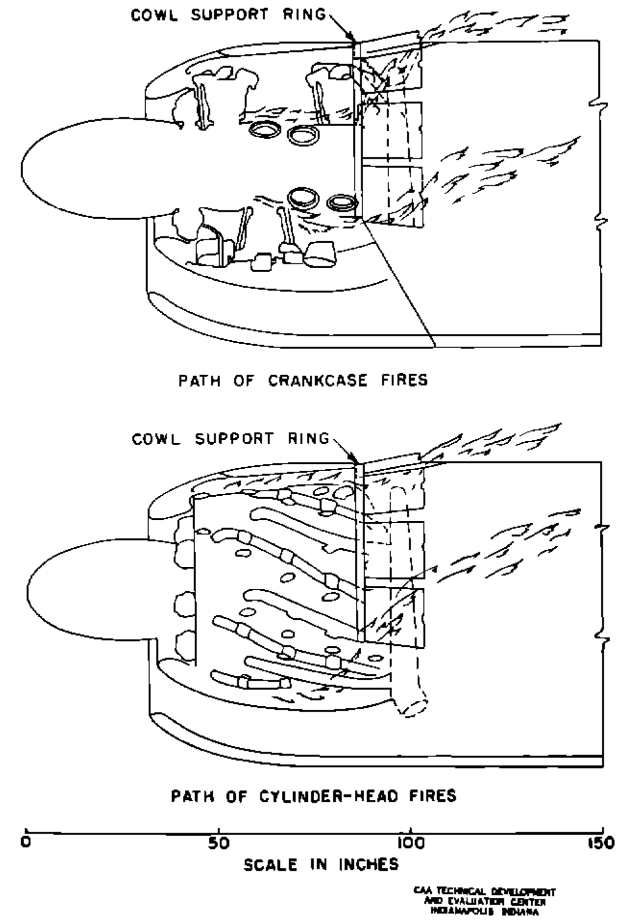


Fig 10 Sketch Showing Path of Engine-Section Fires

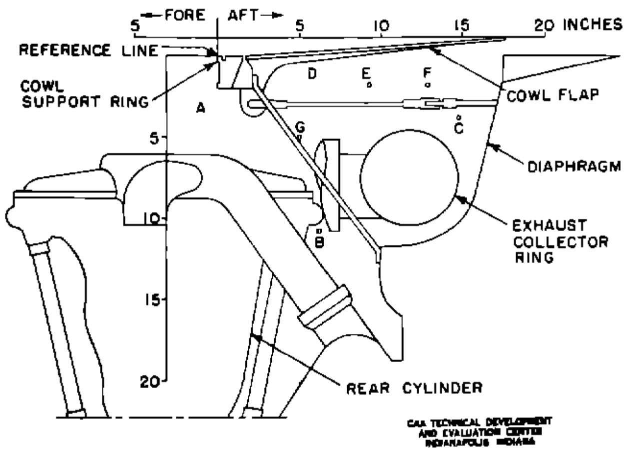


Fig 11 Sectional View Through Cowl-Flap Region Showing Relative Locations of Detector Systems Subjected to Tests

of the engine and out of the cowl-flap openings Since the cowl flaps are open only slightly in normal flight, the flames are constrained to travel to the diaphragm before they can escape However, when the cowl flaps are open wider than normal, and especially during take-off or taxiing operations, engine fires may not proceed as far as the diaphragm and therefore may not be detected The region close to the diaphragm was not considered to be a suitable location for detectors

The area of best detection under all conditions appeared to lie in the cowl-flap area somewhere between the cowl support ring and the diaphragm The relative positions of these two regions and others which were tested are indicated in Fig 11 The three positions designated as D, E, and F were tested simultaneously The detector located at E detected 81 of 84 fires in this series, and the three failures occurred under the improbable condition of flight with the cowl flaps wide open With them open 50 per cent or less, the detector successfully detected all fires Position E was therefore considered to be the best position Position F was next best, and position D the least desirable

Although the optimum location for a heat-actuated detector system is at position E, the scarcity of supporting structure in this area makes the mounting of detectors difficult The braces between the cowl flaps are 15 inches apart and might not provide adequate support Another series of tests was performed to determine whether another region, more conveniently located for mounting but equally effective for detecting fires, could be found The only logical untested place remaining was near the tie rods which connect the cowl support ring with the diaphragm A detector system was attached to these tie rods at position G and was compared to the detector system located at position E during 52 fire tests

The detector system at E was slightly quicker at detecting fires than the one at G On the basis of this, if there appeared to be any advantage in using the tie rods as the mounting structure, the detector could be installed at position G However, the best position was at E and is the one indicated in Fig 12

A study of that part of the Edison system intended for the protection of Zone 4 where the turbosupercharger and heat exchanger were located revealed the need for rearrangement of the detecting units The units were mounted so close to the shrouds and the bulkhead that they failed to intercept the flames of the fires occurring within the

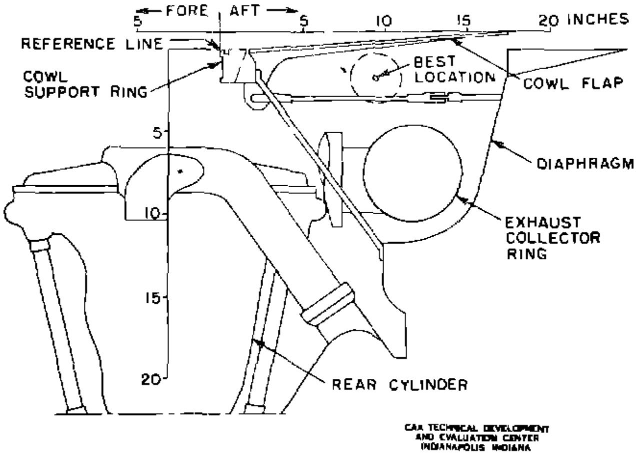


Fig 12 Sectional View Through Cowl-Flap Region Showing Best Detector Location Determined as a Result of the Tests

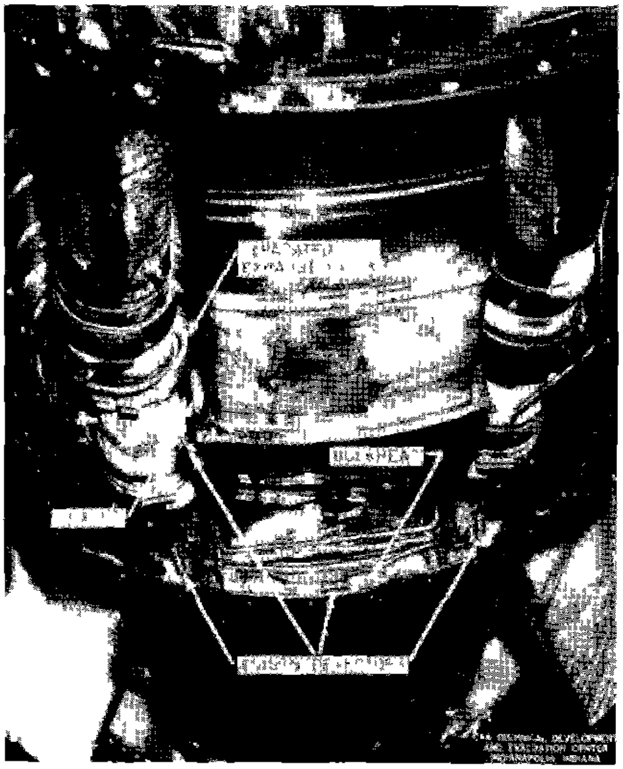


Fig 13 View of Underside of Nacelle with Louvered Access Door Removed

region The units on the bulkhead also failed to detect the leakage of hot exhaust gases during engine operation when a separation was made between two sections of stack near the bulkhead

The efficiency of the system was greatly improved by replacing the three units along the bottom of the bulkhead shown in Fig 13 with four units mounted in the rearmost louver openings on the bottom of the nacelle The location of these units is indicated in Fig 14 Fires emerging from Zone 4 through the louvers are intercepted by units located in this area

The Edison detector arrangements in Zones 2 and 3 were evaluated by fixing thermocouples near the Edison units to measure the rates of temperature rise caused by small fires The Edison system did not operate when exposed to small fires which increased the temperature 20° to 40° F per second, but it did when exposed to larger fires which produced rates exceeding 100° F per second for five seconds or more The results appeared to be satisfactory, and no attempt was made to improve the system in these zones Instead, a general survey of the temperature conditions was made during the fires to obtain data which would be useful in designing any type of detector system for a similar zone through which there is little air flow It appeared from the survey that the best location for detectors which are heat-actuated is at the top of the zone Other desirable locations are across air outlets and near accessories which are possible sources of ignition or of flammable-fluid leaks

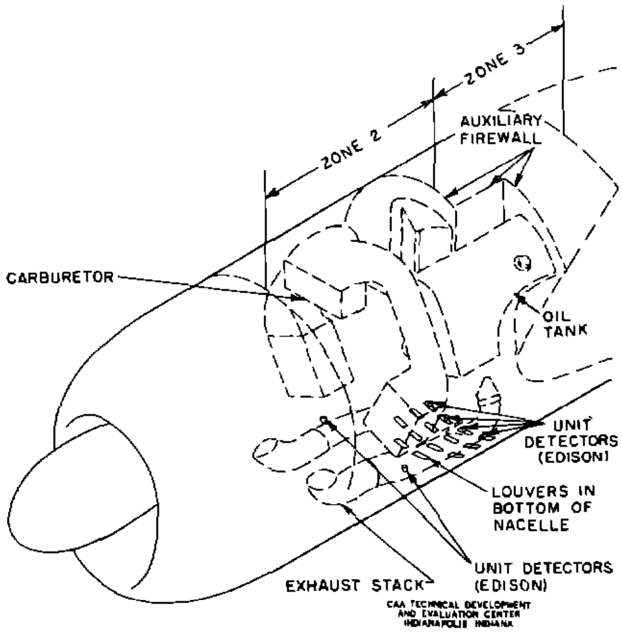


Fig 14 Edison Fire-Detector Test Locations in Zone 4

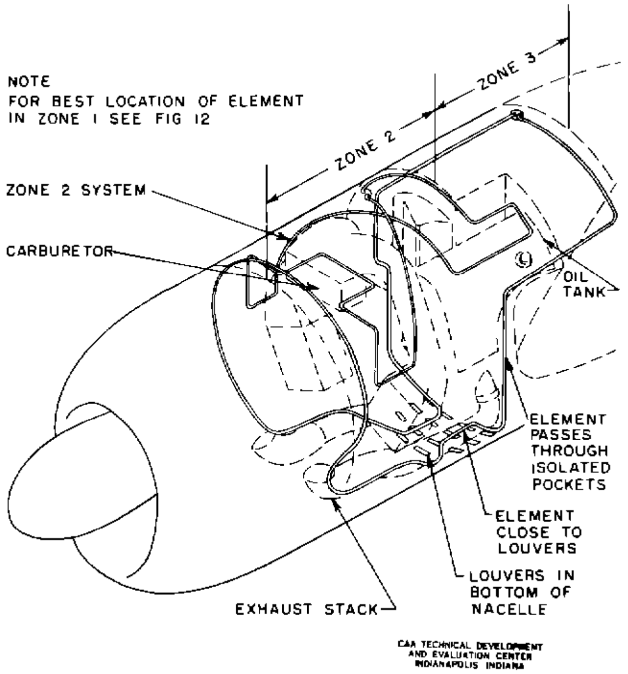


Fig 15 Recommended Routing for a Continuous Fire-Detector System

Much of the testing to find the best locations for detectors in Zones 1 and 2 was accomplished with the aid of Kidde continuous detectors A complete detection system using Kidde elements exclusively would be similar to that shown in Fig 15 This arrangement would protect all zones at points where fires would most probably occur and where flames would tend to egress To facilitate installation and maintenance, the system would be composed of several short lengths of detecting element joined by approved connectors

The effect of the length of the element on the ability to detect fires was determined with three 20-foot lengths Two of the 20-foot lengths were arranged in parallel in Zone 2 in the pattern shown for that zone in Fig 15, and the third 20-foot length was coiled and hung from the ceiling of Zone 3 By coupling the individual 20-foot elements together, lengths of 40 and 60 feet were readily assembled for comparative tests Under simulated flight conditions, fires were started at various points inside of Zone 2 The reaction times of the 20-, 40-, and 60-foot lengths are given in Table II These seem to indicate that long lengths are more sensitive than short ones under the same conditions This is in accordance with the design characteristics and is due to the fact that the total resistance of the insulating material in the element varies inversely with its length

Supplemental tests using these same elements were made in an oven where the temperatures were raised slowly For these tests, the detecting elements were suspended in the center of the oven either in single coils or coupled together as required to form the various lengths The air temperature inside the oven was recorded by a thermocouple, and as each length of element sounded an alarm the temperature was noted Two tests were made of each coil or combined length (1) with the starting ambient temperature of the oven below 200° F, and (2) with a starting temperature above 350° F When tests were conducted on the 40- and 60-foot assembled elements, no attempt was made to determine what effect the relatively large mass of the connectors had on the temperatures at which the elements gave an alarm to indicate fire or at which they recovered to indicate that the fire was out

The results given in Table III show that the trend is for the long elements to alarm at a lower temperature than the short ones, as shown in the previous full-scale tests The recovery temperatures recorded are not strictly comparable because the elements were connected to different channels in the amplifier, which channels may or may not have had the same number of degrees of spread between the alarm and the recovery settings It was found that this spread should be at least 30° F to prevent chattering of the warning signal

The Kidde detector system proved to be highly dependable in every respect It was quick to respond to fire and was singularly free from false alarms In addition, it was strongly built, light in weight, and comparatively simple to install

During the early stages of the fire-detecting program the Type P Fireye system was the only visual detector available Two or three general areas were established in the vicinity of the engine where the detecting units of this system could observe fires and still be shielded from direct sunlight One of these areas was in the cowling surrounding the engine The units were actually imbedded in depressions in the inner liner and directed at the engine Another was on the forward side of the cowl support ring In the latter location the longitudinal axis of each unit was tangent to the ring with the windows of the units facing forward and radially inward to a slight degree Nearly 500 tests were performed using this early version of the Fireye detector system

Later, when the Model FD-2 superseded the Model P, the system for the power section of the XR60-1 consisted of five units attached to the cowl support ring and spaced

TABLE II

RESPONSE TIME FOR VARIOUS LENGTHS OF KIDDE CONTINUOUS DETECTOR DURING FULL-SCALE FIRE TESTS ON THE XR60-1 POWER PLANT

Test No	Fire Fuel	Response Time 20-Foot (seconds)	Response Time 40-Foot (seconds)	Response Time 60-Foot (seconds)	Detector Pattern
1	Hydraulic Fluid	9	8	-	A
2	Hydraulic Fluid	12	11	-	A
3	Hydraulic Fluid	3	2	-	A
4	Hydraulic Fluid	7	6	-	A
5	Hydraulic Fluid	10	7	-	A
6	Hydraulic Fluid	6	6	-	A
7	Hydraulic Fluid	-	-	4	B
8	Hydraulic Fluid	-	-	4	B
9	Hydraulic Fluid	2	2	-	A
10	Hydraulic Fluid	*	1	-	C
11	Hydraulic Fluid	*	6	-	C
12	Gasoline	1	1	-	A
13	Gasoline	5	5	-	A
14	Gasoline	2	1	-	A
15	Gasoline	4	5	-	A

Note Five different points of fire origin in Zone 2 are represented in these tests

A pattern 20-foot length in Zone 2, 40-foot length, half in Zone 2 and half in Zone 3

B pattern 60-foot length with 40-foot portion in Zone 2 and 20-foot portion in Zone 3

C pattern 40-foot length in Zone 2 and 20-foot length in Zone 3

* Fire spread from Zone 2 to Zone 3 and was detected by the 20-foot coil in Zone 3 approximately 15 seconds after the 40-foot element detected the fire in Zone 2

TABLE III

RESPONSE AND RECOVERY TEMPERATURES FOR VARIOUS LENGTHS OF KIDDE CONTINUOUS DETECTOR IN ELECTRIC OVEN

Test No	Element Combination	Length (feet)	Ambient Temperature Below 200° F Response (degrees F)	Ambient Temperature Below 200° F Recovery (degrees F)	Ambient Temperature Above 350° F Response (degrees F)	Ambient Temperature Above 350° F Recovery (degrees F)
1	A	20	500	470	500	460
2	B	20	500	450	500	420
3	C	20	500	425	500	420
4	A & B	40	460	360	425	300
5	A, B, & C	60	410	375	425	350

Fig 16 View of Fireye and Edison Detectors Mounted on Cowl Ring

approximately at equal distances from the center of the lower flap on one side to the center of the lower flap on the other Each pick-up unit was located opposite an intake manifold at the point where the manifold passed beneath the cowl support ring The longitudinal axes of the units were parallel to the longitudinal axis of the engine, and the units were directed to view 45° away from the radial lines directly into the engine Fig 16 shows the Fireyes mounted on the cowl support ring along with Edison detectors which were being tested at the same time The FD-2 Fireye system detected fires started in 13 places on the crankcase and near the cylinder heads Altogether 92 fire tests were performed The reaction time was usually two seconds or less The system afforded the best possible coverage, because the reflection of fire as well as a direct view of the flame would produce an alarm

Unfortunately, the ambient temperature existing in Zone 1 of the XR60-1 was at times in excess of the maximum 220° F temperature for which these units were designed As a result, their sensitivity was reduced somewhat, although not to such a degree that their usefulness was impaired

To determine whether the loss of sensitivity was due in part to the fact that the units viewed the exhaust stacks directly, comparative tests were made in which the units were first directed toward the stacks and then away from them In neither case could a check of the system be made by the test switch after the zone had warmed up to a sufficiently high temperature

Tests were conducted to determine whether the units could detect exhaust-gas leakage from breaks in the exhaust stacks A section of exhaust manifold was separated from the two forward cylinders in one bank which left a gap of 3/4 inch through which exhaust gases could escape With this simulated break, the engine was operated up to 2200 rpm, but no alarm was given by the Fireye units

In order to determine whether the Fireye units were capable of detecting burning water-injection fluid (alcohol and water), a bench test was arranged so that a unit could be exposed to both gasoline and water-injection-fluid fires, each burning in an open cup three inches in diameter The gasoline fire was detected promptly and at a distance of 12 feet while the injection-fluid fire was detected only at a range of less than two feet The gasoline burned with a bright flame while the injection fluid burned with a dull blue flame which was nearly invisible to the naked eye

Occasional false alarms were produced during 27 simulated rain tests using early arrangements of the FD-2 detector units Apparently the water droplets passing between the unshrouded exhaust manifolds and the units produced modulated infrared radiation of the critical frequency No false alarms resulted from this source with the configuration that is shown in Fig 16

Two other causes of false alarms were revealed by the test program These are mentioned mainly because they were associated with maintenance of the system and because knowledge of them could do much to prevent their occurrence in actual aircraft installations In one instance, the malfunctioning was traced to water or moisture that had entered some of the connectors. This was remedied by packing the connectors with a silicone compound In another instance, the trouble was traced to a clamp which had been fastened too tightly around the shielded coaxial cable used to connect the individual units

For tests in Zone 2, three Fireye units (shown in Fig 17) were located as follows

1 Above the auxiliary fire-wall door facing forward toward the engine accessory drive case

2 Four inches below the main floor level and to the right of the recessed area under the accessory drive case, facing upward.

3 On the right wall 14 inches forward of the auxiliary fire wall and 20 inches above the floor, facing to the left

One hundred eighty tests were performed using small gasoline fires (0 1 gpm) started at six places within the zone All three of the units were able to detect these small fires, but the best performance was shown by unit No 3 and the next best by No 1

Evaluation

In testing different fire detectors under full-scale conditions, some of the advantages and disadvantages of the systems became apparent The extent to which these were revealed was necessarily limited by the scope of the tests

In general, unit detectors can be used advantageously in small enclosed spaces In large compartments, unless the units are spaced quite close together, there is a strong possibility that a fire may pass between two adjacent units without causing an alarm Electrical lines from one unit to the next may be damaged by fire before the unit operates

The Edison unit may be considered to have a certain advantage in that it responds to a rapid rate of rise in temperature However, it does not indicate an excessively high temperature, unless achieved rapidly The Fenwal units, on the other hand, will detect an abnormally high temperature but do not respond to rapid temperature increases if the temperature of the preset alarm is not exceeded

One of the Fenwal units tested (Model 17343-16) incorporated an adjustable feature which would provide a degree of flexibility during installation and would preclude the need for preset units like the Model 17343-61

Continuous detectors give wider coverage than unit detectors, because the entire lengths of such elements are capable of detecting fires The blank spaces which exist between units of the unit detector system are eliminated The flexibility of the elements makes them readily adaptable to volumes of different shapes and allows them to be routed near accessories if desired Usually the elements extend to some point outside the hazardous area, thereby making any wiring inside the fire zone unnecessary The elements can be fabricated in the most appropriate lengths to fit any installation

The Kidde and Dittmann continuous detectors both respond to abnormally high

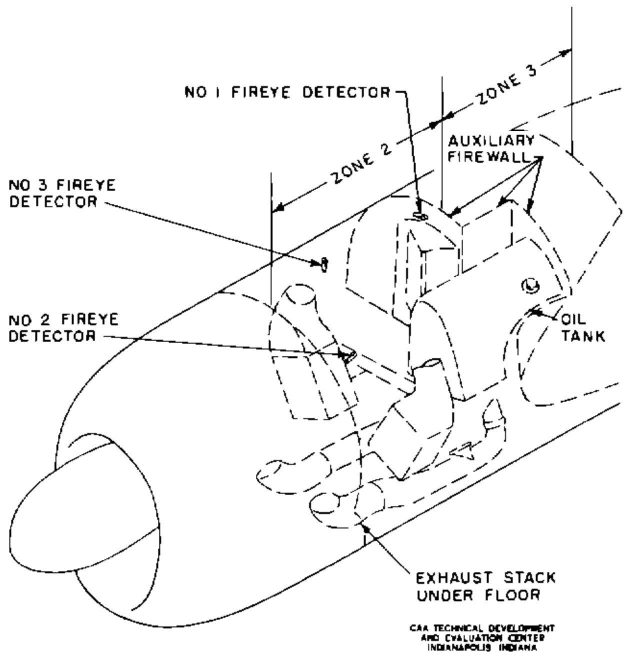


Fig 17 Fireye Detector Locations in Zone 2

temperatures, and the preset alarm temperature may be adjusted within a reasonable range The ATMO detector was designed to react to a rapid rise in temperature

The main disadvantage of the continuous detectors is that they may be damaged by careless handling, although they are not fragile At the time of the tests, the Dittmann detector would not reset after the fire was out until the ambient temperature of the zone returned to that which existed before the fire began This was a disadvantage in that it was slow to indicate when a fire had been extinguished The ATMO was unduly affected by temperature changes associated with engine operation and was therefore subject to false alarms

The Adams detector had the advantage of requiring fewer units than the other unit detector systems and had fewer blank spaces It was not affected by the usual engine operating temperature It could not fit into small spaces like a unit detector and was not as flexible as a continuous detector It was not particularly easy to mount Since its operation depended on the creation of a temperature differential between opposite ends of the element, the unit could be caused to operate by the application of cold to one end as well as by the application of heat If a fire was evenly distributed over the element so that no differential existed, the detector would also not sound an alarm It was necessary for the connecting electrical wires to be exposed in the hazardous area

The Fireye detector, Model FD-2, had advantages over unit and continuous type detectors It was not necessary for the units to be in the flame paths but only to be located at a few well-chosen points from which fire or reflections of fire could be observed The coverage was infinitely greater than with either of the other types of detectors Unfortunately, the detector was not capable of detecting an abnormally high temperature or a rapid rise in temperature Therefore, it is conceivable that overheating might fail to be detected in time High temperature had a tendency to reduce the sensitivity of Fireye units, and the coaxial cable leading to each of the units was exposed in the hazardous zones and subject to damage Since the units operated on modulated light from a flame, other modulated light of the same frequency could cause false alarms

Conclusions

As a result of the full-scale testing of fire detectors and detector systems, it is concluded that

1 Fires in the engine section tend to emerge from the cowl flaps regardless of where they originate in the zone

2 The highest ambient temperatures in the cowl-flap region occurred when the propeller was reversed, and the highest rates of temperature rise occurred while the propeller was reverting to positive thrust

3 The maximum temperature and the maximum rate of temperature rise occurred near the top cowl flaps

4 The rate of rise from usual engine operations was not sufficient to cause the original Edison detector system to sound a false alarm

5 The original Edison system functioned satisfactorily from the electrical standpoint, but the efficiency of the system was improved considerably by modifying the arrangement of units in Zones 1 and 4 The arrangement of Edison units in Zones 2 and 3 was satisfactory

6 The efficiency of Edison and other types of detector systems mounted in the cowl-flap region is better when the cowl-flap opening is small than when it is large

7 Edison units mounted on the cowl support ring should be spaced closer together than eight inches, as they were in the original XR60-1 system

8 Edison units mounted on the cowl support ring near the lower flaps were more effective in detecting fires originating under the engine than units mounted on the lower part of the engine diaphragm

9 The Edison units mounted on the cowl support ring were more efficient at detecting cylinder-head fires than crankcase fires

10 Detectors mounted on the diaphragm near the cowl flaps were effective only under a limited range of flight operating conditions

11 The best location for heat-actuated fire detectors in the engine section regardless of flap opening was that shown in Fig 12

12 The next best locations are indicated as F and G in Fig 11

13 Continuous detectors are more efficient than unit detectors in the engine section

14 The original Edison detecting units in the region under the floor were mounted too close to the shrouds and bulkhead

15 Fires in Zone 4 tended to exit from the louver openings on the bottom of the nacelle

16 For successful detection of fires in Zone 4, detectors were required in the louvered area under the nacelle

17 The detectors originally mounted on the bulkhead were not able to detect the presence of exhaust gases leaking from a separated exhaust stack in Zone 4

18 The Edison units located inside the accessory section were adequate for the detection of fires in that zone

19 The Fenwal detector Model 17343-16 operated satisfactorily as a detector of overheating and fire, and the Model 17343-61 operated satisfactorily as a fire detector

20 The Dittmann continuous detector system is satisfactory for use in an engine section

21 The Kidde continuous detector system is satisfactory for use in all zones of an airplane nacelle

22 The ATMO continuous detector system was too sensitive to normal heat changes in an airplane nacelle to be used as an aircraft fire detector

23 The Adams detector was not suitable for aircraft use because of its undesirable inherent characteristics

24 The Fireye fire-detector system was capable of detecting fires rapidly in both engine and accessory compartments

25 The Fireye system was particularly well-suited for the detection of fires in regions having little air flow

Recommendations (Heat-Actuated Detectors)

1 Unit detectors when used in the cowl-flap region should be spaced not more than six inches from unit to unit

2 Detectors should preferably be located in the best position, which is shown in Fig 12, or at least in the next best positions, which are indicated by F and G in Fig 11

3 Detectors should be mounted on the cowl support ring or on the diaphragm only if suitable means cannot be found to mount them in other positions demonstrated to be superior from the standpoint of detection

4 Detectors should be mounted in the louvers on the bottom of the nacelle to intercept Zone 4 fires

5 Detectors should be separated from the surfaces to which they are attached by a space of approximately two inches and oriented so that flames in their most normal course will impinge on the heat-sensitive portion of the detectors first

6 Detectors in the accessory section should be mounted near the top of the zone, around the engine accessories, and across air exits

Recommendations (Visual Detectors)

1 Units of the system should be mounted on the cowl support ring and oriented to view 45° from a radial line toward the center of the engine, as shown in Fig 16

2 Units should be mounted radially outward from the intake manifolds at the points where they pass beneath the cowl support ring

3 At least six units should be used for the protection of the engine section of the XR60-1

4 At least two units should be used for the protection of the XR60-1 accessory section, which is comparatively free from obstructions

5 Units should preferably be mounted at the sides of Zone 2 and should also be located so that the various fields of vision will be supplemental

EXTINGUISHING SYSTEMS

Purpose

The purposes of the extinguishing tests were (1) to evaluate the nozzle type of fire-extinguishing system with which the test installation was equipped, and (2) to revise the nozzle system or install a new system as required to simplify the piping and avoid the use of individual nozzles if possible

Introduction

The test installation originally was provided with a conventional type of fire-extinguishing system In the engine section there was one nozzle located behind the base of each cylinder for a total of 28 nozzles Nozzles were also provided in the other zones, in ducts, and in places where the greatest hazards were believed or known to be located Fig 18 shows the arrangement of this system

Parts of the system were designed in accordance with the data and formulas given in a previously published work[4] The recommendations and formulas contained in this note were based on data obtained in tests involving single-row and double-row engines It was not known whether they would be applicable to four-row engines, because no tests had been made of the larger-sized ones when that note was published However, that part of the system which was intended to protect Zone 1 did not make use of the formula as developed Note No 31 gave the following formula for determining the quantity in pounds of methyl bromide needed to extinguish fire in the engine section:

$$\text{Methyl bromide} = 0\ 28 \times P \times \frac{N}{14}$$

where

P = pounds of air through the zone in two seconds,

N = number of engine cylinders

In the case of the XR60-1, the amount of air passing through the zone was 64 pounds for a two-second interval and the number of engine cylinders was 28 Therefore, the number of pounds of methyl bromide required for this zone should have been

$$0\ 28 \times 64 \times \frac{28}{14}, \text{ or } 35\ 84 \text{ pounds}$$

In applying the formula, the last factor was omitted altogether, and since its value is two, the system was designed to furnish only 17 9 pounds of methyl bromide (one-half the amount specified for a nozzle system) The sizes of lines and nozzle openings were designed accordingly

The system was also designed to distribute large quantities of extinguishing fluid in Zone 2 and smaller quantities in Zone 3 This was a reasonable arrangement because Zone 2 contained many flammable-fluid lines and the oil tank, as well as some potential ignition sources associated with the engine accessories The fire hazard in Zone 3 was

[4] H L Hansberry, "Design Recommendations for Fire Protection of Aircraft Power Plant Installations," CAA Technical Development Note No 31, September 1943

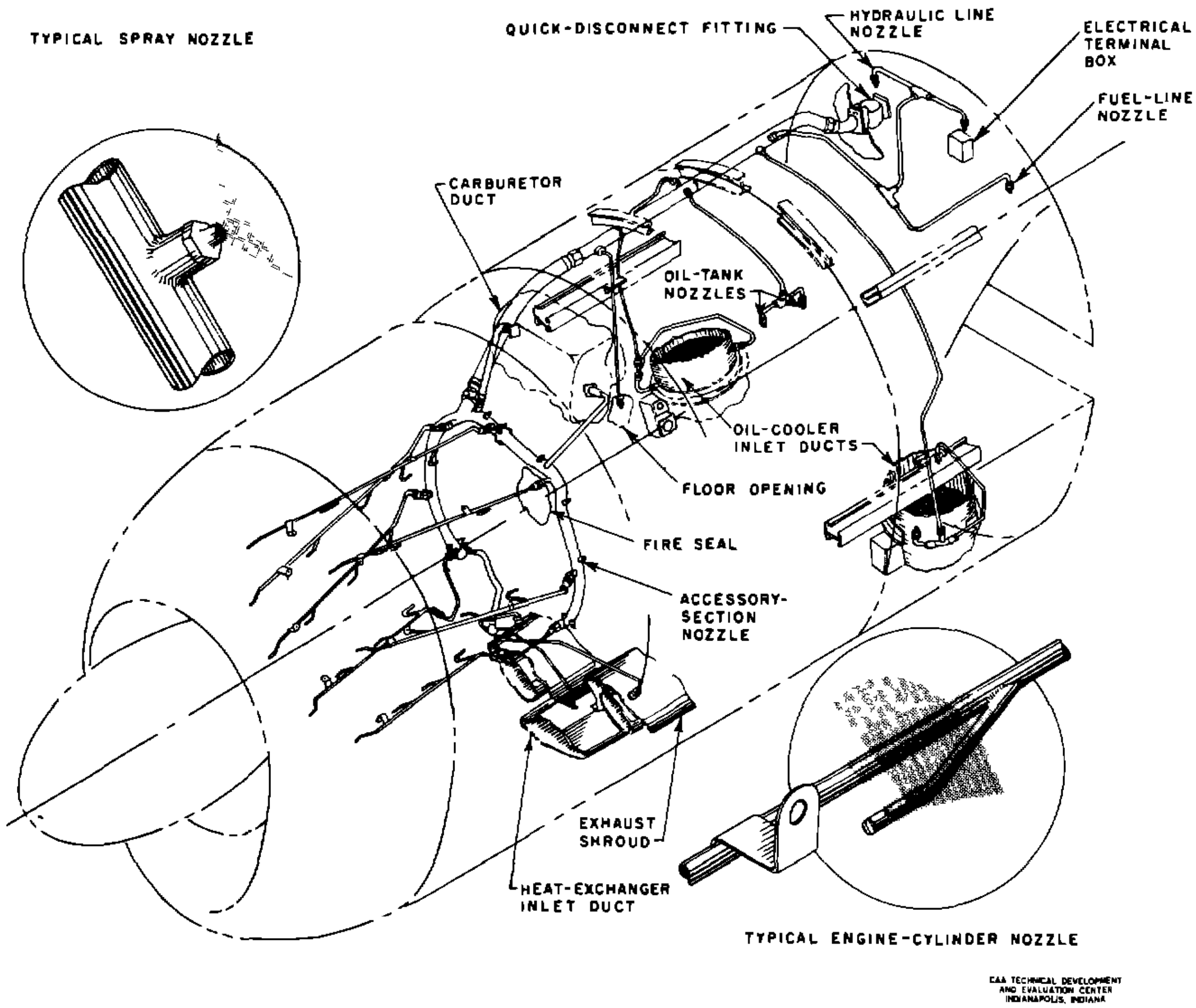


Fig. 18 Original Nozzle Type of Extinguishing System in the XR60-1

less than in Zone 2 because fewer lines and fewer ignition sources were concentrated in the zone and because it was smaller and comparatively free from obstructions

The calculated total quantity of methyl bromide required for distribution in all zones simultaneously was 55 9 pounds Three cylinders, each containing 20 pounds of fluid pressurized with nitrogen to 400 pounds per square inch (psi) were used to supply this in the airplane

Some time prior to the fire tests, a mock-up of the nacelle extinguishing system had been constructed and tested by the Lockheed Aircraft Corporation to demonstrate the distribution and spray patterns of the extinguishing fluid The distribution proved to be satisfactory, but the question of whether the system was capable of extinguishing fires remained to be answered

Test Procedure

The extinguishing-agent supply line to the test nacelle system was made to correspond roughly in such matters as length, turns, and fittings to the supply line in the actual airplane and was connected to the extinguishing-fluid cylinders in such a way that one, two, or three cylinders could be discharged during any single test The capacity of each cylinder was nominally 20 pounds of methyl bromide Since the system was designed for methyl bromide, all tests were made with this fluid except two in which bromochloromethane (known in the fire-extinguishing field as CB) was substituted

During all tests, the engine and wind tunnel were operated to simulate flight conditions The fires in the early tests were small, being produced by burning gasoline supplied to the fire nozzle at a rate of 0 28

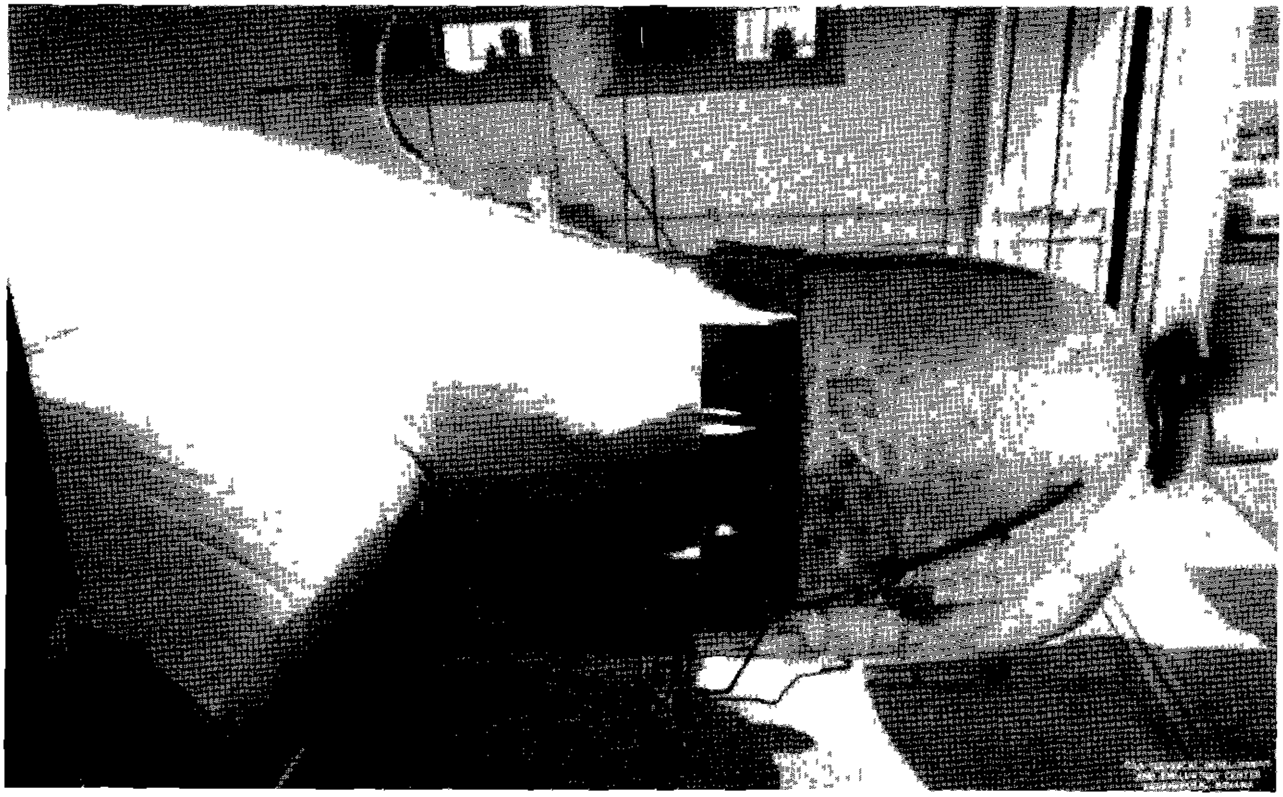


Fig 19 Oil Fire (4-gpm) in the Engine Section

gpm As testing progressed, larger quantities of gasoline and hot oil flowing at a maximum rate of 4 gpm were used The original extinguishing system was modified in an effort to force more fluid into Zone 1 by excluding from the system several small lines intended for the protection of individual accessories in Zones 2 and 3 In another attempt at improvement, the 28 nozzles which constituted the Zone 1 portion of the system were isolated from the rest of the system and fed by separate feed lines

Later, a simplified nozzle system was designed for Zone 1 only This system consisted of seven nozzles equally spaced around the front of the engine between the cylinder banks Each nozzle was designed to produce a 260° spray pattern through a single 1/16-inch slot, and all the nozzles were arranged so that the sprays overlapped to produce across the face of the engine a vaporous curtain which could be forced back by the air stream to sweep out the engine compartment Hot oil was burned in all but two of the 28 tests used to evaluate this system

Tests continued to be directed toward the development of a simplified extinguishing system One such system consisted of a number of plastic capsulelike containers located wholly within the zone to be protected Each capsule stored a quantity of bromochloromethane which was discharged electrically by detonating a blasting cap located inside the capsule The explosion burst the capsule and dispersed the fluid in all directions

Another type of simplified system was one which later came to be known as the High Rate Discharge (HRD) system This utilized the standard aircraft extinguishing equipment By eliminating the complex distribution system, the rates of agent discharges were increased significantly

Zone 1 test fires, one of which is shown in Fig 19, were started and allowed to burn for 10 or 15 seconds before the emergency procedure was initiated The total time during which these fires burned was approximately 18 to 20 seconds The flow of oil and gasoline would normally diminish as a result of such emergency actions as turning off valves and feathering the engines, but for these tests the oil and gasoline were allowed to continue flowing at the constant rate The net effect of this constant rate of flow was a condition which might have been experienced had it been impossible to stop the flow of the flammable fluid or had the flow been reduced to this established rate from an initially higher one by the emergency actions The fuel continued to flow after extinguishment of the fire until it was evident that reignition would not take place

Measurements of the air speed at the top and bottom of the engine front and rear made it possible to calculate the quantity of air passing through Zone 1

Seventy fire tests were conducted in Zone 2 of the XR60-1 to develop an HRD system for this zone Most of the fires burned gasoline and hydraulic fluid, a few burned oil Methyl bromide and carbon dioxide were the extinguishing fluids used In the course of testing in Zone 2, it was discovered that the intercooler flap position entered into the extinguishment problem and therefore required special study

To extinguish fires under the floor (Zone 4), extinguishing fluid was directed into the underfloor ventilating ducts and into isolated volumes on each side of the nacelle

After the fire tests had been completed, measurements were made of the rates at which the various agents were discharged through the lines which comprised the HRD system This was done by removing the lines and cylinders from the nacelle and mounting them on a structural framework in the same attitude which they had during the tests As the cylinders that were filled with the same quantities of fluid used in the tests were discharged, the rates of discharge were measured by two methods One method made use of an oscillograph for recording a signal from a photoelectric cell mounted at the discharge end of the line being tested The other method made use of a camera to take timed motion pictures of the discharge

Results and Discussion

Twenty-one fire tests were performed with the original nozzle system or with the slightly modified one intended to increase the amount of fluid entering Zone 1 In the earlier tests, the full 60 pounds (in three 20-pound cylinders) for which the system was designed were discharged without effect It was obvious that the quantity of extinguishing fluid being released in Zones 2 and 3 was far in excess of what was needed because the fluid was flowing in liquid form out of drains, seams, and other openings No such evidence of surplus fluid was observed in the engine section Even after removing some of the lines in Zones 2 and 3, the amount of improvement in Zone 1 was negligible

The 28 nozzles in Zone 1 when isolated and fed by separate feed lines showed some improvement, but there appeared to be too much restriction in the lines and nozzles Fires which originated near the cylinder heads seemed to be easier to extinguish than those started near the crankcase Closing the cowl flaps appeared to assist the extinguishment of cylinder-head fires but still did not make the extinguishment of crankcase fires possible Charge pressures of 100 psi above or below the 400 psi normally used made little difference No fire was extinguished with a quantity of less than 40 pounds of extinguishing agent, and crankcase fires could not be extinguished with this quantity

Failure of the original Zone 1 extinguishing system left two courses of action (1) to rebuild the system as called for by existing formulas, or (2) to develop new and simpler systems It was decided to adopt the latter course

The test objective in designing a new system was to introduce an extinguishing agent at such a high discharge rate that (1) it would blast across the normal air flow and saturate the zone with the agent vapors, and (2) elaborate agent distribution systems could be eliminated or reduced to a minimum

The seven-nozzle system previously described was the first step in this direction The results obtained with it seemed to be as good as, if not better than, the results obtained with the original 28-nozzle system, but they were still unsatisfactory

Two totally different systems were then proposed One was the capsule system and the other the HRD To test the former, seven capsules each containing 2 8 pounds of bromochloromethane (19 6 pounds total) were mounted in Zone 1 in the openings between cylinder banks approximately in line with the front row of cylinders, as shown in Fig 20 The blasting caps inside the capsules contained 0 4 grams (gm) of powder

Four attempts were made to extinguish 4-gpm oil fires with the following results one successful extinguishment, one flash back after apparent extinguishment, and two failures High-speed moving pictures made during the tests revealed that a considerable amount of fluid was being spilled out the front opening of the cowling The capsules were moved deeper into the engine, and another test was made The high-speed pictures showed that some spillage still occurred, although not so much as previously Unfortunately, one capsule broke loose from its mounting before being exploded, so its effect was lost on the fire The fire was not extinguished but was subdued momentarily

The capsule system has the advantage of being light in weight because the capsules were fabricated of lightweight plastic material and no plumbing was required The disadvantage of the system was that the capsules fastened between the cylinder banks in Zone 1 obstructed the passage of cooling air to the engine cylinders In spaces where the air flow was not critical, the disadvantage disappeared

Although the limited number of tests involving capsules indicated that further development work is warranted, considerable testing must be undertaken before the capsule system can be considered for use in aircraft power plants Briefly, the testing would involve the development of capsules and detonators capable of withstanding normal nacelle temperatures and vibration and the selection of a suitable fluid having low vapor pressure, low freezing point, chemical stability, and noncorrosive properties

For preliminary tests of the HRD system in the engine section, one extinguishing-agent container was located just aft of the cowl flaps on the right side of the nacelle and a one-inch outside diameter (OD) line was installed from the container to the front face of the engine The line was bent at 90° near the end, so that fluid discharged from the container would be directed across the face of the upper half of the engine

Sixteen tests were conducted with this simple arrangement using methyl bromide pressurized with air to 400 psi The fact that some success in combating 3-gpm oil fires was achieved with such a small quantity as six pounds of methyl bromide indicated that this type of system might prove to be far superior to a nozzle system in an engine installation

Another extinguishing-agent container similar to the first was mounted on the opposite side of the nacelle, and tubing was installed from it to the front of the engine The system then consisted of two extinguishing-agent containers attached to the sides of the nacelle aft of the cowl flaps Two one-inch OD tubes were installed extending from each container to the front of Zone 1 where they were bent inward at right angles and terminated without restriction Extinguishing fluid from one tube discharged across the upper half of the face of the engine and from the other one across the lower half The fluid actually passed between the forward cylinders and the magnetos in each case

The most persistent fires were those which originated on the lower half of the engine It is believed that the reason for this was associated with the cowl-flap configuration Fires on the upper half of the engine found no difficulty in emerging from cowl flaps because the flaps extend around the upper half of the nacelle, but fires on the

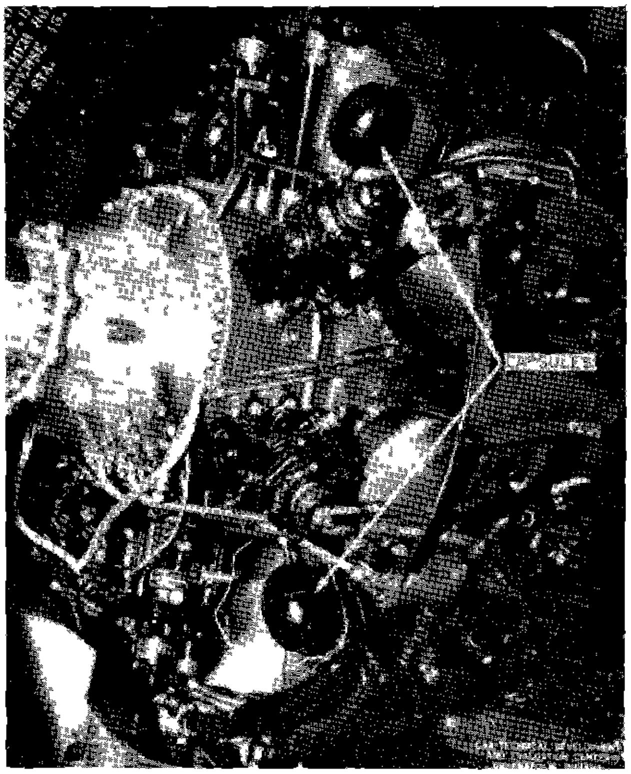


Fig 20 Capsules Mounted Between Engine Cylinder Banks as a System for Extinguishing Zone 1 Fires

lower half had no flaps directly aft of them from which to emerge They had to curve upward around the engine in order to exit through the flaps over the upper half of the nacelle It was evident that the air entering at the lower front part of the engine tended to divide into two main courses in passing through the zone to the cowl flaps on either side This undoubtedly created a region near the rear underside of the engine where turbulent fires could exist Such fires could escape extinguishment because the extinguishing agent discharged at the front of the engine would also tend to divide in order to reach the exits and would have negligible effect on the turbulent fires This appeared to be the logical explanation for the flash backs which occurred in the early tests A tube having a 3/4-inch diameter was therefore installed to discharge fluid under the rear of the engine to prevent flash backs

It should be noted that at the time these tests were conducted the internal surface of the cowling or pan under the engine was smooth As originally designed, the pan was crossed with several exposed transverse structural ribs which caused considerable

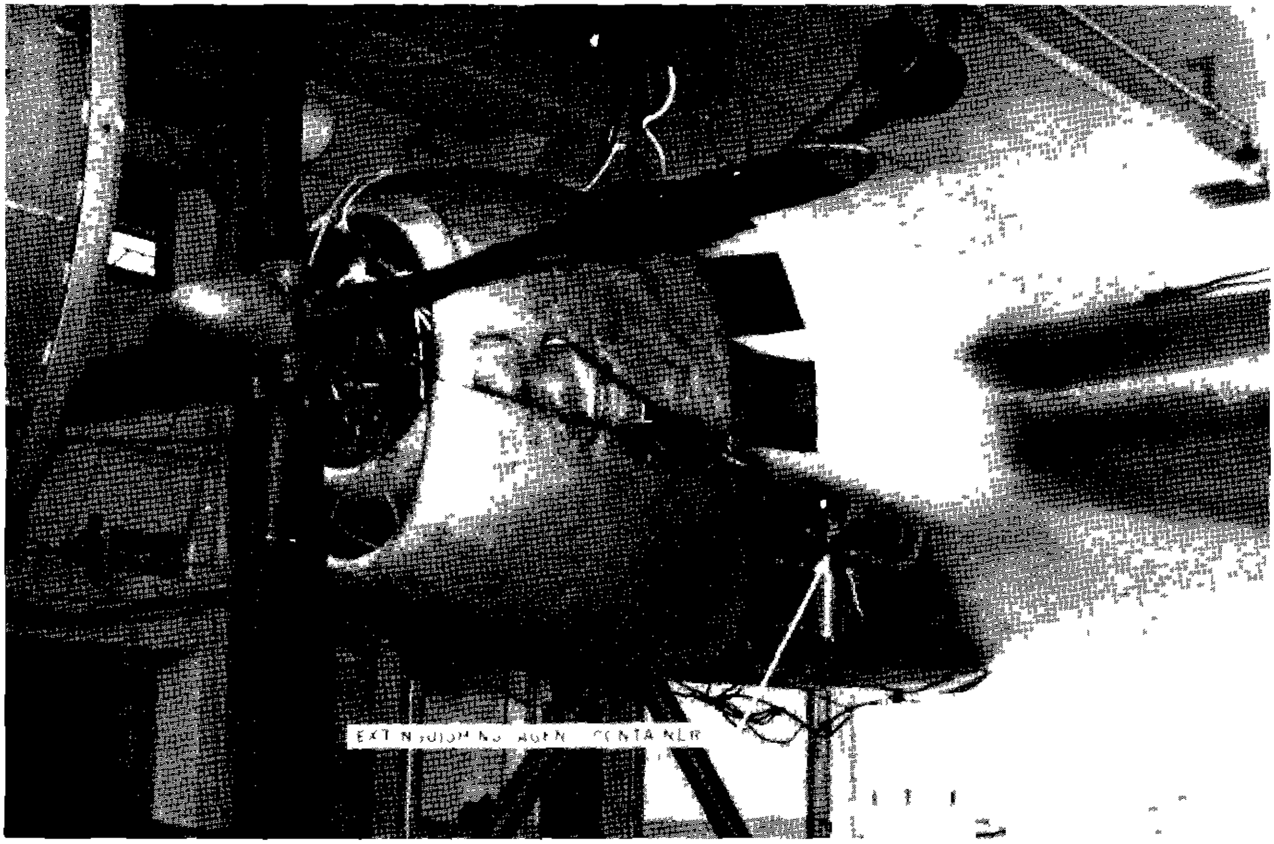


Fig 21 Oil Fire (3-gpm) in Engine Section Extinguished with HRD System Using Eleven Pounds of Methyl Bromide as the Agent

turbulence under the engine and formed pockets where fuel and oil could collect Fires occurring in this area were extremely difficult to extinguish, and the pan was damaged severely on several occasions before a smooth liner was installed to provide an aerodynamically clean internal surface The original drainage was also inadequate Provision had been made for draining only a small amount of anticipated leakage at two points This condition was corrected at the time the lining was installed by inserting a 1 1/2-inch diameter drainpipe from the low point of the pan to the outside of the nacelle The external end of the pipe was shielded to maintain the proper air-flow conditions inside the zone

In the tests, the flaps could be opened or closed as desired during the emergency procedure Fig 21 shows the prompt extinguishment which occurs when the flaps are open Occasionally, the discharge of a quantity of an agent would fail to extinguish a fire when the flaps were open but would extinguish the same-sized fire when the flaps were closed The action of the agent in the latter case seemed to be slower at first but of longer duration At initial discharge, the main body of the fire was snuffed out, and if small residual fires persisted or if small flash backs occurred, the remaining agent would slowly smother them Fig 22 shows a fire being smothered

Seventy-nine extinguishing tests were made with the HRD system in Zone 1 in order to determine the proper minimum quantities of each of the following extinguishing agents methyl bromide, dibromodifluoromethane, carbon dioxide, and bromochloromethane Table IV gives some of the properties of these fluids, and Table V gives the required weights of the three most satisfactory of these fluids with their rates of discharge Methyl bromide appeared to be most satisfactory from the standpoint of weight, requiring a minimum of 13 pounds distributed as follows 5 pounds discharged in each line across the face of the engine and 3 pounds discharged at the rear of the zone under the engine The rate of discharge into the zone was 23 pounds per second Dibromodifluoromethane appeared to be as effective as methyl bromide Its rate of discharge was 25 7 pounds per second However, the number of tests in which

TABLE IV

EXTINGUISHING-FLUID PROPERTIES

Name	Formula	Molecular Weight	Boiling Point (degrees C)	Freezing Point (degrees C)	Specific Gravity	Vapor Pressure at 20° C (millimeters)
Carbon Dioxide	CO_2	44 0	-78 2	- 57	0 77	42,400
Methyl Bromide	CH_3Br	95 0	4 6	- 93	1 73	1,250
Dibromodifluoromethane	CBr_2F_2	209 8	24 5	-142	2 31	645
Bromochloromethane	CH_2ClBr	129 4	67 0	- 88	1 92	135

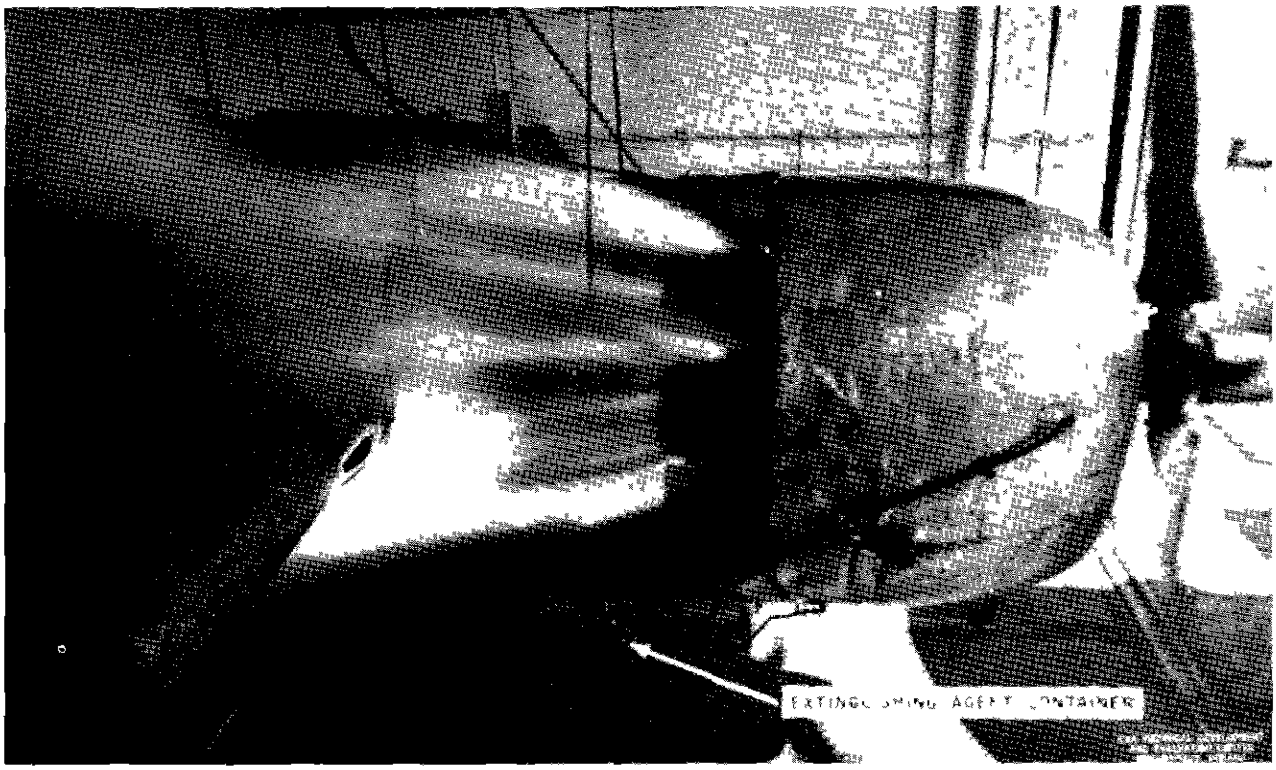


Fig 22 Oil Fire (4-gpm) Extinguishment with 13 Pounds of Methyl Bromide After the Cowl Flaps Were Closed

this fluid was used was not sufficient to warrant definite conclusions After the minimum amount of methyl bromide had been determined for a certain fire condition, a similar amount of dibromodifluoromethane was tested under the same conditions and found to be sufficient in each case The quantity of carbon dioxide required was 20 pounds, of which 15 pounds were supplied to the front of the engine and 5 to the region under it The rate of discharge was 15 pounds per second Bromochloromethane did not appear to be particularly well-suited to the HRD type of system, and fires could not be extinguished with 25 pounds of the fluid To be effective, a fluid should vaporize as it emerges from the end of the line, but bromochloromethane tended to remain in a liquid state and to discharge as a stream Normally such a stream could be broken up

TABLE V

MINIMUM WEIGHTS OF EXTINGUISHING FLUIDS
AND THEIR RATES OF DISCHARGE REQUIRED IN HRD SYSTEM

Zone	Area	Air Flow or Zone Volume	CH_3Br		CBr_2F_2		CO_2	
			(lb)	(lb/sec)	(lb)	(lb/sec)	(lb)	(lb/sec)
1		36 lb/sec	13	23 0	13	25 7	20	15 0
2		60 cu ft	3	4 3	3	-	6	5 5
3		48 cu ft	3	4 3	3	-	4	5 7
4	Pocket A, Left Side	1 1/2 cu ft	3	5 0	3	-	4	5 7
4	Pocket A, Right Side	1 1/2 cu ft	3	5 0	3	-	4	5 7
4	Ducts, Left Side*		3	5 0	3	-	4	5 7
4	Ducts, Right Side*		3	5 0	3	-	4	5 7

*Underfloor ventilating air duct and ventilating air duct of the turbosupercharger compartment

by a nozzle, but a nozzle would restrict the flow and negate the inherent advantages of this type of extinguishment

At the time these quantities were established, the air flow through the zone was approximately 36 pounds per second when the engine was operating at 1800 rpm with the cowl flaps wide open and with the wind tunnel supplying air at 110 mph This weight compares favorably with the 32 pounds per second originally calculated for the zone to provide design data for the original nozzle type of extinguishing system The difference can be explained by the fact that the spinner which normally shrouds the propeller hub was removed prior to the fire tests for the express purpose of increasing the air flow through the zone

Since the fluid discharge in this type of system is forward of the engine cylinders, there was some tendency toward spillage over the front of the cowling The spillage was not excessive, and sufficient fluid passed through the engine section regardless of whether the wind tunnel was in operation (simulating flight) or whether the engine propeller alone was rotating (simulating ground operation)

During the test program it was convenient to fasten the extinguishing-agent containers to the outside of the nacelle, as shown in Figs 21 and 22, but in an actual aircraft installation such cylinders would be located inside the nacelle, as suggested in Figs 23 and 24, or in the wing In any case, they should be located as near as possible to the nacelle which they are intended to protect, because the effectiveness of the system depends largely on the total saturation of all zones simultaneously and promptly

No changes were considered to be necessary to the nozzle system in Zones 2 or 3, although later in the program a much simpler system was found to be adequate It was observed during the tests that fires could spread from Zone 1 into Zone 2, and two fires occurred because of a backfiring of the engine No cases were known where fires ignited from any of the accessories inside Zones 2 or 3 It is not known whether fire would spread from under the floor, because extinguishing fluid was always introduced into Zones 2 and 3 as a control measure during the Zone 4 tests

Because of reignition after apparent extinguishment, both Zones 3 and 4 were suspected at times of harboring extensions of the main fires from Zone 2 One of the most troublesome problems of extinguishment in Zone 2 was caused by leakage of fire through the joints around the intercooler Such fires lodged behind the intercooler

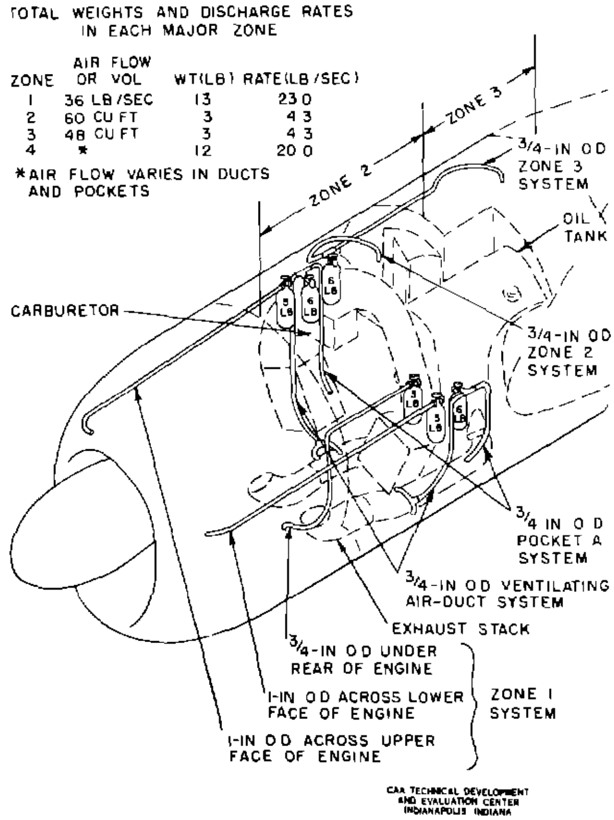


Fig 23 HRD System for the XR60-1 Nacelle Using Methyl Bromide as the Agent

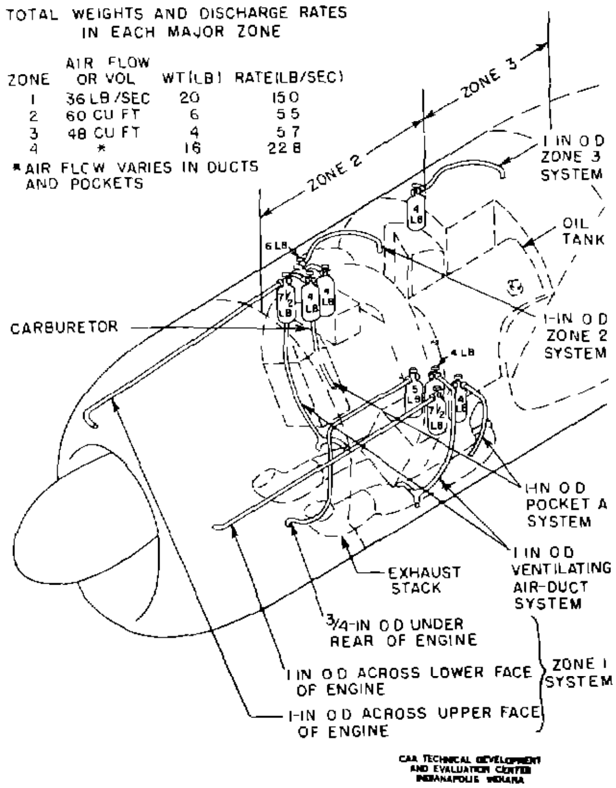


Fig 24 HRD System for the XR60-1 Nacelle Using Carbon Dioxide as the Agent

flaps where they were protected from the slip stream

The final form of the extinguishing system for Zones 2 and 3 consisted of single lines discharging downward from the top center of each zone When methyl bromide or dibromodifluoromethane were used as the extinguishing fluids, 3/4-inch OD lines were used, both of which were fed from the same container When the fluid was carbon dioxide, one-inch OD lines were used and each line was fed from a separate container

No fires were started intentionally in Zone 3, but it is highly probable that smaller quantities of fluid would have been required there than were required in Zone 2 because its volume is less than that of Zone 2 and because it contains fewer accessories and ignition sources Since carbon dioxide was fed into each zone from a separate container, it was a simple matter to supply different quantities to each one Six pounds were required for Zone 2, and four pounds were used in Zone 3 Since the other fluids were fed into both Zones 2 and 3 from the same container, it was not feasible to reduce the quantity going into Zone 3 Therefore, three pounds were used in each zone The net volume of Zone 2 was approximately 60 cubic feet, and that of Zone 3 was approximately 48 cubic feet The air flow was negligible in the two zones

The danger of fire in Zone 4 did not appear to be particularly great There was little tendency for fluids to drain into the zone, and it seemed rather unlikely that the quantity gaining entrance would continue to flow at a high rate for any great length of time, especially if emergency shutdown procedure were used During the tests conducted under normal flight conditions, no cases of natural ignition were incurred by the introduction of flammable fluids into the zone Nevertheless, in order to determine the magnitude of the extinguishing problem the assumption was made that moderate-sized fires could gain entrance to the zone in some manner

The tests showed that the fires which were intentionally ignited in the zone tended to exit from the louvers on the bottom of the nacelle, as shown in Fig 25 Since this area was protected with stainless steel, such fires were not very damaging The tests also

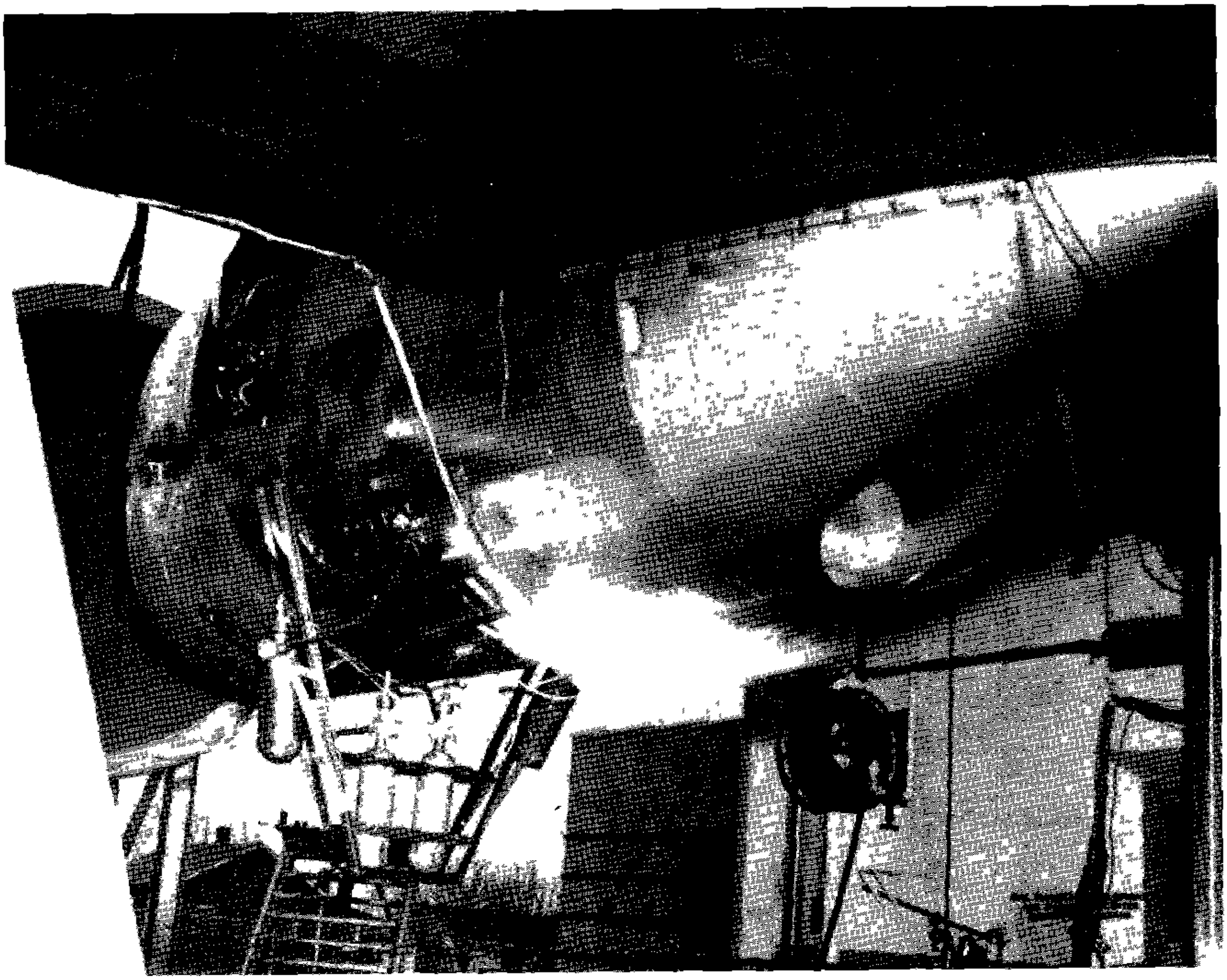


Fig 25 Zone 4 Fire (2-gpm)

showed that the larger the quantity of oil used to feed a fire, the more difficult the extinguishment became In view of the apparently safe conditions in the zone, extinguishing requirements were established for a maximum of 2 gpm of initial flow and reduced to 1/2 gpm after emergency procedure

The first method tried for extinguishing Zone 4 fires was to introduce extinguishing fluid into the front scoop However, the fluid supplied in this manner tended to enter those ducts where the air flow was the greatest, and since the air flow through the underfloor and the ventilating ducts to the turbosupercharger compartment was of comparatively small magnitude (approximately one or two pounds per second), these latter ducts were not adequately purged See Fig 26

There appeared to be little reason to use an extinguishing agent in the intercooler, heat-exchanger, or turbosupercharger air ducts The only fires which lodged in the intercooler ducts were those which spread from Zone 2 into the intercooler flaps, and these could be controlled by the extinguishing agent in Zone 2, provided the flaps were closed when the extinguishing system was discharged Neither the heat exchanger nor any of the ducts gave evidence of being sources of ignition or shelters for fire The turbosupercharger and its duct did not appear to be hazardous

The extinguishing system being tested was then installed so that the fluid was introduced only into the two ventilating air ducts on each side of the nacelle It was soon discovered, however, that even this method did not produce the desired results because two pockets were found in each side of the nacelle where the extinguishing agent could not penetrate with sufficient concentration to be effective These pockets on the left side of the nacelle and designated A and B are shown in Fig 27 Pocket A, formed by the bracket and shroud of the turbosupercharger and by the skin of the nacelle, had a volume of approximately 1 5 cubic feet Pocket B, the enclosed space surrounding the oil cooler, had a volume of approximately 4 5 cubic feet The air flow in both of the spaces was negligible

Extinguishing fluid should have been introduced into these pockets on each side as well as into the ducts, but in the interest of simplicity no fluid was directed into the B pockets during the tests The only fluid entering these spaces came from Zone 3 through openings around the oil-cooler ducts

During the tests two or four containers were used to protect Zone 4, the number depending on which extinguishing fluid was being used Four lines were used in each case Of these, two lines supplied fluid to Pocket A on each side of the nacelle and each of the other two lines supplied fluid to the ventilating air ducts The discharge from each of the latter lines was divided evenly between the duct to the turbosupercharger compartment and that of the underfloor space When carbon dioxide was the extinguishing agent used, four pounds were discharged from each of four cylinders at a rate of 5 7 pounds per second through one-inch OD lines When methyl bromide or dibromodifluoromethane was used, six pounds were discharged from each of two containers Each container fed two 3/4-inch OD lines, and the discharge rate of each line was 5 pounds per second The quantities of extinguishing fluid and the discharge rates required for each of the nacelle zones are shown in Table V Fig 23 shows the HRD system for the XR60-1 using methyl bromide as the extinguishing fluid and with all containers and lines mounted inside the nacelle Fig 24 shows a similar system using carbon dioxide as the extinguishing agent Table VI lists additional data for the HRD system

The total quantity of methyl bromide required for the whole nacelle was 31 pounds, and the total carbon dioxide was 46 pounds Although several containers were used to store the fluids during the tests, there is no reason why fewer large containers could not be used provided that no reduction takes place in the number of lines, the line sizes, the quantities of fluid, or the rates of discharge

The preceding HRD requirements were found adequate for the XR60-1 They are not necessarily applicable to similar installations Too little is now known about this type of extinguishment to derive formulas

Fig 26 Zone 4 Ducts

for general use In installations which have cowl flaps almost completely around the engine, it is highly probable that no fluid would be needed under the engine Moreover, not all types of installations have accessory sections which are as well-sealed as the one in the XR60-1, and therefore more agent may be required in the accessory sections of such installations The complicated duct system in the XR60-1 made extinguishment of fires in Zone 4 difficult and added considerably to the fluid weight requirements It is not yet possible to calculate what the requirements for a corresponding region would be in another installation on the basis of the results obtained in these tests

In a large installation such as the XR60-1, the HRD system should compare favorably with the nozzle system, especially when methyl bromide is used This fluid loses much of its effectiveness when it is obliged to travel long distances before discharging The HRD system uses a minimum of piping, few valves, and no nozzles As a result, less fluid per nacelle is needed than with a nozzle system The total quantity of fluid required for a multiple-engine airplane would be slightly greater than that required for the conventional nozzle system using a centralized source of agent A few more

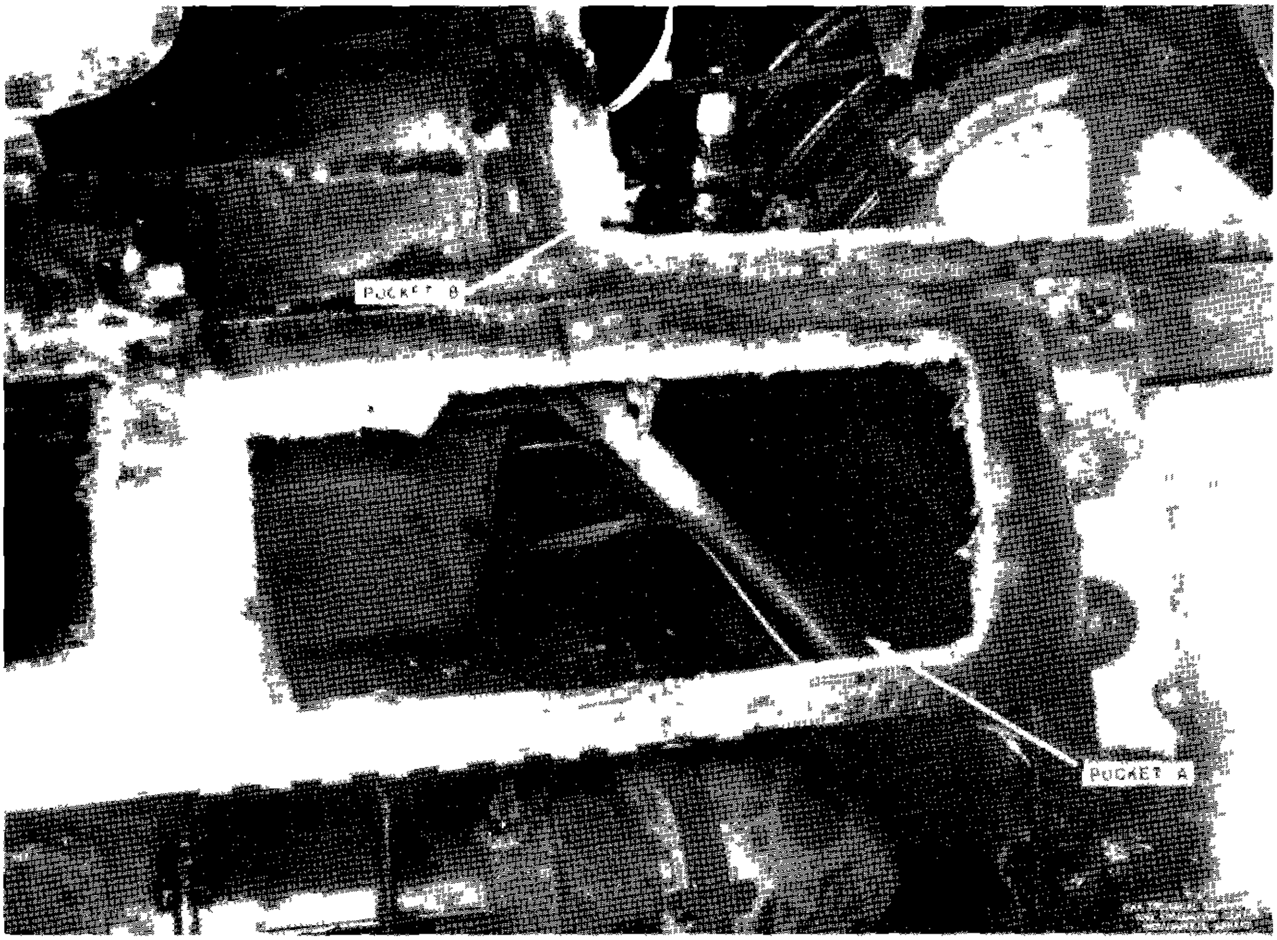


Fig 27 View of Nacelle from the Left Side with Sections of Skin Removed to Show Isolated Pockets in Zone 4

containers would be needed, since each nacelle would have an independent system However, the added weight of the extra containers tends to be balanced by the saving in weight resulting from the use of shorter feed lines and by elimination of complex distribution systems The simplicity of the HRD system should reduce both the installation and maintenance problems associated with power-plant fire-extinguishing systems In addition to the consideration of weight, complexity, and maintenance, the HRD system is inherently qualified to give better fire protection than the conventional nozzle system In an HRD system the fluid achieves maximum effectiveness and can be applied with minimum delay Ultimately, the HRD system may be coupled with the proper type of triggering mechanism and may become useful against crash fires as well as against fires in flight This future advantage cannot be obtained from existing centralized extinguishing systems

Conclusions

As a result of the extinguishing-system tests, it is concluded that

1 The portion of the original nozzle system which was intended for the protection of Zone 1 was not adequate

2 Closing the cowl flaps improved the effectiveness of extinguishing fluid in extinguishing Zone 1 fires

3 A simplified arrangement of seven nozzles was as effective as the original 28 nozzles in Zone 1

4 The portion of the nozzle system which was intended for Zones 2 and 3 was more than adequate

5 Zone 2 was comparatively free from ignition sources, but fires could occur in that zone as a result of engine backfiring

6 An HRD system of extinguishment could be used successfully in Zones 1, 2, 3, and 4

TABLE VI

HRD SYSTEM DATA

Test No	Line Designation	Line Dimensions		Cylinder Volume (cubic inches)	Extinguishing Fluid	Weight (pounds)	Time (seconds)	Fill Ratio (per cent)	Rate (pounds per second)
		Length (inches)	OD (inches)						
1	Front of engine	75	1	295	CO_2	7 5	1 35	70 0	5 5
2	Front of engine	75	1	205	CH_2ClBr	7 0	0 70	48 5	10 0
3	Front of engine	75	1	205	CH_3Br	5 0	0 52	39 0	9 6
4	Front of engine	75	1	205	CBr_2F_2	5 0	0 50	29 0	10 0
5	Rear of engine	86	3/4	205	CO_2	5 0	1 25	67 7	4 0
6	Rear of engine	86	3/4	205	CH_2ClBr	5 0	0 90	34 7	5 6
7	Rear of engine	86	3/4	205	CH_3Br	3 0	0 80	23 4	3 8
8	Rear of engine	86	3/4	205	CBr_2F_2	3 0	0 53	17 4	5 7
9	Zone 2	45	1	295	CO_2	6 0	1 35	70 0	5 5
10	Zone 3	45	1	205	CO_2	4 0	0 70	54 0	5 7
11	Zones 2 & 3	45*	3/4	205	CH_3Br	6 0	0.70	46 8	4 3**
12	Zone 4 (A)	45*	3/4	295	CH_3Br	6 0	0 60	32 5	5 0**

*Cylinder discharges into two 3/4-inch OD lines each 45 inches long
**Rate of discharge at end of each line

7 Methyl bromide, dibromodifluoromethane, and carbon dioxide were suitable for use in an HRD system

8 Bromochloromethane was not well-suited for use in an HRD system

9 Dibromodifluoromethane had approximately the same effectiveness as methyl bromide in the HRD system, and both were more effective than carbon dioxide on a weight basis

10 The effectiveness of the HRD system depends upon the discharge of extinguishing fluid at such a high rate that the normal air flow in a zone is disrupted momentarily, and the zone is saturated with vapors of the agent

11 The maximum effectiveness of the HRD system is realized by the use of short, straight, open-end lines

12 Fires which originated on the underside of the engine were more difficult to extinguish than others in the same zone

13 Fires can spread from Zone 1 to Zone 2

14 Fires in Zone 2 can escape extinguishment by partially lodging behind open intercooler flaps

15 Fires do not occur readily in Zone 4 under flight conditions

16 Fires which do lodge in Zone 4 are the most difficult to extinguish in the whole nacelle

17 Pockets in the underfloor ventilating duct are partly responsible for the difficulty involved in extinguishing Zone 4 fires

18 A high rate of discharge is of prime importance in any aircraft extinguishing system

19 Additional full-scale aircraft testing must be done before definite general recommendations can be made for the design of an HRD system

20 A capsule type of extinguishing system shows promise and warrants further development

Recommendations

1 A simpler extinguishing system than the 28-nozzle arrangement should be used in the engine section of the XR60-1

2 In case of fire cowl flaps should be closed to assist the Zone 1 extinguishing system, provided the skin aft of the cowl flaps is stainless steel Otherwise, the cowl flaps should be opened

3 Consideration should be given to the use of HRD systems rather than nozzle systems in large aircraft nacelles

4 Methyl bromide, dibromodifluoromethane, or carbon dioxide rather than bromochloromethane should be used as the extinguishing fluids in HRD systems

5 The extinguishing-fluid containers should be located near the zones they are intended to protect, and the tubing runs should be kept as short and straight as possible

6 Extinguishing fluid should be discharged into all protected zones simultaneously

7 The intercooler flaps should be closed as part of the emergency procedure, if there is any possibility that fires may be able to lodge behind them

EMERGENCY PROCEDURES

Purpose

The purpose of the investigation for emergency procedure was to study and evaluate the possible courses of action to be taken by the flight crew in the event of fire occurring in an airplane nacelle

Procedure

Whenever a series of tests was in progress, some of them were made with the cowl flaps open and some with them closed The difference in effect was noted In some tests, fires were extinguished by use of a fluid, and in others, fires were permitted to burn out The necessity for the use of extinguishing fluid was judged on the basis of the results produced in each case Finally, time studies were made of various combinations of actions to determine the measures which would result in the fastest engine shutdown

Results and Discussion

The closing of cowl flaps during any engine-section fire tended to spread the flames over a greater surface area, to retain more heat within the nacelle, and to force fire into the accessory section By being restrained from escaping to the outside, the fuel and fire were forced against the diaphragm and occasionally into the accessory section The flames which escaped through the cowl-flap openings tended to stay close to the accessory-section skin and to penetrate it if possible These were the undesirable features of closing the cowl flaps during a fire in the engine section However, the stainless steel skin on the accessory section of the test installation kept out fires very effectively, and for this reason it was feasible to close the cowl flaps to facilitate extinguishment

It was found that fires would burn out whether flaps were opened or closed, provided that all flammable fluids could be stopped from flowing With the flaps closed, more of the flammable fluid was retained in the zone and the fires tended to continue for a longer period In several tests, fires burning oil at an initial rate of 4 gpm were reduced in size by decreasing the oil flow to zero as the engine stopped turning All such fires burned out completely within one minute of engine shutdown Fires which were extremely large and hot and which extended beyond the trailing edge of the wing were extinguished within five seconds of the time that the emergency procedure was initiated and that the oil supply was cut off completely This occurred whether the cowl flaps were opened or closed as part of the procedure Although the fires usually burned out completely in the engine section, they occasionally found their way into the accessory section Such complications are less likely to occur when cowl flaps are open

Fig 28 demonstrates the effect produced by opening or closing the cowl flaps as part of the emergency procedure when attempting to extinguish an engine fire These curves show the temperature-versus-time relationship at one point in the opening of cowl flap No 2 during four successive oil fires originating in the engine, approximately 17 inches forward of the flaps Time is recorded from the start of each oil fire Each curve shows the rapid initial rise to the maximum within ten seconds from the start of the fire, at which time the emergency shutdown procedure was initiated In three of the fires, the oil was fed at a rate of 4 gpm and in one at 3 gpm Curve No 1 is a record made while the cowl flaps were kept at 75 per cent, which was nearly wide-open, all during the test Curve No 2 differs from No 1 only in that the cowl flaps were opened 25 per cent until emergency action was initiated, at which time they were opened 75 per cent Note the similarity of these curves Curve No 3 is the record of a 3-gpm oil fire test during which the flaps were opened 25 per cent until emergency action closed them completely Curve No 4 differs from No 3 only in the quantity of oil which is 4 gpm instead of 3 gpm Note the similarity of these curves

By comparing Curves Nos 2 and 4, it will be seen that in the case where the cowl flaps were opened as part of this procedure (Curve 2) the temperature returned to ambient very quickly, but, where the cowl flaps were closed (Curve 4), it will be seen that the temperature diminished slowly In each case, the oil flow was reduced simultaneously with the progress of the shutdown procedure so that the oil flow was zero by the time the engine was stopped (eight seconds after the start of emergency procedure) If the supply of oil had not been reduced to zero, the fire would have continued to burn and the size of the fire would have depended upon the amount of oil available for burning

The fact that opening of the cowl flaps tends to cool the section quickly and tends to reduce the possibility of spreading the fire into the accessory section does not mean that opening the flaps is necessarily the best course to follow if the aircraft is equipped with a Zone 1 extinguishing system When the diaphragm is an effective barrier, when the accessory-section skin is stainless steel, and when a Zone 1 extinguishing system is provided, then the cowl flaps could be closed during the emergency procedure Such action would be preferable because it would facilitate extinguishment in Zone 1 This was demonstrated during the extinguishing tests

Because engine fires continue to burn as long as flammable fluid is being fed to the fires and because the longer a fire burns the more damage it does, it appears desirable to provide a Zone 1 extinguishing system

It is also always desirable, even when an adequate extinguishing system is provided, to stop or reduce the flow of flammable fluids before discharging the extinguishing fluid There are two reasons for this (1) extinguishment is facilitated, and (2) the chances for flashback after discharge are minimized

Shutoff valves in the fuel, hydraulic fluid, lubricating oil, and any other lines which could supply flammable fluids to a fire should be closed as part of an emergency

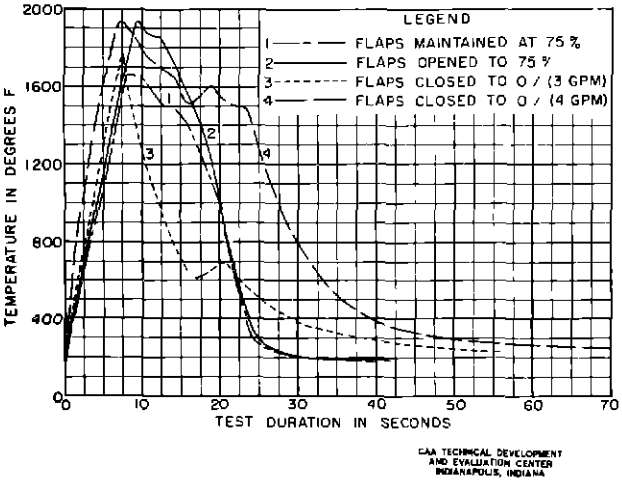


Fig 28 Curves Showing the Effect of Cowl-Flap Opening or Closing on Engine-Section Temperature During Fire-Extinguishing Procedure

procedure In addition, the engine should be stopped so that it will cease to pump oil and will cool off, thus starving the fire and eliminating a source of reignition Stopping the engine usually involves feathering of the propeller as well as some other action or actions

Tests were conducted to determine the most expeditious method of stopping an engine The results of this investigation are shown in Table VII

The test conditions were as follows cowl flaps were maintained 25 per cent open, the engine was operated at 1450 rpm with a torque pressure of 100 psi, and each test was begun when the cylinder-head temperature reached 350°F All actions involved in any one test were simultaneous The wind tunnel was not used in the first 14 tests because the air blast furnished by the tunnel would have caused the engine to windmill, except in those tests where the propeller was feathered, and thus would have prevented a direct comparison of the various combinations In the last three tests, the wind tunnel supplied an air blast of 110 mph

Table VII shows that by simply moving the mixture control to idle-cutoff position or by performing this action plus closing the throttle the engine stopped turning in 14 or 15 seconds (Tests 1 and 2) Closing the fuel valve in addition to either of these actions did not reduce the time appreciably (Tests 3 and 4) Turning off the ignition switch was also of negligible value as long as the mixture control was in idle-cutoff position (Tests 5 and 6), but this step was of prime importance when the mixture control was

TABLF VII

TIME REQUIRED TO STOP TEST ENGINE BY VARIOUS CONTROL COMBINATIONS

Test No	Mixture at Idle Cutoff	Throttle Closed	Fuel Valve Closed	Propeller Feathered	Ignition Off	Methyl Bromide in Carburetor	Time (seconds)
1	x						15 0
2	x	x					14 0
3	x		x				14 5
4	x	x	x				13 5
5	x	x			x		14 0
6	x		x		x		15 0
7			x		x		15 0
8	x			x			9 0
9	x	x		x			8 0
10	x		x	x			8 0
11	x	x	x	x			8 0
12	x		x		x	x	14 5
13			x				41 5
14			x			x	47 0
15	x		x	x	x		7 0
16	x		x	x			7 2
17			x	x	x		7 3

not involved For instance, when action was limited to closure of the fuel valve (Test 13) the engine continued to run for 41 1/2 seconds with a great deal of unevenness and back-firing Test 7 shows that when the ignition was turned off at the same time that the fuel valve was closed, the results were comparable to those obtained by putting the mixture control into idle-cutoff position (Test 1), and no time was saved by adding this step to the others (Test 6)

When the propeller was feathered at the same time that the mixture control was placed in idle-cutoff position (Tests 8 to 11, 15, and 16), or at the same time that the fuel valve was closed and the ignition was off (Test 17), the time was reduced to about 7 to 9 seconds

The extinguishing agent discharged into the induction system was of little value in retarding the engine, as shown by a comparison of Tests 5 and 12 In fact, when methyl bromide was discharged into the carburetor at the same time that the fuel valve was closed (Test 14), the engine continued to run longer than it had without the methyl bromide (Test 13) The wind-tunnel air blast combined with propeller feathering had a marked effect on the performance time, as shown by Tests 15 to 17 which were the only ones of the series in which the wind tunnel was used

In brief, the engine could be retarded most quickly by adjustment of the mixture control to idle-cutoff position or by closing the fuel valve and turning off the ignition The time was not reduced by completing all of these three actions at once, but the latter two were desirable in any event Feathering was most effective and highly important. The discharge of extinguishing fluid into the induction system was of no value with respect to time

The control panel for the XR60-1 test installation, as received from the manufacturer, incorporated an emergency switch which made it possible to accomplish all of the following operations by one action shut off the fuel, hydraulic fluid, and oil valves, open the cowl flaps, set the extinguishing-system directional valves, and feather the propeller Immediately before that action, it was necessary to move the mixture control to idle-cutoff position and to close the throttle As soon as the engine stopped turning, the extinguishing fluid was discharged as a separate action This simplified procedure was a step in the right direction, but efforts should be directed toward the achievement of an even simpler and more effective procedure

In view of the fact that fuel shutoff when combined with engine-ignition shutoff was just as effective in reducing the engine speed as adjustment of the mixture control, there would be no need to operate the latter Since the throttle control would not need to be operated either, the emergency shutdown system could be entirely electrical The extinguishing-fluid discharge operation could be included with the aid of a timing device to delay the action until the engine stopped, or the operation could be left to be completed at the discretion of the crew

Every precaution should be taken to assure that all parts of such a system can withstand fire for a matter of minutes The propeller-feathering mechanism especially should be well protected, since so much depends on engine stoppage, as previous fire investigations have revealed [5] Solenoids and motors would be considerably more heat-resistant if covered with some material such as FRS-10 or Albi-RX All wiring should be of the best available heat-resistant type

All of the efforts heretofore described in this part of the report were directed toward the control of fires which originated within the engine section This section is particularly hazardous because both the flammable fluids and the means to ignite them are always present when the engine is operating But fires are not limited to this section They may originate in the accessory section, in the turbosupercharger section which is under the accessory section, or in other places Such fires could occur as a result of fire spreading from the engine section, as a result of overheating or arcing of some accessory, or by leakage of flammable fluids into the turbosupercharger section In reality, it is all one problem, and while attention was centered on determining the needs for one region at a time, it was necessary in most cases to take adjoining regions into account In an actual emergency in flight, it is not always possible to tell where the fire is located and it is not really necessary that the location be definitely established Whatever emergency action is taken should be effective regardless of the place where the fire is centered Closing of flammable-fluid valves, for instance, is an effective measure regardless of the precise location of the fire in a nacelle

Flames escaping from the accessory section tended to hang behind the open intercooler flaps When extinguishing fluid was discharged within the accessory section, these fires behind the intercooler flaps were unaffected Although the fire within the zone had been extinguished, it was reignited within a few seconds by the fire still hanging behind the flaps With the flaps closed there was no projection from the nacelle surface behind which fires could hang, and therefore this reignition source was eliminated Since the closing of the flaps had no adverse affects, this action should be included as part of the procedure

Previous tests on other installations showed that, "cooling air should flow through the entire oil cooler at all times during a fire "[6] However, there is no oil flowing in the XR60-1 intercooler, and if fire should damage the intercooler, no additional oil would be added to the fire

In summation, much is gained by proper procedure when fires occur in an aircraft power plant Valid reasons were found for opening the cowl flaps and for closing them When the flaps are opened the zone tends to cool more quickly, the leaking fluids have a greater opportunity to escape

[5] Tarbell and Keeler, op cit

[6] A W Dallas and H L Hansberry, "Determination of Means to Safeguard Aircraft from Power Plant Fires in Flight, Part I," CAA Technical Development Report No 33, September 1943, p 38

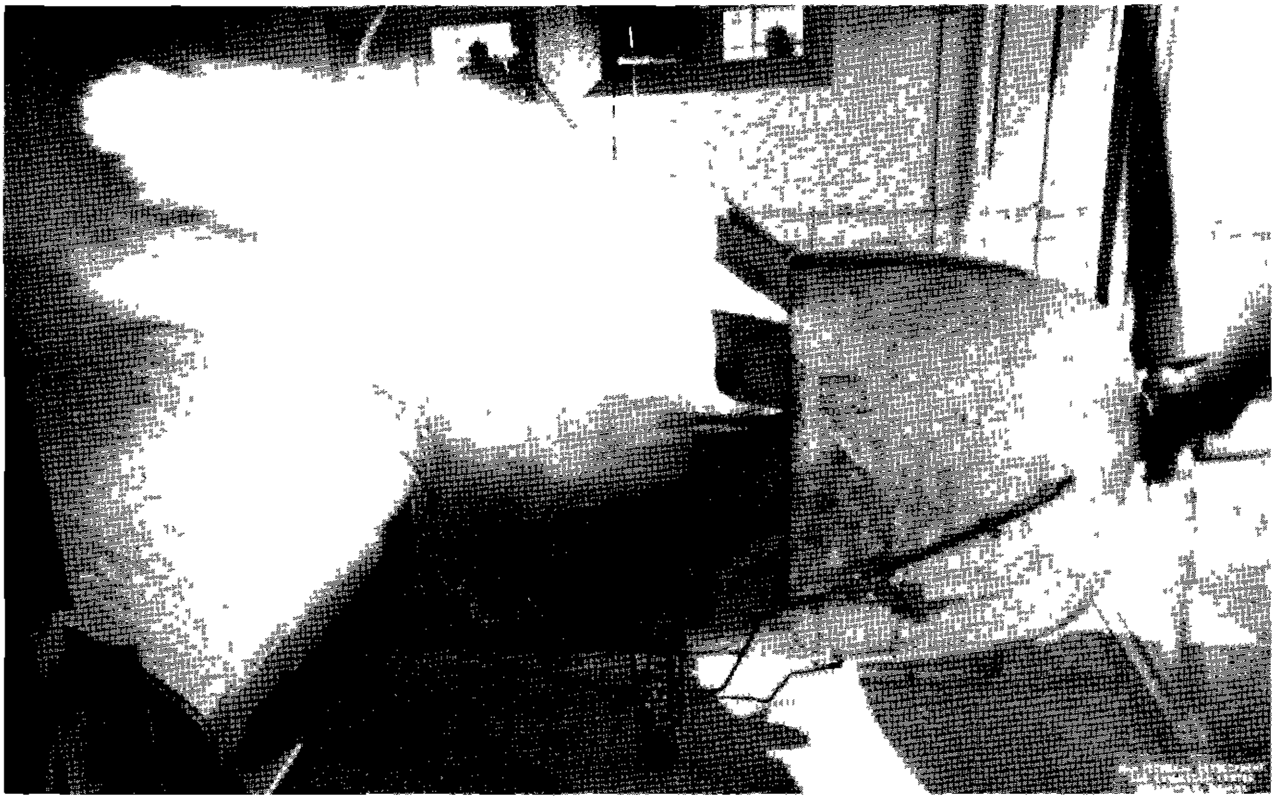


Fig 29 View Showing the Course of a 4-gpm Oil Fire When the Cowl Flaps Are Open

and there is less danger of spreading the fire and forcing it into the accessory section through the diaphragm Finally, the flames leaving the cowl flaps depart from the skin, thereby decreasing the possibility of their entering the accessory section either as a result of the destruction of the skin or as a result of infiltration through louvers Fig 29 shows how the flames of an engine fire tend to depart from the skin when the cowl flaps are open The opening of these flaps is an effective measure when no extinguishing system is available in the engine compartment When one is available in Zone 1 and in the accessory section also, there is a definite advantage gained by closing the cowl flaps before discharging the extinguishing agent If fire should spread to the accessory section, the simultaneous discharge of the agent into all nacelle zones would counteract any ill effects

As to the need for a fire-extinguishing system for an engine section, the indications were clear While it was possible to demonstrate that fires in this section would burn out without the aid of extinguishing fluid, the conditions under which this occurred were not necessarily typical In these tests, the fire fuels were under complete control But since there is no way of guaranteeing that all fluid flow can be stopped from feeding an actual aircraft fire, a more positive means of extinguishment should be available, and this means that the zone should be protected with an effective extinguishing system

In the excitement of an unexpected fire in flight, the crew members must not be required to perform a large number of operations, especially in a fixed sequence They should be able to put into effect all the different operations conducive to successful extinguishment with one or two simple actions If the desired result can be accomplished in this manner, it is not even necessary that they know how many operations are involved or why they are performed The design engineer should relieve them of this analytical process

The tests indicated that immediate stopping of the engine is an effective step in the control or extinguishment of fires and that certain operations were more effective than others in bringing this about The essential operations involved mixture control, or fuel and ignition shutoff, and propeller feathering All flammable-fluid valves should be closed to prevent flow of fluids which will not be stopped by stopping the engine, and the main electrical system should be turned off to remove possible electrical ignition sources

Closure of the intercooler flaps in the test installation was found to be a desirable action because it eliminated a place for residual fires to hang and, consequently, one possible source of flash backs The oil coolers presented no fire problem even though the ducts leading to them were sometimes in the fire path

Conclusions

1 Engine fires will burn out whether cowl flaps are opened or closed, provided that all flammable fluids can be stopped from flowing

2 Closure of the cowl flaps increases the possibility of forcing a Zone 1 fire into Zone 2, but it also assists a Zone 1 extinguishing system to extinguish Zone 1 fires

3 Stopping the flow of flammable fluids aids extinguishment and decreases the possibility of a flash back after the extinguishing system has been discharged

4 Stopping the engine prior to discharge of the aircraft extinguishing system facilitates extinguishment

5 An engine may be stopped most quickly by feathering the propeller and pursuing either or both of the following courses of action (1) adjustment of the mixture control to idle-cutoff position, or (2) closing the fuel valves and turning off the ignition

6 Closure of the intercooler flaps removed a reignition source for Zone 2 fires in the XR60-1 power plant

7 Emergency crew action in the event of a fire in flight should require only one or two simple steps

8 A simplified emergency control panel was feasible

Recommendations

1 In an installation having stainless steel skin covering the accessory section, a sound diaphragm, and a Zone 1 extinguishing system, the cowl flaps should be closed as part of the emergency procedure

2 In an installation lacking a Zone 1 extinguishing system or lacking stainless steel skin around the accessory section, the cowl flaps should be opened as part of the emergency procedure

3 In the event of an engine fire in flight, the affected engine should be stopped as quickly as possible and not restarted until after the airplane lands

4 In the event of an engine fire in flight, all flammable-fluid valves should be shut off

5 Intercooler flaps should be closed as part of the emergency procedure in the case of the XR60-1

6 Extinguishing fluid should be discharged into all potential fire zones simultaneously regardless of the location of the fire which is to be extinguished

7 The fire emergency panel should be as simple in arrangement and as foolproof as possible

MATERIALS AND DESIGN

Purpose

The main purpose of this investigation was to evaluate the fire safety and fire resistance of the design of the power plant, the original materials used, and any changes in design or new materials introduced in the course of the program

Introduction

The power plant of the XR60-1 test installation was well-constructed for withstanding severe fires This is evidenced by the fact that 2010 fires were started inside the nacelle in the course of the test program Some of the fires were small, for all tests did not require large fires Even small fires repeated at the same point can be damaging The large fires naturally were much more destructive both to the inside and to the outside of the nacelle Many parts had to be replaced to keep the power plant in operation Where parts were destroyed and no replacements were available, it was necessary to improvise Toward the end of the program, because of a lack of materials and a reluctance to spend the time making repairs, some of the systems became inoperative Tests were arranged to fit the conditions At the end of the program, the engine was still operating and the basic nacelle structure was intact

Procedure

In the course of the regular fire-test program for the development of fire-detecting and fire-extinguishing systems, certain weaknesses were revealed and changes in design and materials were made as the situation demanded

Results and Discussion

One of the most vulnerable parts of the installation was the metal pan under the engine This pan was actually the upper part of the main air scoop It was made of aluminum alloy and strengthened by aluminum-alloy ribs which were exposed in the engine zone Moderate-sized fires, if they originated on the underside of the engine, could

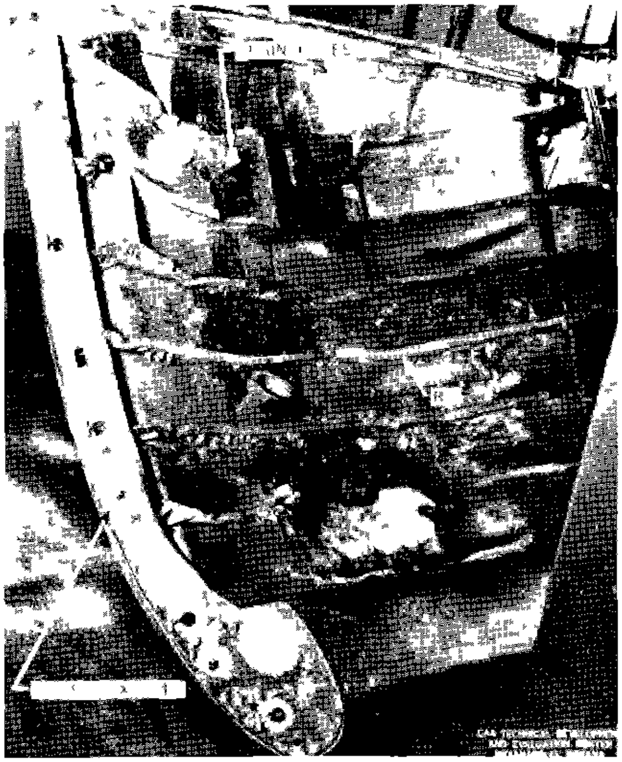


Fig 30 View of Pan Under Engine After Fire

burn through the aluminum alloy within a few seconds

While the metal itself has little resistance to fire, the ribs were partly responsible for its rapid deterioration The ribs acted as lateral barriers which trapped fuel, caused turbulence in the air passing over them, and provided shelter for fires The drainage facilities were incapable of removing even moderate quantities of leaking fuel or oil, and the hazard was compounded

Three severely damaging fires occurred under the engine before corrections were made in the design One of these fires started as a result of the engine backfiring and breaking open oil lines and then igniting the oil The oil could not drain away, and the flames were partially shielded by the ribs from the blast of air entering the zone The fire was difficult to detect and even more difficult to extinguish, and in a very short time it burned through the pan into the main air scoop See Fig 30

A liner of sheet copper was installed to cover the ribs and form a smooth surface Copper was used because it could be shaped easily In production, stainless steel would probably be used A 1 1/2-inch diameter drain hole was provided in the center of the pan

The smooth surface under the engine was found to assist Zone 1 extinguishment, and all of the engine cowling was lined to eliminate ribbed surfaces The liners were not needed to prevent destruction of the upper cowling, because there was very little tendency for the fire to damage it except where the upper cowling mated with the lower

Normally, the rubberized fabric seal between the upper and lower cowling prevented fires from escaping through the joint However, from constant opening and closing of the cowling and exposure to fire, the sealing material became worn and charred to the extent that fire did penetrate The original material was replaced by Silastic X-1740 See Fig 30

In surveying the damage which resulted from the pan fire previously described, it was found that the Silastic had been blackened and charred, especially along sharp, squared edges, but it appeared to retain some resilience It would crack when bent sharply, and hardened portions when broken off and rubbed between the fingers felt like sand A bubble was formed in one place and when broken open was still resilient on the inside The material effectively prevented the fire from escaping through cowling joints

Supplementary bench tests were made of this material under controlled conditions One side of a sheet 1/8 inch thick was exposed to a 2000° F flame for 15 minutes Only that portion of the material which had been in contact with the flame was hardened to a depth of approximately 1/16 inch The remaining 1/16 inch was still fairly pliable

This material may be found suitable where flexibility and fire resistance are desired in an aircraft nacelle and for numerous other applications such as seals, grommets, and duct connections

Some of the parts which first needed replacement as a result of Zone 1 fires were the cowl flaps, particularly the actuating horns The aluminum-alloy flaps were replaced with sheet iron and the horns with bronze castings Although the actuating motors for the flaps were not located in Zone 1, they were damaged by Zone 1 fires and had to be rewound The motors located behind the diaphragm were damaged either by fire or by intense radiant heat which penetrated the diaphragm

In this particular power plant, fires were extinguished with flaps opened or closed, so that precise control of cowl-flap opening was not critical In other aircraft with aluminum skin aft of the fire wall, cowl-flap control can be essential Large cowl flaps were used on the test installation during

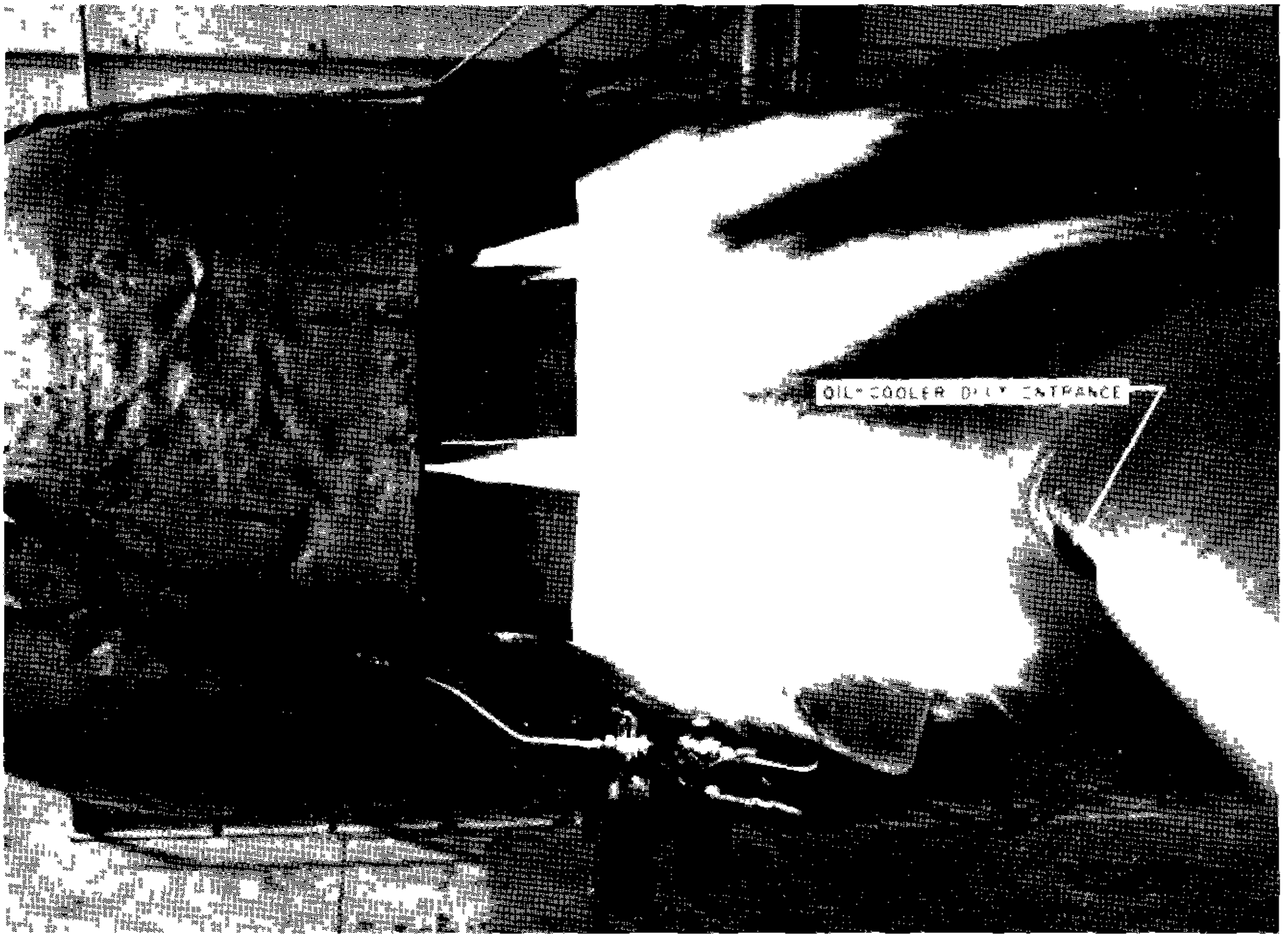


Fig 31 Oil Fire (3-gpm) in Power Section of XR60-1

some of the tests in an effort to see what effect full-closing flaps would have on Zone 1 extinguishment Unfortunately, the flaps did not form a true seal and some of the flames escaped Extinguishing fluid was more effective in Zone 1 when discharged with the flaps closed in this manner than when discharged with the flaps open On the basis of the tests conducted it is not known whether fluid discharged at the front of the zone would purge the zone if the flaps formed a tight seal, although it is possible that the most effective extinguishment could be obtained in this way

When the flaps were closed or nearly closed, the flames spread over the accessory section skin This did not damage the test installation because the skin was stainless steel The fillets between the nacelle and the wing were aluminum alloy and were damaged. Since the flames leaving the cowl-flap openings impinge on the wing surfaces aft of the leading edge for a distance of about two feet out on either side of the nacelles, stainless steel should be used to cover the wings in this area exposed to the flames

The entrances to the oil-cooler ducts were located in the leading edge of the wing, one on each side of the nacelle and approximately ten inches from it Flames of large fires enveloped the duct entrances but did not appear to be drawn into the ducts to any extent See Fig 31 To be out of the paths of fire, the duct entrances would have to be at least 18 inches from the nacelle Subsequent study of the oil coolers failed to show any effects of fire, possibly because the oil coolers were 3 or 4 feet aft of the duct entrances The flaps at the outlets of the oil-cooler ducts were far enough downstream that the fires did not reach them

The fires along the sides of the nacelle burned holes through the intercooler flaps, but this gave no cause for concern The main difficulty with these flaps was associated with accessory-section fires which could spread behind them, escape extinguishment by the agent discharged in the accessory section, and then reignite the original fire This necessitated closing of these flaps prior to fire extinguishment

The construction of the accessory section was such that there was a minimum movement of air through the zone at all times Consequently, the fires confined strictly to the zone did not exceed a certain maximum size and were extinguished with equal facility regardless of whether large or small quantities of fuel were involved

Extinguishment of fires in Zone 4, the region under the floor of the accessory section, was extremely difficult The contained ducts were designed to provide ventilation and cooling for the whole region, but in the process of fitting the ducts in with the various components, pockets were built in unintentionally One of these pockets is indicated as A in Fig 27, and near that is a larger pocket indicated as B These pockets were not well-ventilated, and extinguishing fluid introduced at the entrances to the ventilating and cooling ducts did not penetrate them As a consequence, complete extinguishment of fires in Zone 4 could be accomplished only by discharging additional quantities of fluid directly into the pockets Such measures resulted in a complicated extinguishing system

The engine oil tank before being installed in the nacelle had been given a special covering to protect it from damage by fire The covering, developed by the Lockheed Aircraft Corporation, consisted essentially of Refrasil fibre-glass cloth and a fire-resistant sealing compound called FRS-10 applied in alternate layers and properly cured

The oil tank occupied a position on the left side of Zone 2 When fires were ignited in that zone, the tank was always exposed Many fires were started near the tank not only because it seemed to be a realistic place for them to start, but because fires originating near the tank were more difficult to extinguish than those originating at other points in the zone

After exposure to over 400 gasoline, hydraulic fluid, and oil fires of various sizes, the tank was still undamaged There is no way of knowing how important the covering was in keeping the tank intact, because no unprotected tank was subjected to the same conditions However, it has been demonstrated that an unprotected oil tank nearly full of oil, as the tank was during the tests, will fail only after several minutes of continuous exposure to fire[7] The tank in Zone 2, although subjected to fires many times, was not exposed to more than a one-half minute fire in any single test

Refrasil cloth and FRS-10 were also applied to the Y-duct which goes into the carburetor These materials were applied under difficult working conditions while the duct and carburetor were in place in the nacelle In spite of this fact, the duct remained undamaged in any way by the fires to which it was exposed

Fire-resistant hoses produced by Aeroquip Corporation and fireproof flexible metal hoses produced by Titeflex, Incorporated, were used in Zone 2 throughout the tests The Titeflex hose which carried gasoline was known to be exposed to the main body of fire by the erratic action of the engine The fire appeared to starve the engine temporarily and cause it to operate unevenly At the end of the tests both types were undamaged After removal from the engine, they were subjected to pressures up to 1000 psi without failure

During the detector tests, two types of wire were used to connect the detector units Both of these were used when the Fenwal detectors were installed On the right side of the nacelle, Fig 3B, Rockbestos Firezone wire was used, and on the left side, Fig 3A, Inconel-covered wire was used The latter consisted of a No 18 tinned-copper conductor covered with glass braid and a wall of felted asbestos with glass-yarn braid both shielded with seamless Inconel tubing of 1/8-inch inside diameter (ID) and 0 010-inch wall thickness This wire is a patented Metal Shielded Wire manufactured by Uniform Tubes of Collegeville, Pa The tubing not only provided protection for the insulation on the wire during a fire but also protection against mechanical damage, and at the same time it lent stiffness to the wire which made it easy to support

Fires impinged directly on both types of wire many times before any deterioration was evident Eventually the insulation on the Firezone wire hardened and chipped off leaving the bare wire exposed If the insulation on the other wire did the same, it was not apparent because the tubing held it in place Either of these types of wire would be able to withstand the effects of fire long enough to transmit a fire signal if the insulation had not been damaged previously

Tests were made of the effectiveness of Albi-RX in protecting equipment on the engine Where it was applied to metal surfaces it remained intact and was not affected by engine heat On rubber, such as the ignition harness leads, the material had poor

[7] J J Gassmann, "Investigation of the Vulnerability of Aircraft Engine Oil Tanks to Accessory Section Fires," CAA Technical Development Report No 159, Feb 1952

adherence characteristics and chipped extensively leaving the leads unprotected On all surfaces where the adherence was good, the material fluffed up into a fairly thick protective coating during fires

Conclusions

As a result of constant observation of changes made and materials substituted during the program, the following conclusions were reached

1 The pan under the engine had three weaknesses (a) the aluminum alloy of which the pan was made was not fire-resistant, (b) the lateral ribs caused turbulence of the air and prevented rapid drainage of accumulated fuel and oil, and (c) drainage from the pan was inadequate

2 The original rubberized fabric used as a sealing material between the upper and lower parts of the cowling was fairly effective in retaining fire within the engine section as long as the fabric was free from breaks

3 Silastic X-1740 made an effective sealing material because of its fire resistance and resilience

4 Aluminum-alloy cowl flaps were damaged by engine-section fires

5 A large engine-section fire could damage cowl-flap actuating motors located aft of the diaphragm if the fire continued for a long period with the flaps in a closed or semiclosed position

6 The stainless steel used as skin material aft of the cowl flaps effectively prevented fires which emerged from the cowl flaps from burning through the skin and entering the accessory section

7 The flames emerging from the cowl flaps, although they enveloped the oil-cooler duct entrances, did no serious damage to the oil coolers

8 The intercooler flaps, under certain conditions, can complicate the extinguishing problem by providing a shield behind which extensions of a Zone 2 fire can persist

9 Pockets exist in Zone 4 where small fires can persist and complicate the extinguishment problem

10 The protective covering of Refrasil cloth and FRS-10 was effective in preventing the oil tank and the Y-duct from fire damage

11 Fire-resistant Aeroquip hose and Titeflex flexible metal hose were relatively undamaged by the numerous fires to which they were subjected

12 Rockbestos Firezone wire is sufficiently fire-resistant to be used in connecting fire-detector systems electrically

13 Inconel-covered heat-resistant Metal Shielded Wire was sufficiently fire-resistant, abrasive-resistant, and stiff to be suitable in fire-detector systems

14 Albi-RX adhered to metal parts in the engine section and protected them from fire, but it chipped off and gave little protection to rubber parts

Recommendations

1 The internal surface of the cowling, especially underneath the engine, should be made aerodynamically clean

2 Some material more fire-resistant than aluminum alloy should be used underneath the engine

3 Adequate drainage facilities should be incorporated in the engine section to drain accumulated fuel and oil rapidly

4 Silastic X-1740 should be given consideration for use as fire-resistant sealing material where flexibility is desired

5 In addition to its use as nacelle skin, stainless steel should be used to cover the wings within two feet of the nacelle

6 Pockets in Zone 4 should be ventilated so that fire cannot persist in them or should be handled as individual fire-extinguishing problems

7 FRS-10 when used alone or with Refrasil cloth should be considered as a fire-protective covering on any accessories and components which may be subjected to abrasion

8 Albi-RX should be considered for use as a fire-protective coating for metal surfaces which are not subject to abrasion

9 Flexible connections for the main fuel and oil lines should be as fireproof as possible

10 Fire-resistant wire such as the Firezone or Inconel-covered wire should be used in fire-detector systems

IGNITION SOURCES

Purpose

The purpose of these investigations was to determine the locations within the nacelle of any areas which appeared to be hazardous from the standpoint of fire ignition and if possible to eliminate the sources of such hazards

Procedure

The investigations were carried on during the program before fire tests were conducted in each zone or whenever results indicated that ignition was occurring in some manner which was not clearly understood To accomplish this phase of the program aviation gasoline, aircraft hydraulic fluid, and hot lubricating oil were released in

TABLE VIII

IGNITION SOURCE TESTS

Test No	Engine (rpm)	Cylinder-Head Temperature (degrees F)	Cowl-Flap Opening (per cent)	Tunnel Air Speed (mph)	Fluid	Fluid Origin	Fluid Flow (gpm)	Ignition
1	1450		25	110	Oil	Crankcase*	2 5	No
2	1450	450	25	0	Oil	Cylinder No 2B	2 0	Yes
3	1450	460	25	Just Starting	Oil	Cylinder No 2B	2 0	Yes
4	1450	450	25	110	Oil	Cylinder No 2B	2 0	No
5	1450	450	25	0	Oil	Shroud Bank 2	0 to 4	Yes
6	1450	450	25	0	Oil	Main Bank 1	0 to 4	Yes
7	1800	400+	Not Pertinent	110	Gasoline and Hydraulic Fluid	Exhaust Elbow	0 28 + 6	No
8	1800	400+	Not Pertinent	110	Gasoline and Hydraulic Fluid	Floor Depression	0 28 + .6	No
9	1800	400+	Not Pertinent	110	Gasoline and Hydraulic Fluid	Through Louvers	0 28 + 6	No
10	1800	400+	Not Pertinent	110	Gasoline and Hydraulic Fluid	Zone 2 Hole	0 28 + 6	Yes**
11	1800	450	Not Pertinent	0 to 110	Gasoline and Hydraulic Fluid	Heat-Exchange Duct	0 28 + 6	No
12	1800	450	Not Pertinent	0 to 110	Gasoline and Hydraulic Fluid	Intercooler and Stack	0 28 + .6	No

* Crankcase between banks 2 and 3.

**Ignition occurred only after engine shutdown.

spray form at selected points near the engine and accessories while normal and abnormal operating conditions were in effect

Results and Discussion

The recommended maximum temperature of the engine cylinder head was 475° F All the regular aircraft flammable fluids could be ignited on the hot exhaust stacks when cylinder-head temperatures were less than this allowable maximum The ease with which ignition took place was influenced by other factors These were the engine speed, the per cent of cowl-flap opening, the speed of the air supplied by the wind tunnel, the location of the source of the flammable fluid, the quantity of fluid involved, the rate of fluid discharge, and the fluid itself

The results of this phase of the investigation are given in Table VIII None of the tests in this table show gasoline alone as the test fluid, but preliminary investigations of sources of ignition proved that gasoline could be ignited on the engine exhaust stacks under many air-flow conditions and engine settings Tests Nos 1 to 6 involve the use of hot (200° F) oil and are similar in all respects, except for the amount of air furnished by the wind tunnel The tendency to ignite seemed to be reduced by increased air flow through the engine section

A brief study was made of the effect of exhaust-stack shrouds on the ignition of oil Test 5 of Table VIII, which represents four attempts with the same results, shows that oil introduced between a shroud and an exhaust manifold would ignite under normal conditions Test 6 shows that ignition also occurred when the oil was sprayed on a bare exhaust manifold The two tests indicated that ignition could occur with or without shrouded manifolds The quantity of oil used in these tests was varied, but ignition took place when the flow was between 0 and 4 gpm

Gasoline and hydraulic fluid were sprayed on the lower elbows of the exhaust collector ring (Test 7) so that the fluid could follow the exhaust stacks back to the turbosupercharger These flammable fluids were then sprayed into the depression under the engine in the accessory section in the expectation that they would find their way through cracks and onto the stacks and turbosupercharger Finally, the gasoline and hydraulic fluid were sprayed from below into the exhaust stack and turbosupercharger well As a further and more thorough test of this latter procedure, attempts were made to obtain ignition with and without the turbosupercharger in operation and with and without the tunnel in operation No fires resulted from any of these tests while the engine and wind tunnel were operating, even though the engine cylinder-head temperature was in excess of 400° F

When gasoline and hydraulic fluid were introduced into the turbosupercharger region through a hole in the floor of the accessory section, fires ignited and explosions occurred immediately after the engine was shut down from an overheated condition The fire could not be controlled by the wind-tunnel blast and was unaffected by the discharge of three pounds of methyl bromide into the accessory section

Other possible hazards in the same general region were studied by spraying gasoline and hydraulic fluid into the heat-exchanger duct and into the underfloor ventilating air ducts See Fig 26 for location of these ducts No fires were ignited even when a spark-plug ignitor was arcing inside the accessory section The engine was operated at 1800 rpm with and without added air from the wind tunnel, and the cylinder-head temperature was above 450° F Even shutting down the engine quickly from a heated condition did not cause the fluids to ignite

In these tests, the sources of ignition were obviously the hot surfaces existing within the nacelle

Some fires occurred from another cause, the backfiring of the engine During fire tests of the engine section, severe damage was done to the ignition harness Considerable roughness and backfiring of the engine resulted Once, as the engine was being warmed for fire tests, backfiring followed by fire occurred before any fuel was released Examination of the engine section led to the belief that some of the severe initial backfiring had blown off small sections of drain line and had released a quantity of oil into the pan under the engine Additional backfiring ignited this accumulated oil

On two other occasions, backfiring was the cause of accidental fires in the accessory section In each instance, the metered fuel-line connection at the carburetor had become loose and allowed gasoline to spray into the zone This may or may not have caused the engine to backfire, but the backfiring through the induction system ignited the gasoline It must be pointed out that the induction system during this period was not in good condition One of the bird-cage doors, which are located in the intake ducts as a release to prevent collapse of the ducts when there is no ram air present, had become detached As a result, an opening existed in the duct through which fire could be admitted to the zone whenever backfiring occurred

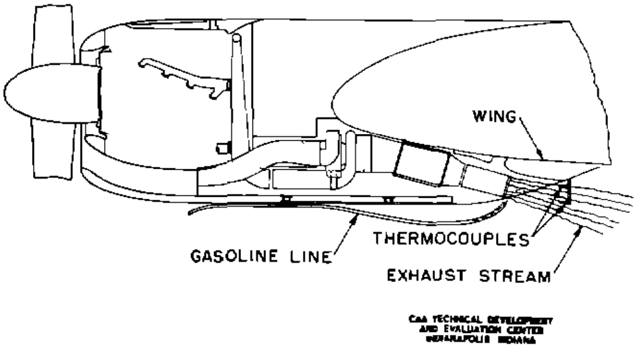


Fig 32 Arrangement Used to Study Ignition of Gasoline by Hot Exhaust Gases

Either of these types of fires could conceivably occur in flying aircraft under similar conditions, although the better maintenance of flying aircraft should make such a possibility remote

No induction-system fires occurred accidentally in any of the tests during the fire-test program No specific tests were conducted on this phase of the aircraft fire problem because it had already been established (as a result of a special series of tests conducted by the Experimental Department of Pratt & Whitney Aircraft, Division of United Aircraft Corporation) that induction-system fuel fires are not self-sustaining in the R-4360 engine [8] Moreover, the replacement of the magnesium inducer (used in early engines) by an aluminum inducer practically eliminated the danger of any type of induction-system fire within the engine even when mechanical failure occurs

Although hot surfaces in the presence of highly flammable fluids would seem enough to cause a fire, the suggestion has been made that the exhaust gases are the real ignition sources This suggestion stemmed from a study of fires occurring in aircraft with short exhaust stacks A flammable-fluid leak occurring in such aircraft could conceivably produce a vaporous atmosphere surrounding the exhaust stacks It has been theorized that (1) changing the fuel mixture of the engine from lean to rich in the presence of such an atmosphere extends the exhaust flame to some part of the atmosphere where the velocity of the flame propagation is greater than the velocity of the slip stream, or (2) reduction of the velocity of the slip stream (by reducing the speed, opening flaps, and the like) to a point less than the velocity of flame propagation of the air-fuel mixture produces the same effect with the shorter exhaust flame As a result, fluid leaks can be ignited

In the XR60-1 test installation, the exhaust gases leave the tail pipe at a considerable distance from the engine This condition is entirely different from the one which exists in an installation having short stacks Since the installation could not be easily transformed to resemble an installation with short stacks, the theory could not be verified in a straightforward manner It did seem advisable to conduct a limited number of tests in an effort to learn what effects, if any, would be produced in a flammable atmosphere by the exhaust gases when changes were made in the engine fuel mixture or when the simulated air speed was varied Fig 32 is a sketch showing how a gasoline line was attached to the underside of the nacelle in such a manner that a spray of gasoline could be mixed with the engine exhaust gases Thermocouples were used to measure the exhaust-gas temperature Operation of the engine at 1800 rpm produced exhaust-gas temperatures as high as 900° to 1000° F While these conditions were maintained, gasoline was sprayed into the exhaust gases in quantities from 0 to 3 gpm Simultaneously the engine fuel mixture, the flaps, the wind-tunnel air speed, and the engine rpm were varied No indication of flame propagation was noticed by any of the observers during this period

The condition of the engine was such that considerable misfiring of the cylinders occurred at all times, but even this did not ignite the gasoline The ignition of the gasoline was finally achieved by backfiring the engine, but the flame blew out immediately afterward Torching could not be produced at the end of the tail pipe, so this condition could not be tested

Conclusions

1 Gasoline, hydraulic fluid, and lubricating oil will ignite on the engine exhaust system under normal operating conditions

2 Readiness to ignite is influenced by engine cylinder-head temperature, engine speed, per cent of cowl-flap opening, simulated forward speed, location of the flammable-fluid sources, and the quantity of fluid involved

3 The tendency for ignition to occur on the engine is diminished by increased air flow through the engine section

4 Ignition can occur on the engine exhaust manifolds whether they are shrouded or not

[8] "Report on R-4360 Engine Induction System Fire Investigation," PWA-643, Pratt & Whitney Aircraft, Division of United Aircraft Corporation, November 26, 1946

5 Leakage of flammable fluids into the heat-exchanger duct, the underfloor ventilating air duct, or the ventilating air duct of the turbosupercharger compartment was not a serious hazard under flight conditions

6 Leakage of flammable fluids into the turbosupercharger region can result in ignition of the fluids and in explosions after engine shutdown

7 Backfiring can cause fires to ignite in both Zones 1 and 2

8 The metered fuel-line connection at the carburetor is a possible source of gasoline leakage in Zone 2

9 Induction-system fires were not a problem in this installation

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