DETERMINATION OF MEANS TO SAFEGUARD AIRCRAFT FROM POWERPLANT FIRES IN FLIGHT

PART I

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SUMMARY

The problem of providing adequate fire protection, in flight, for modern, tightly cowled, air-cooled radial aircraft powerplant installations of conventional design was attacked experimentally. A full scale, operating Douglas DC-3 engine-nacelle-wing combination was constructed and placed in a controlled air blast to simulate actual flight conditions. Quantities of gasoline and oil were ignited at locations throughout the powerplant installation where fire might occur as a result of failures of the engine or the fuel or oil systems.

The test procedure consisted of 4 phases of investigation: (1) fire detection, (2) fire extinguishment, (3) effect of fire on materials, and (4) sources of ignition.

The detection tests proved that quick, positive fire detection of gasoline and oil fires is practical. Design criteria for detectors and the method of correctly locating the detectors in the powerplant installation are given.

The extinguishing tests showed that the extinguishing of fuel and oil fires in flight is practical within certain limitations of fire size and duration. Such limitations arise primarily from the necessity of using extinguishing systems of reasonable size and weight. In addition, the tests resulted in an evaluation of various fire extinguishing agents, the determination of optimum methods of application of the agents to the powerplant installation, and the establishment of correct operating conditions during extinguishment. Criteria for the detailed design of fire extinguishing systems are presented.

The tests on materials were confined to the actual materials and equipment comprising the test set-up. During oil and gasoline fires of various sizes and in various locations, temperatures of cowling, wing, and nacelle skin, and the firewall were recorded. In addition, observations were made of the general effect of fire on the oil and gasoline systems, the engine accessories, the oil tank and cooler, the engine mount, the landing gear and tire, and miscellaneous components. The superiority of steel over aluminum alloy in locations of high temperature, and the ability of filled oil systems to withstand serious fires were clearly indicated in the tests.

The ignition tests were conducted to determine the possibility of spontaneous ignition of fuel and oil. The tests clearly indicated that ignition sparks, exhaust system muffs for obtaining carburetor heat, or cracks and openings in the exhaust system are possible ignition sources. These tests also showed that spontaneous ignition would not occur on unmuffed exhaust systems in good condition.

In general, the methods developed to provide adequate powerplant fire protection in flight, and variations of these methods, should lead to practical solutions of the problems encountered in this field of fire protection.

INTRODUCTION

The problem of applying additional safety measures against fires in the powerplants of public air carrier aircraft became urgent during the latter part of 1938, because of the occurrence of several engine cylinder failures in flight, some of which resulted in powerplant fires. The Civil Aeronautics Administration was requested by the air transport industry, through the Air Transport Association, to expand a fire test program, then being planned, to include investigations on fire detection, extinguishing, and other pertinent phases of the fire problem in an effort to reduce the hazards associated with aircraft powerplant fires. Accordingly, the Technical Development Division of the Civil Aeronautics Administration began the investigation by circulating questionnaires throughout the industry which resulted in the preparation of a proposed test program for the approval of all concerned. Actual tests of a DC-3 type powerplant installation were started in November, 1939, and concluded in May, 1941. Tests on other type installations were immediately begun and are now in progress.

The ever-present quantities of fuel and oil may be released by the failure of fuel and oil systems, or by engine structural failures, and ignition may follow from sparks (friction, static or ignition), or from the exhaust system. The control of fires thus started and the reduction of their damaging effects is of primary importance.

Most present day aircraft are not equipped with fire detectors or with means for shutting off the flow of engine oil while in flight. Fire-proof steel bulkheads separate the engines (power sections) from the accessory sections, and the accessory sections from the nacelles in air carrier aircraft, but aluminum alloy is used extensively throughout the rest of the engine installation and in the nacelle construction. Fire extinguishing systems are confined to the accessory sections and these normally consist of perforated aluminum alloy tubular rings connected to a supply of carbon dioxide located elsewhere in the airplane. Little effort has been made to provide fire protection in the power section of a radial air cooled engine.

Little was known of the efficacy of the accessory section fire extinguishing systems commonly used and almost nothing was known of power section protection. Available literature on aircraft fire protection revealed that some full scale testing had been done by the military services and private industry. However, in these tests, actual flight conditions were only partially simulated and the test equipment consisted mainly of now obsolete in-line engines. It was obvious that the results of such tests were inadequate for application to modern, high powered, tightly cowled, air-cooled radial engine installations.

Because of the meager and inapplicable information available on the subject of aircraft powerplant fire protection, it was decided to conduct a comprehensive test program including as objectives investigations of fire detectors, fire extinguishers, materials and equipment, and fire ignition possibilities. Information was desired as follows

1. Fire detectors: Determination of suitable detector types for powerplant use and of optimum detector locations in the powerplant installation. Also, information on time of operation, ability to withstand severe operating conditions and proof against false alarm.

2. Fire Extinguishers: A knowledge of the possibilities of extinguishing fires in aircraft powerplants, evaluation of fire extinguishing agents and methods of their application. Information on the rates and durations of their applications in the power and accessory sections, on the weights of the agents and distribution systems, and on the design of the necessary piping and controls.

3. Materials and Equipment. Determination of the relative fire resistant properties of various materials comprising powerplant installations and of the temperatures encountered in the cowling, firewall, nacelle and wing during typical oil and gasoline fires. Also, information on the proper use of materials to obtain maximum fire protection.

4. Fire Ignition Possibilities Information on the causes of ignition of oil and gasoline fires and the determination of methods whereby this hazard may be reduced.

It was considered necessary to simulate, as closely as possible, the conditions existing in an aircraft powerplant installation in flight. This simulation required the use of an operating full scale engine installation, nacelle, and wing section with the necessary controls and a wind tunnel to produce an air blast to simulate the forward motion of the airplane.

The tests described in this report pertain only to radial air cooled aircraft engines of conventional design, as described on Page 5. However, certain results of this program are applicable to other powerplant installation types.

Through the cooperation of the National Bureau of Standards, where all tests were conducted, an outside wind tunnel and other necessary facilities were made available.

As this test program was the first of its type and highly important to aeronautical safety, and because of the lack of published information on the subject, it was considered desirable to solicit the advice and suggestions, before and during the tests, of experts in this field. Excellent cooperation was received and acknowledgment is given to the following organizations, which supplied the personal services of their engineering staffs, valuable test materials, and equipment·

Aluminum Company of America
American Airlines, Inc.
American District Telegraph Company
American-LaFrance-Foamite Corporation
American Steel and Wire Company
Carnegie-Illinois Steel Corporation
Douglas Aircraft Company, Inc.
Dugas Engineering Corporation
Eastern Air Lines, Inc.
Eclipse Aviation
Edward G. Budd Manufacturing Company
Fenwal, Inc.
National Bureau of Standards
Pan American Airways, Inc.
Phister Manufacturing Company
Pratt & Whitney Aircraft
Pyrene Manufacturing Company
Stop, Inc.
Summerill Tubing Company
The Fyr-Fyter Company
The Sealand Corporation
The Weatherhead Company
Thomas A. Edison, Inc.
United Air Lines Transport Corporation
United States Navy Department
Walter Kidde & Company

DESCRIPTION OF TEST EQUIPMENT

A sketch of the complete test layout is shown in Figure 1, and a sketch of the nacelle unit in Figure 2. A photograph of the test set-up is shown in Figure 3.

The wing, nacelle, powerplant test set-up was identical in dimensions to a standard commercial Douglas DC-3, Pratt & Whitney 1830-B engine installation. (See Figures 4 and 5). The engine installation proper was identical to that of the DC-3 except that a special oil system was installed in which the oil tank was located ahead of the firewall. (See Figure 6.) A standard DC-3 firewall and engine mount were used. All engine accessories, fuel lines, and the outside of the oil cooler were protected against fire by a lagging, consisting of asbestos cloth soaked in waterglass. In the early fire tests the crankcase also was lagged but this was later found to be unnecessary. The oil system (including tank), firewall and engine mount were unprotected. A photograph of some of the lagging used appears in Figure 5.

The engine was completely equipped for remote control operation during the tests.

The test equipment consisted of:

Engine: Pratt & Whitney 1830-SB3G, Wasp - 14 cylinders, twin row, radial, air-cooled aircraft engine, rated at 1000 HP at 2650 RPM (Take-off power), and 900 HP at 2450 RPM (Maximum except take-off power).

Propeller. Hamilton Standard, 3 blades, metal, constant speed, controllable pitch, 11 1/2 feet in diameter, type 3E50.

Engine Cowl: Standard DC-3 aluminum alloy NACA cowl equipped with adjustable aluminum alloy cowl flaps.

Accessory Section Cowling: Standard DC-3 accessory section cowling of .049 aluminum alloy and .018 stainless steel, of the 18-8 Grade Type 302.

Engine Air Intake System. Hot and cold air intake systems as shown in Figure 7.

Nacelle and Wing Section. External dimensions identical to DC-3, skin of .012 stainless steel, of the 18-8 Grade Type 302. Nacelle and wing skin carried no load. Engine loads supported by internal welded steel tube truss shown in Figure 8. The wheel well in the nacelle was fitted to receive a standard DC-3 landing wheel.

Engine Control Shed: (See Figure 1) Houses engine controls and instruments, oil and fuel control valves, controls for regulating fires in the powerplant, a bank of 25 pyrometers and recording camera and a detector signal panel. See Figures 9, 10, and 11.

Oil and Fuel Tower: (See Figure 1) Supported drums containing gasoline for engine operation and gasoline and oil for producing fires. Oil drum was equipped with immersion type electrical heaters. A diagrammatic sketch of the piping from the tower, through the engine control shed, to the powerplant installation and the fire nozzle is shown in Figure 12.

Fire Nozzle: (See Figure 13) The fire nozzle was attached to flexible tubing to permit application at any point within the powerplant installation. A small auxiliary gasoline supply line was attached to the main nozzle to supply small quantities of gasoline to facilitate the ignition of the oil. An aircraft spark plug for producing a high tension ignition spark was provided at the nozzle outlet.

Extinguisher Shed: (See Figure 1) Housed the extinguishing agent containers and valves which were connected by the extinguisher feed lines to the power and accessory section distribution systems.

Wind Tunnel: (See Figure 1) Maximum air speed at outlet was 70 m.p.h.; outlet diameter 7 feet; outlet located 5 feet forward of propeller.

GENERAL TEST PROCEDURE

In order to properly simulate the condition of fire in flight it was necessary to control the two principal factors involved - air blast and fire conditions.

The volume of air passing through the power section was of major concern and was affected by cylinder baffling, wind tunnel air speed, engine speed, and the degree of cowl flap opening. The maximum wind tunnel outlet air speed attainable was approximately 70 m.p.h. The standard inter-cylinder baffles were removed (See Figure 5) to simulate higher air speeds by allowing a greater volume of air to pass through the power section. (See discussion under Section 2 for effect of air blast on extinguishment.) The approximate air volumes passing through the power section, measured by means of a pitot static tube, were as follows.

AIR VOLUMES

Flaps	Wind Tunnel Air Speed	Engine Speed	Airflow lbs/hr
Full Open (23°)	70 m.p.h.	0	46,500
Full Open (23°)	70 m.p.h.	2000 r.p.m.	69,100
Closed	70 m.p.h.	0	33,100
Closed	70 m.p.h.	2000 r.p.m.	49,800

Except in a few instances, all the tests were run at 70 m.p.h. wind tunnel air speed, at 2,000 engine r.p.m. and with the cowl flaps fully open. (The tests indicated that the use of greater air speeds would not alter the general conclusions.)

The factors affecting fire condition were: type of fuel burned; fuel flow rate; fire location, and fire duration.

No. 10 SAE oil, rather than heavier oils, was used in the majority of oil fire tests to facilitate handling and ignition. Some tests were conducted using actual 100-hour aircraft engine drain oil to compare the burning characteristics of the light and heavy oils. In all cases the oil was preheated to 300° F. to simulate the release of hot oil from an overheated engine.

87 Octane aviation gasoline and safety fuel were used in the fuel fire tests in the accessory section. The safety fuel flash point was 105° F, and the distillation end point 400° F.

The maximum rate of oil flow used to feed power section oil fires was 5 g.p.m. (gallons per minute). The oil weighed 6.5 pounds/gallon. This corresponds to an engine oil inlet rate of 130 pounds/minute, if it be assumed that 25 percent of the inlet oil reaches the power section and flows out through a fracture. Further, if the engine were stopped and the oil flow shut off at the tank immediately after an actual fracture occurred, the 5 g.p.m. maximum oil flow used in the tests would correspond to 2.5 gallons of residual oil uniformly jettisoned for 30 seconds. Figures 14, 15, and 16 show typical 5 g.p.m. oil fires with the source in the power section. Tests were also conducted using flow rates of less than 5 g.p.m. for comparative results.

The maximum rate of oil flow used to feed accessory section oil fires was arbitrarily set at 11 g.p.m. Fires burning such a quantity of oil could occur as a result of rupture of the oil tank or of the oil lines between oil tank, engine and oil cooler. An 11 g.p.m. oil fire with the source in the accessory section is illustrated in Figure 17.

The rates of gasoline flow used to feed accessory section gasoline fires were varied from .33 to 7 g.p.m. Figures 18 and 19 show 6.5 g.p.m. gasoline fires with the source in the accessory section. Tests were conducted in which gasoline was allowed to accumulate in the accessory section prior to ignition (explosion ignition).

In the power section, fires resulting from cylinder failures were simulated by introducing a burning stream of oil between the engine cylinders. The fire nozzle is shown in the power section in Figure 20. The nozzle direction was varied at each inter-cylinder location around the engine. The fore and aft limits of the fire nozzle locations were the forward edge of the front row cylinders and the rear edge of the rear row cylinders, and the radial range extended from the crankcase out to the cylinder heads. In addition, the fire nozzle was located just aft of the propeller to simulate a propeller governor oil supply line failure.

In the accessory section, fires resulting from oil and fuel line failures were simulated by placing the fire nozzle outlet just inside the accessory section cowl (See Figures 35 and 36). This was done at four locations around the cowl and, at each location, the nozzle angle was varied with respect to the cowl.

The fire duration used in the majority of tests was limited to 30 seconds. It was assumed that an airplane crew, aided by a quick acting fire detector, would apply the fire extinguisher well within this time. Tests were also conducted using very short fire durations to simulate automatic fire extinguishing systems.

The test fires were ignited by an electric spark. In the case of oil fires a small stream of gasoline was first ignited by the spark to facilitate the ignition of the oil.

SECTION 1 - DETECTORS

PURPOSE

The purposes of the tests on fire detectors were:

(1) To develop, test, and compare various types of fire detectors to be used for detecting gasoline and oil fires occurring in both the power and accessory sections of an aircraft powerplant in flight, and

(2) To determine for each detector type the number required, the optimum locations, and the time necessary for operation.

DESCRIPTION OF DETECTORS TESTED

All suitable types of fire detectors were investigated to determine those which might best be used in aircraft powerplant installations, and as a result, several types were obtained and tested. The detectors tested were of two general classifications - unit and continuous. A unit detector is an individual type capable of detecting flame at or near the particular detector location. (See Figures 22 to 28.) A continuous detector may be in the form of a wire capable of detecting a fire anywhere along its length (see Fig. 21). A continuous detector could be considered a large number of unit detectors connected closely together in series.

Five detector types tested were:

(1) Flame types which operate by the burning of a combustible material, which forms a part of the detector element.

(2) Metal expansion types which operate on the principles of direct or differential expansion of metals due to increases of temperature.

(3) Fusible alloy types which operate by the melting of metal alloys.

(4) Thermocouple type which is operated by an excessive rate of temperature rise.

(5) Ionization type which is operated by the electrical conducting properties of a flame.

The individual detectors tested are described as follows:

Unit Flame Type - Walter Kidde & Co. See Figure 22.

The flame detecting elements of this detector consist of two nylon elements in tension, holding open two spring loaded electrical contacts contained within a switch housing. Two nylon strands are provided to prevent a false alarm due to the accidental breakage of either strand. The nylon strands are furnished in two lengths - 3/8 and 1 3/4 inches, and two diameters - .012 and .016 inches.

Unit Flame Type - Dugas Engineering Corporation. See Figure 23.

The flame detecting element of this detector consists of a flame sensitive cord holding an electrical switch in the open position by means of a metal clip.

Unit Flame Type - Graviner Manufacturing Co., Ltd. See Figure 24.

The flame detecting element of this detector consists of a cotton flame link which holds a spring loaded electrical switch in the open position.

Unit Metal Expansion Type - American District Telegraph Company See Figure 25.

This detector consists of a convex sheet metal disc fixed to a base at three points on its periphery. An increase of temperature causes the disc to "oil can" making electrical contact between a plunger on the disc center and contact points built into the base.

Unit Metal Expansion Type - American-LaFrance Foamite Corp. See Figure 26.

This detector is similar in operation to the American District Telegraph Company type described above but differs in detailed design. See Figures 25 and 26 for comparison.

Unit Metal Expansion Type - Thos. A. Edison Inc. See Figure 27.

This detector operates on the principle of bimetallic strip deflection and resultant electrical contact. The entire unit is enclosed in glass.

Unit Metal Expansion Type - Fenwal, Inc. See Figure 28.

This detector consists of a hollow cylindrical metal housing enclosing two curved metal strips, the ends of which are securely attached to the ends of the housing. Longitudinal expansion of the metal housing results in lateral displacement of the metal strips breaking the electrical contact between them.

Continuous Fusible Alloy Type - Fenwal, Inc. See Figure 29.

This detector consists of a wire conductor upon which are strung porcelain beads of uniform size. This "necklace" is enclosed in a sheathing of soft tin alloy plated with nickel. The melting point of the alloy sheathing determines the temperature at which the detector operates. When this temperature is reached the alloy fuses but the nickel plating, having a much higher melting point, remains in tubular form. The fused alloy then completes an electrical circuit between the nickel tube and the wire conductor.

Continuous Fusible Alloy Type - Sealand Corporation See Figure 30.

This detector, commercially known as the "Garrison Wire", is similar to the Fenwal type described above. In this detector, however, the fusible alloy is contained in the core of the wire rather than near the surface.

Thermocouple Type - Thos. A. Edison, Inc. See Figures 21 and 31.

This detector consists of hot and cold junction chromel-constantan thermocouple units connected together in series and housed and insulated within a flexible metal tube. Since only the hot junctions are open to the flames, the detector operates on the rate of temperature rise principle. The small current produced by one or more of these thermocouples in case of fire is sufficient to operate the relay furnished with the detector. The cold junctions are not fully enclosed but are shielded from flame in order that ambient temperature changes due to engine operation produce no temperature differential between hot and cold junctions.

Continuous Ionization Type - American District Telegraph Company

Air, under normal conditions, contains neutral gas molecules not electrically conductive. However, in the presence of flame the neutral gas molecules are split into positive and negative ions capable of conducting electricity. This phenomenon is utilized by impressing a D.C. voltage across a bare wire separated from the metal structure (firewall) by insulators. Passage of flame between the bare wire and the firewall allows a small current to flow in the detector circuit actuating a relay.

PROCEDURE

A basic size gasoline fire (.33 g.p.m.) was arbitrarily established for power section detector tests. The spread of this fire as it emerged from the power section is shown in Figure 32. A fire of this size, occurring in flight, would not be immediately damaging to the primary structure. However, it was considered that this or larger fires should be rapidly detected. Although the rapidity of power section fire detection depended upon fire size, there was found to be no such relationship in the accessory section. Therefore, no basic fire could be established for detector fires in the accessory section. The accessory section detector tests were conducted using gasoline fires ranging in quantity of gasoline flowing from .33 g.p.m. to 7 g.p.m. - including "explosion" fires, i.e., fires ignited after gasoline had been flowing into the accessory section for some time.

The detectors were electrically connected to signal lights in the engine control shed. The time lag between the start of the fire and the light signal was observed.

For power section tests the basic detector fire was ignited at an arbitrary location and its spread on the diaphragm was observed. A unit type detector was placed an arbitrary distance outside the fire spread as shown in Figure 32, and the time lag observed. This procedure was repeated, moving the detector closer to the fire each time, until the time lag did not exceed three seconds, or until the detector was within the flame. Using an average determined fire spread around the diaphragm of 22 inches the necessary spacing for unit detectors was determined. Continuous detectors were placed within the flame and the time lag noted.

To determine the effect of rain on the operation of detectors a stream of water at the rate of 50 g.p.m. was introduced into the air stream forward of the propeller by means of a fire hose, both before and during detector fires.

Detectors in the power section were located only on the diaphragm in the general locations shown in Figure 33 and 34.

To determine the operation of unit detectors in the accessory section when located as far as possible from the fire source, the detectors were placed with respect to the fire as shown in Figure 35.

Figure 36 shows the method employed to determine the required proximity of unit detectors to fire in stratified form emerging from the accessory section. This is a similar procedure to that employed in the power section. The effect of gasoline explosions on detector operation was noted in the accessory section.

RESULTS & DISCUSSION

The detector tests resulted in obtaining criteria for the design of fire detectors and for the application of detectors to aircraft powerplant installations rather than in determining the suitability of the particular detectors tested. Most of the detectors tested were designed specifically for these tests and further development is necessary before they will be suitable for use on actual aircraft powerplant installations. However, the data obtained in testing these detectors permit the establishment of design criteria which may serve as bases for continued development of the detectors tested and for the design and development of future detectors.

The tests showed that small power section fires, due to the high velocity turbulent air blast conditions, always spread appreciably over the outside of the accessory section. The average width of this spread, using the basic power section detector gasoline fire of .33 g.p.m. was approximately 22 inches, as shown in Figure 32. Although the temperature of this flame was in the range of 2000° F, the air immediately adjacent to both edges of the flame was of much lower temperature, and therefore, the power section detectors had to be actually contacted by flame for quick detection, or for any detection at all. Heat radiation from the flame to a detector located outside the flame resulted in very slow detector operation, due to the cooling effect of the stratified air. The proper locations and spacing for unit detectors as given in Figure 33 were based on the 22-inch average fire spread of the basic power section detector fire.

Temperatures during fires in the accessory section were recorded and are shown by the curves in Figures 98, 99, 100, and 101. These curves show that large variations in temperature existed throughout the accessory section regardless of the quantity of gasoline used to feed the fire. This lack of temperature uniformity was probably due to fire stratification caused by air currents entering through cowl cracks, blast tubes, and similar openings as well as the cooling effect of unburned gasoline. The accessory section detector tests substantiated this probability in that the operation of unit type detectors was generally very slow unless the detector were placed in a location actually enveloped in flame. Also, under certain fire conditions, the flames would follow a narrow path through the section and would emerge from an opening in the same narrow form, with little or no fire in the rest of the section as shown in Figure 36. Such variable accessory section fire conditions presented detection problems which could be solved by the use of continuous detectors or closely placed unit detectors as shown in Figures 33 and 34. As in the case of the power section, heat radiation from the flame to a detector could not be depended upon for quick detection due to air stratification.

Observations of numerous fires showed that the optimum detector locations were the points of flame egress from the powerplant installation. This limited the power section detector locations in the tests to the diaphragm, and the accessory section detector locations to the firewall edge and the rear of the oil cooler shroud.

The spacings for flame and metal expansion type unit detectors are given in Figure 33. Flame type detectors were sensitive to small tails of flame whereas metal expansion type detectors had to be completely enveloped in flame for rapid operation. Hence, flame type detectors could be spaced 27 inches apart but metal expansion type detectors required 21 inch spacing.

To assure quick detection in the accessory section for cases of stratified fire conditions as shown in Figure 36, the spacing for all types of unit detectors should not exceed 5 inches, as shown in Figure 33. Such detectors were required completely around the firewall as well as around the rear edge of the oil cooler shroud, due to the numerous points of flame egress that existed.

The optimum locations for continuous detectors are shown in Figure 34.

The maximum air temperatures attained during engine operation in both the power and accessory sections of the powerplant installation were in the range of 300° F. The majority of detectors tested, therefore, were designed or adjusted for operation above 400° F. Obviously, any detector temperature setting must be sufficiently higher than the maximum operating temperatures to preclude the possibility of a false alarm when no fire exists.

As the detectors tested were in various stages of development, and because of the difficulty of repeating identical fires, quantitative comparisons between particular detectors were impossible to obtain on the full scale set-up. However, to obtain a basis for the further development of present detectors and the design of future detectors it was necessary to establish a relation between full scale fire conditions and laboratory fire conditions. In a series of full scale fires the American-LaFrance-Foamite Corporation detector was tested and arbitrarily made standard for the tests, as it was considered the most highly developed detector at that time. The time required for operation of this detector under actual full scale conditions was from 3 to 5 seconds. A Bunsen burner was then set up, as shown in Figure 37, and the flame temperature regulated until this detector responded within 3 to 5 seconds after being thrust into the flame. This flame (2050° F.) was then considered to be equivalent to actual full scale conditions since the times required for operation of this detector in this flame and under actual full scale conditions were the same. For comparative results the other detectors used in the tests were also thrust into this flame. The time of operation required for each detector is given in Table 1. The operating time relationships shown in this table substantiate in general those observed during the full scale tests on all the detectors.

By this simple procedure the actual operating time for any detector may be determined in the laboratory. However, the operating time, as determined in the laboratory, will hold good in actual practice only if the detectors are located within the powerplant, as described in the preceding paragraphs.

TABLE 1

TIME REQUIRED FOR DETECTOR OPERATION

Detector Manufacturer	Detector Type	Temp. Setting	Operating Time (Secs.)	Remarks
American-LaFrance-Foamite Corp.	Metal expansion	400° F	3.5	
" "	"	500° F	5.7	
Thomas A. Edison, Inc.	"	400° F	15.5	Glass casing broke
" "	Thermocouple	—	0.8	
Fenwal, Inc.	Metal expansion	400° F	4.0	
" "	Fusible Alloy	—	3.4	
American District Telegraph Company	Metal expansion	500° F	4.5	
" "	Ionization	—	—	Not tested in this flame but operated in 1 sec. in full scale tests.
Gravıner Mfg. Co., Ltd.	Flame	—	0.2	
Walter Kidde & Co.	Flame	—	0.0	
Dugas Eng. Corp.	Flame	—	0.2	
Sealand Corp.	Fusible alloy	160° F	9.1	
" "	"	250° F	10.5	

Note (1) All detectors were tested in an ordinary Bunsen burner flame as shown in Figure 37. The flame temperature was 2050° F, as determined by a chromel-alumel thermocouple of #18 gage wire.

(2) For any particular detector, the operating time should vary with the temperature setting.

Tests in which water was sprayed into the wind tunnel air stream forward of the propeller to simulate rain indicated that the operating times of the following detectors when located in the power section were considerably increased when wet: (1) Dugas Engineering Corp. flame detector; (2) Graviner Mfg. Co. Ltd. flame detector; (3) American District Telegraph Co. bridge type ionization detector.

Although test results indicate that many of the detectors tested are satisfactory from the standpoint of rapid fire detection, further development and testing relative to mechanical construction, resistance to corrosion, fatigue, vibration and other features mentioned in the following may be necessary in order that detectors will be satisfactory for use in actual powerplant installations.

DESIGN CRITERIA

Detector guards should be designed to allow maximum flame access to the detecting elements and to protect the elements and electrical mechanisms against damage.

Detecting elements and electrical mechanisms should be so designed that vibration or accumulations of oil, dirt, water, or any other foreign matter will not prevent quick operation or cause false alarm.

Under normal flight conditions, an open detector circuit is preferable to a closed circuit as no current flow is required except during fire detection.

It is preferable that the mechanical failure of a detecting system make the system inoperative rather than turn in a false alarm.

Any detecting system should be easy to check by the crew to assure the integrity of the system at all times.

Materials used in detectors and systems, ahead of the firewall, should withstand temperatures in the range of 2000° F for at least as long a time as is required for the detector to operate.

The detector operating temperature should be sufficiently greater than the maximum engine section air temperature to preclude the possibility of false alarm. Test detector operating temperatures were 350° - 500° F, which was believed satisfactory for most installations.

CONCLUSIONS

1. Adequate detection of aircraft powerplant gasoline and oil fires can be obtained within reasonable weight limitations provided proper detectors and detector locations are used.

2. The proper locations for fire detectors are the points of air egress from the powerplant installation.

3. The spacing between flame type unit detectors in the power section should never exceed 27 inches. The spacing between metal expansion type unit detectors in the power section should never exceed 21 inches.

4. The spacing between unit detectors in the accessory section should never exceed 5 inches.

SECTION 2 - EXTINGUISHING TESTS

PURPOSE

The purposes of the extinguishing tests were:

(1) To determine the efficacy of various fire extinguishing agents when applied to gasoline and oil fires occurring in both the power and accessory sections of aircraft powerplants in flight;

(2) To determine for each extinguishing agent the quantity required, the rate of application necessary, and the optimum methods of distribution for both the power and accessory sections.

PROCEDURE

A total of 1290 fire extinguishing tests were conducted, using various extinguishing agents. The general test conditions and methods of igniting fires appear on Pages 6 and 7.

The general procedure consisted of applying extinguishing agents, at various rates and durations of discharge, through various distribution systems, to gasoline and oil fires started at all possible locations throughout the powerplant installation. Eight types of fire extinguishing agents were included in the tests. These agents and their characteristics are shown in Table 2.

TABLE 2

EXTINGUISHING AGENTS TESTED AND PROPERTIES

Extinguishing Agent	Molecular Weight	Specific Gravity	Boiling Point	Melting Point	Cu. Ft. per Lb. of Gas or Vapor at 20°C 760 mm.	Specific Gravity of Gas or Vapor at 0°C 760 mm. Air=1.0	Vapor Pressure at 20°C Lbs. per Sq. Inch
Methyl Bromide Ch_3Br	94.94	1.732 [5]	4.6°C [6]	−93°C [5]	4.05 [6]	3.27 [6]	—
Carbon Dioxide CO_2	44.00	0.77 [5]	−78.5°C [6]	—	8.75 [6]	1.52 [6]	817 [6]
Carbon Tetrachloride CCl_4	153.84	1.6326 [5]	76.8°C [6]	−23°C [5]	2.50 [6]	5.31 [6]	1.76 [6]
MIXTURE I [1]	—	1.420 [7]	120°C [7]	−53°C [7]	—	—	—
MIXTURE II [2]	—	— [9]	—	—	4.14 [8]	—	—

Mixture of various percentages of carbon dioxide and carbon tetrachloride – $CO_2 + CCl_4$ [3]

Mixture of 30% methyl bromide and 70% carbon tetrachloride – $0.3\ CH_3Br + 0.7\ CCl_4$ [4]

Mixture of 30% methyl bromide and 70% dichlormethane – $0.3\ CH_3Br + 0.7\ CH_2Cl_2$ [4]

(1) Standard product of Fyr-Fyter Company, known as Karbaloy, which consists principally of potassium carbonate.
(2) Standard product of Dugas Engineering Corporation, known as Dugas, which consists principally of sodium bicarbonate.
(3) Product of Stop, Inc.
(4) Produced by Pyrene Manufacturing Corporation for these tests
(5) International Critical Tables.
(6) "The Comparative Life, Fire, and Explosion Hazards of Common Refrigerants" Underwriter's Laboratories.
(7) Data supplied by Fyr-Fyter Company.
(8) Data Supplied by Dugas Engineering Corporation.
(9) Weighs 70 pounds per cubic foot.

The development of satisfactory agent distribution systems for the power and accessory sections was accomplished by the trial and error method. Eighty-five different systems were installed and tested before the objectives were attained. These systems are shown in Figures 38 to 74. The final satisfactory systems are shown in Figures 72, 73, and 74.

The effects of rate and duration of application of the agents on extinguishment were determined. The rate was varied from approximately 2 to 11 pounds of agent per second, applied to the entire powerplant installation, by changing feed line and nozzle dimensions and by regulating the pressures within the extinguishing agent containers. The duration of agent application was varied from a fraction of a second to one minute. The quantity of agent used in each test was dependent upon the rate and duration of application, and varied from approximately 5 to 50 pounds.

RESULTS AND DISCUSSION

No attempt was made, in writing this report, to tabulate the particular test conditions and results of each individual fire extinguishing test since such data would be of tremendous volume (1290 tests were run), would only confuse, and would serve no useful purpose. Tests were conducted on any one point until the point was accomplished or discarded and consequently, the great majority of intermediate tests are of no value except that they may indicate incorrect methods. However, due to constant repetition of certain phenomena many worthwhile points were brought out which otherwise would have lacked sufficient substantiation. The number of intermediate tests necessary to obtain results impressed upon observers the futility, in tests of this nature, of attempting to obtain dependable results without conducting a great number of tests.

Results obtained from a study of all tests, along with pertinent discussions, are presented here by treating separately the important factors which affected fire extinguishment during the tests. These factors are:

Air Blast	Fire Conditions	Extinguishing Agent
Propeller Slipstream	Type of fuel	Distribution system
Wind tunnel	Size	Rate of Application
Position of cowl flaps	Location	Duration of application
	Duration	Quantity of agent
		Type of agent

The following effects of air blast on extinguishment were noted:

Extinguishing agent applied forward of the cylinders is wasted by overflow around the outside of the NACA cowl. This was observed using various agents, and many failures to extinguish fires aft of the cylinders, by discharging extinguishing agent forward of the cylinders, were probably caused by this waste of agent. Figure 75 shows this effect in the fire spillage over the front of the NACA cowl from a fire source forward of the cylinders.

The cooling air passing through the power (cylinder) section rapidly removes the agent applied near the fire source, and consequently quick application and proper placement of the agent is necessary for extinguishment. In the tests, as the rate of application of the agent was increased, the number of extinguishments increased. This indicated that the agent must be applied with adequate FORCE into all stratified air currents within the power section. Furthermore, unless the agent were distributed uniformly around the crankcase, as shown in Figure 74, continued extinguishment of fires repeated at various locations was not attained. For this reason, general distribution systems as described on Page 25 were unsatisfactory.

The air blast prohibits the confining of the fire to any particular section unless cowling joints (and joints between cowling and parts extending through the cowling) are tightly sealed. It forces fires which occur in the power section into the accessory section, and fires which occur within either section into the exhaust stack well, oil coolers and other areas, such as faulty air ducts and exhaust heating systems. Many cases of this were encountered. Fires were forced into the carburetor intensifier heating pipe and its housing, into the wheel well due to a faulty firewall, and into the closed box section comprising the periphery of the firewall. Such fires are not reached by the extinquishing agent and become sources of re-ignition after the agent has been expelled. Due to air blast, "fire tails" cling to protuberances and other irregularities located on the OUTSIDE surfaces of the cowling and nacelle skin. These fires were difficult to extinguish since the extinguishing agents were expelled within the sections proper, and in many cases such fires served as sources of re-ignition. Only an agent expelled from the power section which flows outside of the accessory section and nacelle is effective in wiping off these tails.

Fires from the power and accessory sections were carried past the wheel well by the air blast. In many cases "fire tails" were observed whipping into the wheel well, but these fires disappeared during extinguishment. Fires which remained in the wheel well after the extinguishing agent was applied in the power and accessory sections were due to leakages through cracks and holes in the firewall. Tests referred to were conducted without the wheel and tire in place.

Fires in the air blast were more intense than quiescent fires, being similar in nature to a blow torch. In general, fires with the cowl flaps closed were more intense than with the flaps open. With cowl flaps closed combustion of the fuel was more complete and the overall effect was to decrease the assurance of extinguishment and increase the probability of re-ignition after extinguishment. The cause of this could not be definitely determined, but it appeared that the relatively smooth air flow over the accessory cowl and nacelle skin, with the flaps closed, caused the fire from the power section to lie close to these surfaces, producing a hotter fire than with the flaps open.

It was originally intended to conduct tests to determine the effect of power section air blast elimination on extinguishment by isolating the power section using full closing cowl flaps, before attempting extinguishment. However, as the program progressed, it became obvious that such tests would be unnecessary. It is quite probable that power section air blast elimination would allow a reduced rate of extinguishing agent discharge, and permit less attention to equal distribution of extinguishing agent behind the cylinders, but these advantages would be more than offset by the disadvantages of loss of agent overflow from the power section necessary for wiping off accessory section "fire tails"; of additional "fire tails" occurring at cowl flap joint leaks with no provision for wiping them off; and of increased heat due to lack of cooling air. The power section would become in effect another accessory section and tests have shown that to extinguish accessory section fires the overflow of agent from the power section is necessary.

The oils and gasolines burned during the tests were: #10 SAE oil, 100 hour aircraft engine drain oil, 87 octane aviation gasoline and safety fuel. Oils only were burned in the power section as it is impossible for appreciable quantities of gasoline to be released in this section in an actual installation.

The general extinguishing problem in the power section was practically the same for #10 SAE oil and 100 hour drain oil fires. The drain oil required a little longer time than the #10 SAE oil to reach the same degree of combustion and consequently extinguishment was easier in the case of drain oil fires of short durations. For fire durations greater than 25 seconds no differences between fires burning the two oils were noted. The tests indicated that for short duration fires, as the temperature of the oil was increased, the degree of combustion increased and extinguishment became more difficult. Complete combustion of all oil released in the power section never occurred.

Types of accessory section fires were:

Oil drainings #10 SAE oil	-	Fires entering the accessory section through accidental openings from a power section source.
Oil drainings #10 SAE oil	-	Fire source in the accessory section. No fire in the power section.
Gasoline and Safety fuel	-	Fire source in the accessory section. No fire in the power section.

Extinguishment comparisons between #10 SAE and 100 hour drain oil fires in the accessory section, which were caused by fire leakage from the power section, were as explained in the foregoing for the power section oil fires. However, there was a marked difference observed in the degree of combustion attained between #10 SAE oil and 100 hour drain oil when the fire source was in the accessory section with no fire in the power section. Under these conditions the accessory cowl remained relatively cool due to the outside air blast in contrast to the hot surfaces attained with the fire source in the power section. In the latter case the hot surfaces, combined with the hot exhaust manifold, progressively increased the degree of oil combustion, and consequently little difference was noted between the two oils, as previously explained. In the former case, since hot surfaces were not present, the degree of oil combustion was low for both oils, and particularly for the drain oil. Neither of these oil fire types was difficult to extinguish compared to gasoline fires which governed extinguishing equipment in the accessory section.

No difference was noted between fires in which safety fuel and regular 87 octane aviation gasoline were burned.

Of the three types of fire with the source in the accessory section, the gasoline fires were by far the most difficult to extinguish. Oil fires caused by leakage from the power section were as difficult to extinguish as the gasoline fires WITHIN the section proper but gasoline fires produced "fire tails" outside the accessory section which were much more difficult to extinguish than similar oil "fire tails". Only a portion of the gasoline introduced into the accessory section burned WITHIN the accessory section. The remainder ignited upon its exit through small cracks and holes. In many tests liquid gasoline ran from cracks in the accessory cowl and ignited on the outside surface of the cowl several inches AWAY from the crack, thus making complete extinguishment by the accessory section agent alone almost impossible. Although there was no fire in the power section it was necessary to discharge the power section agent, which overflowed around the accessory section, along with the accessory section agent to extinguish these itinerant flames and miscellaneous "fire tails". The wheel well was much more vulnerable to gasoline fires than to oil fires since gasoline leaked into the wheel well through tiny cracks in the firewall, ignited, and could not be extinguished by the power and accessory section extinguishing systems.

It was possible to extinguish oil fires while permitting the oil to flow during extinguishment but gasoline "fire tails", outside the section proper, would persist unless the gasoline flow were shut off <u>before extinguishment was attempted</u>. When the gasoline was shut off, the "fire tails" rapidly decreased in intensity and became vulnerable to the overflow of extinguishing agent from the power section.

Oil fires gradually increased in intensity after ignition while gasoline fires reached maximum intensity immediately after ignition. When adequate rate of application and proper distribution of the agent were used large (up to 5 g.p.m. of oil) and small oil fires, within the power section proper, could be extinguished with the same ease. Conversely, when inadequate rate of application or improper distribution were used large and small fires were equally difficult to extinguish. A plausible reason for this may be that the agent must be applied with adequate FORCE into ALL stratified air currents within the power section. Unless this is accomplished extinguishment will not result regardless of the size of the fire contained within the air currents.

The above phenomenon held true only for that part of the fires extending a short distance aft of the fire SOURCE. For the remaining part, which might extend partially around and into the accessory section and along the nacelle and wing, the extinguishing of large fires was more difficult than that of small fires because of the difficulty of extinguishing long "fire tails".

Stopping the oil flow immediately before attempting extinguishment does not simplify the extinguishing problem appreciably. This is due to the slow decrease of intensity of oil fires after oil shut-off. However, the stoppage of oil flow prior to extinguishment precludes the possibility of recurrence of the fire.

In the accessory section proper, because of the limited amount of air available for combustion, there was little difference in the appearance of the fire WITHIN the section regardless of the quantity of gasoline used except for very small fires. The difference appeared in the length of "fire tails" OUTSIDE of the section where sufficient air was encountered by the gasoline to complete the combustion. In all the tests the extinguishing problem, both inside and outside the accessory section, was practically the same whether small or large flow rates (.33 to 7 g.p.m.) of gasoline were used. Extinguishment within the section proper was relatively simple in all cases but numerous "fire tails" which clung to the outside surfaces of the accessory cowl and to miscellaneous parts aft of the cowl could not be repeatedly extinguished unless the gasoline flow were SHUT OFF just prior to the application of the agent and unless the overflowing power section agent were applied at the same time.

Because of the variations in air blast existing behind the cylinders in the power section, fire extinguishment was simple or difficult depending upon the particular location of the fire source in the region around the crankcase. The rate of agent application was increased and the method of distribution developed until numerous fires could be repeatedly extinguished regardless of the location of the fire source.

Oil fires ignited 6 inches forward of the cylinders completely filled the NACA cowl opening, enveloped the propeller hub, spilled around the outside of the cowl and flowed through the cylinder rows. Figure 75 shows this effect. Such fires could not be extinguished by the extinguishing system aft of the cylinders, but it is extremely unlikely that oil in this location would ignite accidentally. Ignition would more likely occur aft of the cylinders and the tests showed that fire propagation forward through the cylinders, against the air blast, would not occur.

The location of the exhaust stack on the right side of the engine caused oil fires from the power section to burn more intensely and be more difficult to extinguish on the right side than on the left side. (An important effect of fire location near the exhaust stack relating to flash back after extinguishment is described in Section 4 of this report.)

The lower part of the accessory section in the test set-up incorporated a shrouded oil cooler which permitted a considerable area of egress for burning fuels and oils. As a result of this condition, accessory section fires introduced toward the lower region of the section presented little extinguishment problem since most of the burning liquids ran out through the opening and the resultant fire within the section was small, as shown in Figure 19. Fires introduced near the top, as illustrated in Figure 18, passed through the section, due to gravity, and were more difficult to extinguish.

The fire duration used generally throughout the tests was 30 seconds for both gasoline and oil fires. Oil fires usually reached a steady combustion state in from 5 to 15 seconds after the fire started (aided in many cases by the small amount of gasoline used for ignition) and from this time on, combustion increased slowly because of the heating of metal parts contacted by the fire. This gradual increase in the degree of combustion made oil fires slightly more difficult to extinguish as the duration of fire increased.

Gasoline fires reached maximum intensity immediately after ignition and were equally difficult to extinguish throughout durations up to 30 seconds.

Short duration gasoline fires, conducted to simulate the operation of automatic extinguishing systems, were not appreciably easier to extinguish than fires of 30 seconds duration.

Long duration fires permit burning gasoline or oil to seep through small cracks into areas which may not be penetrated by the extinguishing agent causing re-ignition of the main fire after the agent has been discharged.

As previously stated under Procedure, correct methods of distribution of the agent to both sections were developed by trial and error. All systems tested are shown in Figures 38 to 74 and the types of nozzles used in Figure 76.

It was found necessary to distribute agent to the power section, accessory section, oil cooler, exhaust stack and other locations, such as, intensifier tubes, blast tubes, shrouds and muffs. Table 3 indicates the correct methods of agent distribution at these various locations. Information on detail design of systems, including nozzles, is given in this report under "Design Information for Extinguishing Systems".

TABLE 3

OPTIMUM DISTRIBUTION METHODS FOR EXTINGUISHING AGENTS

(See Figures 72, 73, and 74)

Extinguishing Agent	Power Section	Accessory Section	Oil Cooler	Exhaust Stack	Other Locations
Methyl Bromide	Double slot nozzle at the base of each cylinder	Perforated ring or nozzles around the rear case	Perforated tube or nozzles	Perforated ring or nozzles	Nozzles
Carbon Dioxide	Single or double slot nozzle at the base of each cylinder	Perforated ring around the rear case	Perforated tube	Perforated ring	Nozzles
Other Liquid Agents [1]	Double slot nozzle at the base of each cylinder	Nozzles around the case	Nozzles	Perforated ring or nozzles	Nozzles
Sodium Bicarbonate Powder Compound	Outlet at the base of each cylinder	Data not obtained	Data not obtained	Data not obtained	Data not obtained

1 Includes all other liquid agents as given in Table 2, Page 17.

Distribution of the agent in the power section was much more critical than in the accessory section due to the higher degree of air blast present in the power section. General type systems, designed to flood the entire volume, without regard to application at specific locations, were satisfactory in the accessory section, but specific type systems, designed to provide systematic and equal distribution of the agent to each cylinder, were required in the power section.

Eleven general type systems (shown in Figures 38 to 42 and 51 to 54) were tested in the power section. The agent was directed inward, outward, forward, aft, and tangentially around the crankcase, both forward of the cylinders, with no success, and aft of the cylinders, with little success. The failure of the forward systems, in particular, was attributed partly to an observed spillage of agent around the outside of the NACA cowl, and that of both systems to the inability of the agent, due to air blast interference, to penetrate and cover all fire areas.

After general distribution systems in the power section proved unsatisfactory, tests were made on specific type systems which applied the agent systematically to each cylinder. During these tests the agent was discharged from the cylinder head toward the crankcase (See Figure 77A); the center of the cylinder toward the crankcase and the cylinder head (See Figure 77B); the center of the cylinders forward and around the cylinders (See Figure 77C); and from the crankcase outward toward the cylinder head (See Figure 74).

Of the above methods tested, the last proved to be the most effective from the standpoint of repeated extinguishments. By this method, the nozzles may be located on the crankcase and would be more likely to remain in position in the event of cylinder failure than nozzles located elsewhere. This method of individual cylinder treatment lends itself readily to other engine installations in that the number of agent outlets may be varied according to the number of cylinders. An additional nozzle located near the head of the lowest cylinder as shown in Figure 46 was found to be desirable because of appreciable collections of burning fuels in this location caused by gravity.

The original test program included tests in which extinguishing agent would be released within the engine crankcase. It was assumed that a fire, occurring as the result of any engine failure, could be extinguished by the agent escaping at the point of failure. Even if this assumption were correct, the tests conducted indicated that such a method would be totally ineffective on "fire tails" or on any fire outside the section proper. Similar agent application methods originally considered for use by incorporating them in engine oil and fuel systems, would be ineffective for the same reason.

Thirty general type systems were tested in the accessory section by directing the agent inward, outward, forward, aft and tangentially around the section (See Figures 51 to 73). A fair degree of success resulted from the use of these systems but the most effective types are shown in Figures 72 and 73. Moderate success was attained using only 4 agent outlets within the section proper (Figure 68) and no success when this procedure was carried to the minimum extreme of one outlet as shown in Figures 61 and 71.

The oil cooler, located at the bottom of the accessory section, required special protection, consisting of nozzles or a perforated tube, to discharge agent between the oil cooler proper and the surrounding metal shroud, as shown in Figures 72 and 73. Such protection was required on account of the inability of the agent discharged in the accessory section to affect this fire.

Exhaust stack protection was necessary to cut off the flames from the power section in the tunnel around the stack. This presented little difficulty and was accomplished equally well by use of a perforated tubular ring encircling the stack (See Figure 72), and by the use of three nozzles as shown in Figure 73.

The tests did not include protection inside the carburetor as such protection now is provided in most aircraft.

Carburetor heater intensifier tubes frequently led to re-ignition of fires due to a collection of burning liquids inside such tubes. To prevent such re-ignition, it may be necessary to design intensifier tubes to prevent the entrance of fire or to locate extinguishing agent spray nozzles to direct spray into the pockets contained in such tubes.

The rate of extinguishing agent application was found to be the most important factor affecting the ability of an agent to extinguish fires. Air blasts rapidly dissipate the agent and penetration of the agent into the fire is possible only by the use of an adequate discharge rate. The minimum rates of application of the several agents necessary to assure extinguishment in the various sections of the powerplant installation are given in Table 4. These are the average rates over a total discharge time of 2 seconds.

TABLE 4

NECESSARY MINIMUM RATES OF APPLICATION OF EXTINGUISHING AGENTS DETERMINED BY THE TESTS

	Carbon Dioxide lbs/sec	Methyl Bromide lbs/sec	Methyl Bromide qts/sec	Other Liquids* qts/sec
Power Section	7.0	5.4	1.5	1.7
Accessory Section	2.9	2.2	0.6	0.8
Oil Cooler	0.3	0.7	0.2	0.2
Exhaust Stack	0.6	0.7	0.2	0.3

*Other Liquids include: Carbon tetrachloride, mixture of 70% carbon tetrachloride and 30% methyl bromide, and mixtures of carbon dioxide and carbon tetrachloride.

The actual rate of discharge of carbon tetrachloride from one nozzle in the power section is shown by the curve in Figure 78. It may be noted that the initial rate of discharge along the flat part of the curve is much higher than the average rate given in Table 4, which is the average discharge over a period of 2 seconds. It was not possible to obtain such a curve for carbon dioxide due to the difficulty of collecting the gas in increments during the discharge.

In the accessory section there was less need for a high rate of agent application than in the power section, because of lower air velocities. As previously described, "fire tails" on the outside of the accessory section and nacelle were extinguished by overflow of the power section agent. As a result of the high air velocity, the effectiveness of this overflow was determined by the rate of power section agent discharge. Thus a high rate of agent discharge in the power section was necessary not only to extinguish power section fires but to extinguish fires OUTSIDE the accessory section as well.

As the tests proceeded, the rates of application of the agents were gradually increased to those shown in Table 4, until practically all fires, under prevailing air blast conditions, were extinguished. However, during this procedure, many fires were extinguished at lower rates and it was vainly attempted to quantitatively determine a rate-extinguishment relationship from the rate at which no fires could be extinguished to the rate at which all fires could be extinguished. It was theoretically possible but physically impractical to conduct the many tests necessary to obtain accurate data on this point due to time and equipment limitations. However, the probable relationship, indicated qualitatively by tests which were conducted, is shown in Figure 79.

When adequate rate of agent application was used the bulk of each fire was extinguished within one second, but a minimum of 2 seconds was required for the agent to reach outside "fire tails". When inadequate rate was used, durations up to one minute were ineffective.

Long durations of agent application are beneficial as they allow time for the cooling of all parts thus minimizing the possibility of re-ignition after extinguishment. However, in the tests, re-ignition did not occur because of hot metal parts, glowing carbon, or dirt particles if the duration time were two seconds or greater. In determining the total discharge time of 2 seconds shown in Figure 78, the end of effective discharge spray was determined as the point at which the discharge no longer appeared as a definite spray pattern.

Hundreds of combinations of quantity and rate of application of the agents were used in the tests. By establishment of the minimum rates required (Table 4) for a duration of 2 seconds the quantities given in Table 5 were determined. These quantities are minimum and were effective only when discharged in 2 seconds. If the duration were increased beyond 2 seconds the quantities would have to be increased proportionally since <u>rate</u>, and <u>not quantity</u>, is the criterion for effective extinguishment.

TABLE 5

NECESSARY MINIMUM QUANTITIES OF EXTINGUISHING AGENTS DETERMINED BY THE TESTS BASED ON DURATION OF 2 SECONDS

	Carbon Dioxide (Pounds)	Methyl Bromide (Pounds)	(Quarts)	Other Liquids** (Quarts)
Power Section	14.0	10.8	3.0	3.4
Accessory Section	5.8	4.4	1.2	1.6
Oil Cooler	0.6	1.4	0.4	0.4
Exhaust Stack	1.2	1.4	0.4	0.6
TOTAL	21.6	18.0	5.0	6.0

** Other Liquids include: Carbon tetrachloride, mixture of 70% carbon tetrachloride and 30% methyl bromide, and mixtures of carbon dioxide and carbon tetrachloride.

Extinguishing agents are effective as a result of any or all of the following actions. The smothering action, which renders air feeding a fire incapable of supporting combustion, was most effective in the more or less closed accessory section. The blanketing action, which prevents air from reaching the fire, was most effective in extinguishing "fire tails" outside the accessory section. Mechanical action, which results from directing the agent across the fire with sufficient force to cut the flame away from the fuel, was of primary importance in extinguishing power section fires. Cooling action had little effect on test fires due to the small agent quantities and short duration necessarily used.

A comparison of the various extinguishing agents tested is given in Table 6 in the order of merit, and is based on the extinguishing ability of the agent in the type of engine installation tested, assuming that a satisfactory method of distribution and comparable rates of application and quantities exist for each agent.

TABLE 6

FIRE EXTINGUISHING AGENTS IN ORDER OF MERIT FOR USE IN THE TYPE OF AIRCRAFT POWERPLANT INSTALLATION TESTED

Order of Merit	Power Section (Oil Fires)	Accessory Section		Overall (1)
		Oil fires with source in power section	Gasoline fires shut off before extinguishment	
1	Methyl Bromide Mixture (A)	Methyl Bromide Mixture (A)	Methyl Bromide	Methyl Bromide
2	Carbon Dioxide Carbon Tetrachloride Mixture (C)	Carbon Dioxide Carbon Tetrachloride Sodium Bicarbonate Mixture (C)	Carbon Dioxide	Carbon Dioxide
3	Sodium Bicarbonate	Potassium Carbonate Mixture (B)	Carbon Tetrachloride Mixture (A) } Mixture (C) }	Carbon Tetrachloride Mixture (C) } Mixture (A) }
4	Potassium Carbonate Mixture (B)		Potassium Carbonate	Sodium Bicarbonate
5				Potassium Carbonate Mixture (B)

Mixture (A) indicates a mixture of 30% methyl bromide and 70% carbon tetrachloride.
Mixture (B) indicates a mixture of 30% methyl bromide and 70% dichlormethane.
Mixture (C) indicates various mixtures of carbon dioxide and carbon tetrachloride.
(1) Only methyl bromide and carbon dioxide are considered satisfactory for general use in the type of engine installation tested.

This method of comparison is essentially qualitative, as attempts made to compare the agents on a quantitative basis could only be approximate. It would be desirable from the designer's viewpoint to present a comparison of the agents as to their relative efficiency versus weights of the complete installations. However, due to the many variables involved and to the necessity for limiting the number of tests it was found impossible to obtain results which would allow quantitative comparisons. Other factors which would be involved in the selection of an extinguishing agent, such as, complexity of the distribution system, containers, pressures required, line sizes, operating and handling conditions, toxicity, corrosion, etc., were not considered in the above comparison since they are design problems which have no bearing on the relative extinguishing merits of the agents themselves.

Methyl bromide, carbon dioxide, carbon tetrachloride and mixtures (A) and (C) (See Table 6) extinguished oil fires with the source in either the power or the accessory section but methyl bromide and carbon dioxide were the only agents, of all those tested, which could be considered satisfactory for all types of fires in the type of powerplant installation tested. All agents, except these two, lacked the ability to extinguish gasoline fires in the accessory section and were ineffective in extinguishing gasoline "fire tails" on the outside surfaces of the cowling and nacelle when discharged over these surfaces from the power section.

For gasoline fires in the accessory section, with the gasoline FLOWING during the agent application, methyl bromide was appreciably more effective than carbon dioxide in wiping off the outside "fire tails" but neither agent could extinguish all such fires. When the gasoline flow was STOPPED just prior to agent application, this superiority disappeared since both agents extinguished all fires. These fires could also be extinguished using carbon tetrachloride, provided a lag of 8 to 10 seconds was allowed from the time the gasoline flow was stopped until the carbon tetrachloride was applied.

For all agents, the gasoline flow into the accessory section should be stopped before extinguishment is attempted.

It is emphasized that the comparison between extinguishing agents given in the foregoing applies only to their ability to extinguish fires in flight in the type of powerplant installation tested.

DESIGN INFORMATION FOR EXTINGUISHING SYSTEMS

The distribution systems, methods of feeding the distribution systems, types and sizes of feed lines, types of agent containers and methods of applying pressures were chosen for convenience from the test standpoint. However, the specific locations for applying the agent were determined by taking into consideration the practicability for installation in actual aircraft.

In the early power section tests, attempts were made to distribute the agents to each cylinder by means of a single supply ring as shown in Figures 43 to 46. A check of this system to determine the quantities of agent discharged by each nozzle was made by collecting carbon tetrachloride from each nozzle and by visual observation of carbon dioxide. The distribution differences when using carbon tetrachloride were as high as 300 percent and were of similar magnitude using carbon dioxide, judging by visual observation. Rather than delay the tests to solve this difficult design problem, individual lines, from the agent container to the nozzles giving equality of ±10 percent, were installed, as shown in Figure 48, and the tests continued. However, later work on single rings indicated that equality of distribution of gases and liquids may be obtained by metering the nozzles and feed lines on a trial and error basis.

Experiments of this nature should be conducted with the distribution system arranged exactly as it would be in the airplane, especially for liquids, since it was found that the attitude of the ring appreciably affected equality of distribution. Also, the total volume of the system should be kept to a minimum, consistent with rate requirements.

For distribution checks on liquid agents the liquid should be collected at each nozzle. It is impractical to collect methyl bromide because of its volatility but results obtained using carbon tetrachloride instead should be satisfactory, since the specific gravities of the two liquids are nearly identical. For carbon dioxide, visual observation by means of a motion picture camera for obtaining distribution equality was satisfactory in the tests.

In the accessory section, close equality of distribution of the extinguishing agent is not critical. However, no nozzle should discharge less than about 50 percent of the quantity it would discharge if the distribution were equal.

For distribution of agent to the sections, separate containers, valves and distribution systems were used in the tests, one system for the power section, the other system for the accessory section, oil cooler, and exhaust stack well. In actual installations, however, all sections would possibly be fed by a single feed line, which introduces the problem of metering the correct quantity of agent to the various sections and locations. This problem is similar to that of obtaining equal distribution, as discussed above. Tolerances on quantities metered to the various locations could not be determined in the tests. In this case, judgment must be exercised so that the quantities distributed to the various sections and locations reasonably approximate those given in Table 5.

The effect of temperature on distribution was noted in supplementary tests in which the lead lines to certain nozzles of a system were heated. This resulted in weak discharge of agent from these nozzles, particularly in the tests using carbon dioxide. To minimize the effect of heating, the distribution rings in both the power and accessory sections should be located as close to the crankcase as possible; also it is desirable, when practicable, to locate feed lines along other parts, as this permits heat transfer away from the lines during fire and prevents fire from entirely encircling the lines.

Rates of agent application were varied during the tests by changing the lengths and diameters of feed lines, the numbers and sizes of holes in perforated tubing, the bores and slot sizes of nozzles, and the pressures in the agent containers.

For checking the rate of discharge of gaseous agents, a motion picture camera, taking 32 frames per second, was used. From these pictures the actual beginning and end of the discharge were observed and the intervening time determined. Ordinary visual observation with stopwatch timing was not satisfactory.

For checking the rate of discharge of liquid agents, the method used was much more involved and more accurate than that used for gases. The test set-up shown in Figure 78 was identical to the system on the actual engine installation. In this case motion pictures were taken of two nozzles only at the rate of 32 frames per second. One nozzle was used to determine the start of the discharge. In successive tests the discharge from the other nozzle was collected during various time intervals from the start. When the quantities thus collected were plotted against the time for these quantities to be discharged, as determined from the film, the rate curve as shown in Figure 78 resulted. One test is required for each point on such a curve.

To determine the best methods of spraying the agents into the fire areas, 20 types of nozzles, as shown in Figure 76 were used in the tests. Types N-1 and N-2 were used for individual cylinder protection in the power section. Either the single or double slot type is satisfactory for carbon dioxide, but the double slot type should be used for liquid agents. The included angle of the spray pattern for each slot should be at least 180° for both types. In the accessory section the spray patterns of nozzle types N-7, N-15, N-16, and N-20 were satisfactory but N-16 and N-20 were particularly susceptible to plugging. The apex angle of these types is unimportant and may vary between 50 and 80 degrees.

The detail design of the nozzle is immaterial provided the nozzle allows adequate flow and produces the correct spray pattern of the agent. Aluminum alloy or other low melting point materials should not be used in nozzles. All nozzles used in the tests were brass.

Nozzles designed for carbon dioxide should be checked for their tendency to plug with carbon dioxide snow during the discharge and all nozzles should be removable for periodic cleaning.

Nozzles in the power section should be located with respect to the cylinders as shown in Figure 74. Their exact locations should be adjusted with respect to obstructions to allow as clear a path for the spray pattern as practicable. Figure 73 shows the nozzle locations in the accessory section. Substantial variations in their locations and spray angles are permissible and, if possible, the nozzles should be spaced around the ring to avoid obstructions. Figure 72 shows the optimum locations for perforated tubing. The number and exact size (1/16" diameter used in the tests) of holes required in the accessory and exhaust stack rings and in the oil cooler line will depend upon the metering tests for determining the rate of application and agent distribution. The diameters of the holes should be as small as possible so that the greatest number may be used, but holes less than 1/16 inch in diameter may be subject to freezing during carbon dioxide discharges.

Release valves should be quick opening so that the metering effect of the valve during opening is reduced to a minimum. This is essential in order to obtain the high rate of discharge of the agents necessary over a period of 2 seconds.

The location of carbon dioxide containers is an important design detail because the temperature of the container and agent considerably affects the rate of agent discharge, as shown by the curves in Figures 80 and 81. From Figure 81 it may be seen that the total time required to discharge 5 pounds 10 ounces of carbon dioxide increased approximately 70 percent as the temperature of the container and agent dropped from 79° F to 32° F and the pressure from 950 lbs./sq.in. to 500 lbs./sq.in. For convenience in many tests, the rates of carbon dioxide discharge were controlled by regulating the container temperature. In locating liquid agent containers the possibility of the agent freezing should be considered.

CONCLUSIONS

1. Extinguishment of most aircraft powerplant gasoline and oil fires occurring in flight can be accomplished within reasonable weight limitations, provided adequate rates of extinguishing agent application and optimum distribution methods are used and provided further that gasoline flow is shut off before extinguishment is attempted.

2. Extinguishment of oil fires occurring in flight can be accomplished without stopping the oil flow but oil shut-off is advisable to prevent recurrence of the fire.

3. Air blast is the most serious factor to overcome in the extinguishment of aircraft powerplant fires, and is overcome by using adequate rates of agent application.

4. Gasoline fires are more difficult to extinguish in the accessory section than oil fires.

5. The safety fuel fires in the tests were as difficult to extinguish as fires burning 87 octane aviation gasoline.

6. Within limits, large fires are no more difficult to extinguish than small fires.

7. The power section, accessory section, oil cooler, and exhaust stack well much be individually protected against fire.

8. The extinguishing agent in the power and accessory sections, and all other locations, should be discharged simultaneously.

9. Tests indicated that wheel well protection is unnecessary, provided the firewall be leakproof.

10. The discharge of extinguishing agent from the power section is necessary to extinguish accessory section fires.

11. Tests indicated that methyl bromide and carbon dioxide are the only extinguishing agents of those tested which are satisfactory for general protection against fires in flight in the type of powerplant installation tested. Methyl bromide was found to be the most satisfactory agent from the fire extinguishing standpoint.

12. The rate of extinguishing agent application is the most important factor in the application of an extinguishing agent. For the entire engine installation, a rate of application of 9 lbs/sec. of methyl bromide or 10.8 lbs/sec. of carbon dioxide is required.

13. The minimum duration of extinguishing agent application should be approximately 2 seconds.

14. Tests indicated that extinguishing agent applied ahead of the engine cylinders is ineffective and unnecessary.

SECTION 3 - MATERIALS

PURPOSE

The purpose of the tests on materials was to study under flight conditions the effects of gasoline and oil fires on the materials and equipment commonly used in aircraft powerplant installations.

DESCRIPTION OF MATERIALS TESTED

The materials used in the components of the nacelle unit were as follows:

Engine Mount - SAE 4130 steel tubing of .065 wall thickness. Rubber engine mount bushings were not installed.

Accessory Section Cowl - Both .018 stainless steel (18-8 Grade Type 302) and .049 aluminum alloy.

Diaphragm (bulkhead separating the power section from the accessory section) - .018 stainless steel (18-8 Grade Type 302).

Wing and Nacelle Skin - .012 stainless steel sheet (18-8 Grade Type 302).

Firewall - .018 stainless steel (18-8 Grade Type 302) except for an aluminum alloy box section periphery (See Fig. 82).

Engine Fuel System - Standard DC-3 installation lagged with asbestos.

Engine Oil System - Oil tank and oil lines - aluminum alloy. Oil tank support straps - stainless steel. Hose connections - standard AN (neoprene) types. Oil cooler, United Aircraft Products - Model U-4210, standard soldered construction, exposed to accessory section fire due to its location at the bottom of the section as shown in Figures 2 and 5. To prevent power section fires from entering the oil cooler, the air intake was extended forward (see Fig. 2). The exterior of the oil cooler was lagged with asbestos. Otherwise the entire oil system was exposed to the test fires.

Engine Accessories - As described under "General Test Procedure", many of the engine accessories were protected from fire by an asbestos lagging.

PROCEDURE

A majority of these tests was conducted in conjunction with the extinguishing and detector tests, and accordingly the air blast, fire conditions, and methods of producing fires were as described under "General Test Procedure".

Using 25 chromel-alumel thermocouples, and the bank of 25 pyrometers and slow speed camera shown in Figure 11, temperatures were recorded throughout the nacelle unit, under various fire conditions. The thermocouple locations used are shown in the following figures:

Figure 83 - cowling, diaphragm, wing and nacelle skin; Figure 97 - firewall and within the accessory section; Figure 106 - behind the firewall.

Tests were conducted with the wheel and tire installed in the retracted position illustrated in Figure 3. Observations were made on the effect of fire on the tire and the ability of various fire extinguishing agents to extinguish tire blazes.

An operating Eclipse Model E-160 starter was installed in the accessory section and subjected to several gasoline fires of 30 seconds duration, and the effects of these fires on the starter were observed.

In addition, the effects of fires were noted on cowl fasteners, silver soldered connections, blast tubes, intake ducts and aluminum alloy brackets, supports, straps and clips.

RESULTS & DISCUSSIONS

The standard DC-3 engine mount supported the weight of the powerplant only, since no additional "G" factors were applied. The unprotected mount was subjected to the accessory section temperatures discussed on Page 11 and shown in Figures 97 to 105. The mount used throughout the tests was undamaged, except for some scaling. Although no rubber engine mount vibration bushings were installed, tests on other rubber parts indicated that such bushings would ignite and continue to burn after extinguishment of the fire, resulting in eventual loss of the engine unless the shock units were designed to support the engine after the destruction of rubber components.

In Figures 84, 97, and 106 are shown the maximum temperatures recorded throughout the nacelle unit, at locations shown in Figures 83, 97, and 106, for a series of sixty-seven fires at various locations. The maximum temperatures shown are not those reached during any one fire but are the maximum temperatures attained at each thermocouple location during the 67 fires.

Continuous temperature recordings during particular fires of this series are shown as follows:

Figures 85 to 96 with thermocouples located as shown in Figure 83;
Figures 98 to 105 with thermocouples located as shown in Figure 97;
Figure 106 with thermocouples located as shown in Figure 106.

The rates of temperature rise shown in Figures 85 to 96, and 98 to 106 are slightly slower than actual rates due to the time lag introduced by the thermocouples, but the range of high temperatures indicated by these curves, and the maximum temperatures noted in Figures 84, 97 and 106, should prove of value in the selection of materials for use in wing-nacelle-powerplant installation designs.

Figure 84 shows that the wing skin, toward the leading edge remains relatively cool, at the zero wing attack angle used in the tests, possibly due to boundary layer effect (See Figs. 107 and 108). However, wing skin temperatures near the trailing edge, caused by fires such as that shown in Figure 19, could seriously damage fabric covered ailerons and flaps within a few seconds.

The effect of a 3 g.p.m. power section oil fire of 30 seconds duration on an .049 aluminum alloy accessory section cowl piece may be seen in Figure 109. In this instance the metal began to melt within 15 seconds after the fire ignition.

Accessory section gasoline fires of 30 seconds duration did not melt this aluminum alloy cowl, due to cooling air on the outside of the cowl dissipating the heat produced by the fire within the accessory section. Power section oil fires generally burned both inside and outside the accessory section cowl with resultant cowl damage. A comparison of cowl temperatures resulting from these two fire types may be seen in Figures 85 and 90 and Figures 86 and 91.

The firewall, of steel with an aluminum alloy box section periphery (Figure 82), withstood all fires, except for the melting of small areas in the forward face of the box section in a few tests. In the tests, the firewall supported no engine loads, such loads having been taken by the nacelle inner structure shown in Figure 8. The firewall was subjected to temperatures shown in Figure 97. In connection with firewall failure during fire, extinguishment tests indicated that the firewall should prevent the passage of even small quantities of gasoline into the nacelle, since it was impossible to extinguish small nacelle fires caused by leakage through the firewall, by means of the power and accessory section extinguishing systems. Such fires caused re-ignition of accessory section fires through openings in the firewall.

The aluminum alloy NACA cowl was used in all tests and was undamaged except for the melting of a few stiffener channels inside the cowl. Although the .040 aluminum alloy cowl flaps occasionally melted during particularly severe fires, the tests indicated that such flaps were generally satisfactory.

There were no cases of stainless steel (.012 nacelle skin, .018 accessory section cowl, or .018 firewall) melting during the tests and the superiority of steel over aluminum alloy for all parts which must resist fire was clearly indicated. In designing stainless steel structures, proper cognizance must be given to the fact that buckling of "oil canning" may occur at high temperatures, thus seriously reducing the load carrying capability, particularly of thin sheet monocoque structures. Such strength reduction may be much greater than that due to temperature alone.

The unprotected aluminum alloy oil tank and oil lines were undamaged by any fire. The contained oil in all parts of the oil system dissipated the absorbed heat rapidly enough to prevent the melting of any part of the system. Although no oil was contained in the upper section of the oil tank (vent space) the tank was undamaged by any fire, although in many tests several minutes were required to extinguish residual fires after extinguishment failures. Other aluminum alloy parts not containing liquids, such as the standard perforated tubular extinguisher ring, melted within a short time of fire ignition. The aluminum alloy extinguisher rings were replaced by copper rings, which gave excellent service in the tests. Standard AN (neoprene) hose connections, used throughout the oil system, were undamaged by any one fire, but gradually, as a result of many fires, such hoses baked, swelled and became loose fitting. These hoses withstood all fires of 30 seconds duration, and appeared capable of remaining undamaged in fires of much greater duration. In general, the tests indicated that oil systems, containing oil, and consisting of aluminum alloy tank and lines, and AN neoprene hose connections would not be seriously damaged in any one fire before the main aluminum alloy monocoque structure would be so weakened that a major structural failure would occur. Of course, this would not be true with heavy structures designed to withstand long duration fires.

The oil cooler, when open to a flow of cooling air using the extension shown in Figure 2, was undamaged by hundreds of fires. During two fires a decrease in the volume of cool air flowing through the cooler caused by partial blanketing of the forward core face, resulted in rapid melting of the soldered joints in the core. Engine oil spraying out of the damaged cooler ignited from the test fire immediately in both instances. The oil cooler should be separated from the accessory section if possible; the air inlets to such coolers should be so located as to prevent entrance of fire; and cooling air should flow through the entire oil cooler at all times during fire.

The part of the fuel system within the accessory section was lagged with asbestos to prevent vapor lock and consequent stopping of the engine during test fires. Oil system tests proved that unlagged aluminum alloy lines, carrying a flow of oil, would not melt during fire. However, fire tests of fuel systems proved that vapor lock could occur within 5 seconds of fire ignition and that aluminum alloy lines would be destroyed within 15 seconds of the fire ignition. Under the same conditions copper fuel lines withstood many fires of durations up to one minute.

Fires of 30 seconds duration (See Figures 14 to 19) easily ignited the tire in the retracted position (See Figure 3). Such tire blazes disappeared when the powerplant installation fires were extinguished, but the tire continued to smolder since extinguishing agents carried aft by the air blast were incapable of arresting this smoldering, which burned through the rubber to the fabric within one minute. However, tests indicated that the smoldering would not continue indefinitely until tire failure.

In installations of the DC-3 type, the tire is less vulnerable to fire when the landing gear is in the lowered position. In other designs, in which the tire is completely enclosed within the wheel well, tire damage due to fire is highly improbable.

Aluminum alloy brackets, supports, straps, and clips ahead of the firewall melted quickly during the test fires. Such parts, if important to structure or operation, should be constructed of steel. The aluminum alloy engine cylinder baffles were undamaged in all the tests although in many cases they were directly within oil fires.

The Eclipse Starter Unit (Model E-160) installed within the hottest portion of several accessory section fires, was unaffected by several large gasoline fires of 30 seconds duration.

Steel Dzus fasteners, used throughout the cowling assembly, became loose fitting after numerous fires, due to cowl and fastener warpage, and to loss of spring temper, but continued to hold the cowling in place. An aluminum alloy fastener attached to one of the accessory section cowls melted within 10 seconds from the start of an oil fire.

Aluminum alloy ducts and blast tubes were protected in the test fires by lagging to prevent melting. Such ducts and tubes provided dangerous re-ignition sources by melting at vulnerable locations, allowing fire to enter, and re-igniting the main fire after extinguishment.

Silver soldered connections in extinguishing agent distribution systems failed in the tests and were replaced by ferrule and compression type tube fittings.

The results of the temperature surveys in the accessory section (See Figures 98 to 105) indicated stratified conditions with peak temperatures of approximately 2050° F for both large and small gasoline fires. This data may be used for determining the fire resistance of any parts to be used in accessory sections in the future by setting up laboratory conditions to simulate this condition. A uniform fire temperature (not stratified) of 2000° F would be slightly conservative.

In determining the degree of fire resistance necessary for parts within the accessory section, the overall fire resistance of all parts should be evaluated, as closely as possible, to obtain uniformity between critical parts as to their ability to resist fire. For example, nothing is gained by installing oil lines capable of resisting gasoline fires for periods of time up to five minutes, when the engine supporting structure would be capable of resisting the same fire for one minute or less.

CONCLUSIONS

1. Temperature data obtained indicates that the integrity of conventional monocoque nacelle structures can be seriously jeopardized by engine fires within a few seconds from the start of such fires.

2. The 2000° F temperature of cowl and nacelle skin resulting from gasoline and oil fires will melt aluminum alloy; such conditions will not melt stainless steel but will reduce its load carrying ability.

3. Flame temperatures within the accessory section, during gasoline fires, reached peak values of 2050° F.

4. The conventional welded steel tube engine mount used in the tests supported the engine with no apparent damage during 1422 gasoline and oil fires of durations from 15 to 60 seconds each, the majority being of 30 seconds.

5. The firewall of .018 stainless steel was undamaged by 1422 gasoline and oil fires of durations from 15 to 60 seconds each, the majority being of 30 seconds.

6. Aluminum alloy oil lines and AN neoprene hose connections containing a flow of oil were not damaged by gasoline or oil fires of 40 seconds duration. Tests showed that aluminum alloy fuel lines were destroyed by fire within 15 seconds due to vapor lock. Other aluminum alloy lines, not carrying flows of liquid, were also damaged by such fires. Copper tubing, or tubing of equal heat resistance, should be used for fuel lines, extinguishing systems and similar installations.

7. Oil cooler air intakes must be so located as to prevent the entrance of fire, and cooling air should flow through the cooler during fire.

8. Unless protected or removed from flame contact, the landing gear tire will ignite and continue to smolder for some time after fire extinguishment.

9. The aluminum alloy NACA cowl assembly was not seriously damaged by the fires.

10. Silver soldered connections in extinguishing systems failed during fire tests of 30 seconds duration. Ferrule and compression type fittings should be used in extinguishing systems.

SECTION 4 - IGNITION

PURPOSE

The purpose of the ignition tests was to study the causes of gasoline and oil ignition in an aircraft powerplant in flight and to determine methods whereby these hazards may be reduced.

PROCEDURE

The majority of data on ignition was obtained during the tests on extinguishers, detectors, and materials.

Oil vapor explosions in the confined areas of the carburetor air heating system (see Figure 7) accidentally occurred early in the fire extinguishing tests in the form of flashbacks after fires had been extinguished. Approximately 200 tests were conducted to obtain data on this source of ignition. Tests were also conducted to determine the possibility of spontaneous ignition of gasoline and oil in which those fuels were sprayed over confined areas and the exhaust system.

Gradual deterioration of the exhaust system as the tests proceeded presented conditions which were ideal for observing the possibility of ignition because of faulty exhaust systems.

Accidental spark ignition of oil and gasoline was simulated by spraying these liquids over electric sparks (15,000 volts and 30 milliamperes) deliberately produced.

RESULTS AND DISCUSSIONS

At the beginning of the tests it was determined to investigate the possibility of ignition of gasoline and oil in an aircraft powerplant due to oil vapor explosions within confined high temperature areas, high temperatures of exhaust systems and other parts, faulty exhaust systems, and sparks produced by the ignition system, static conditions, or friction.

Early in the extinguishing tests, extinguishment was frequently followed by the relighting (flashback) of the fire in the vicinity of the exhaust stack. In many instances there was considerable doubt as to whether or not the fires had been completely extinguished and it was thought that small unseen parts of the original fire were causing the relighting.

To eliminate this doubt approximately 200 tests were conducted in which: all materials which could have acted as wicks were removed, smoke was forced into the exhaust system to ascertain that no leaks were present, excessive quantities of extinguishing agent were used to positively insure extinguishment, fire tests were conducted at night to improve conditions for viewing the fires, windows were installed in the cowling for observations within the accessory section, and high speed motion pictures were taken of fires and flashbacks. All these tests indicated that the fires were being completely extinguished before flashback and finally, during extinguishment of one fire, the engine was quickly stopped, and upon the occurrence of flashback, a distinct explosion was heard, proving beyond doubt that the fire had been completely extinguished and that relighting had occurred.

Further tests were conducted in which it was found possible to obtain vapor explosions without previous fire, with the engine either running or stopped. The ignition of oil, without previous fire, could be produced at will by varying the air blast or by the addition or removal of certain parts of the carburetor hot air heating system (Figure 7). These tests proved that vapor explosions were caused by the confining of air due to the muffing of exhaust manifold and stack which permitted accumulations of oil vapor in these regions of high temperatures. Since it was impossible to obtain flashback with the fire source at any location other than on the right side of the nacelle unit in the vicinity of the exhaust stack, the overall hazard due to this condition is reduced accordingly.

Under operating conditions, the highest exhaust stack temperatures were found to be 1150° F, but immediately after a fire such temperatures were as high as 1400° F. In laboratory tests drops of oil (#10 SAE or drain oil) would not ignite on a steel plate heated to 1400° F, but oil vapor, produced by heating a quantity of oil in a container would ignite at approximately 750° F, without the flame contacting the vapor. These laboratory tests confirmed the full scale tests in that they provided an explanation as to why flashbacks occurred with no flame present and at temperatures much below 1400° F. Removal of the shrouding, muffing, and baffling from the exhaust system made vapor collections near the exhaust system impossible for the remainder of the tests and eliminated flashback. This shrouding is shown in Figure 7.

This ignition hazard, caused by the muffed type of carburetor hot air heating system, may be somewhat reduced by ventilating the stagnant regions and suffering a loss in heating efficiency. Another method of reducing this hazard is to locate the exhaust stack, shrouding, muffing, and baffles as close as practicable to the top of the engine, since the release of oil is much less probable near the top of the engine than in lower regions. Furthermore, it is possible that the air inlet to the carburetor air heating system could be so located as to prevent the entrance of fire or fuel.

The probability of flashback occurring after an extinguishment would be greatly reduced by stopping the engine before the extinguishing agent is applied, thus allowing a reduction in temperature of the exhaust system.

In the majority of tests on this type of ignition #10 SAE oil was burned. Other tests were conducted in which drain oil produced the same results as the #10 SAE oil.

Since it is impossible for appreciable quantities of gasoline to be released in the power section and enter the carburetor air heating system, no power section gasoline fires were tested in connection with flashback. However, many large accessory section gasoline fires burning in and around the exhaust stack muffing never resulted in flashback after extinguishment. It is quite likely that the narrow explosion range of gasoline as compared to that of oil makes gasoline much less susceptible to this type of ignition than oil.

Aside from oil vapor explosions as described above, accidental ignition, due solely to hot parts, never occurred during the tests. Recorded temperatures of the exhaust system, even during fires, were never higher than 1400° F. Since, in laboratory tests, steel plates had to be heated above 1400° F before oil, applied to the plates in drops, would ignite, it was obvious why accidental ignition did not occur during the full scale tests. The cooling and smothering action of the oil released over the hot parts was undoubtedly an important factor preventing the ignition of the oil by the hot parts. Apparently the oil cools the hot parts rather than accept ignition from such parts.

Spontaneous ignition of gasoline did not occur, although gasoline was in direct contact with the hot exhaust system in many of the tests.

As the result of gradual deterioration of the exhaust system, small flame ignition sources occurred at system joints and at burned-through spots and such sources re-ignited oil and gasoline fires after extinguishment in many instances. Stopping the engine before extinguishment would eliminate this source of re-ignition. The tests indicated that initial oil ignition due to this source would not be as probable as ignition due to vapor explosion, unless a major exhaust system failure occurred. Minor cracks and holes in the exhaust system could be very hazardous ignition sources in stagnant regions where oil vapor might collect

Gasoline ignited readily from small holes or cracks in the exhaust system. Relighting of test fires occurred in a few instances at the exhaust stack outlet, making clear the necessity for locating such an outlet as far from the powerplant proper as possible. However, as previously stated, stopping the engine before extinguishment would eliminate this re-ignition source.

In the tests the spark used to ignite gasoline fires was produced by a spark plug operating on 15,000 volts and 30 milliamperes. (Oil fires were ignited by a small spark-ignited gasoline fire.) Gasoline was readily ignited by this spark but hot oil (#10 SAE at 300° F) sprayed over the spark would not ignite in any of the tests.

In many tests, gasoline which had been allowed to accumulate in the accessory section could not be ignited by a spark within the section, probably because of too rich a mixture. In such instances ignition was obtained by locating a spark just outside an opening in the accessory section cowl from which gasoline was flowing.

CONCLUSIONS

1. The most dangerous source of oil ignition in an aircraft powerplant installation is an exhaust system employing shrouds, muffs, and baffles for collecting heated carburetor air.

2. Ignition of oil due to a well ventilated exhaust system, in good condition, operating below 1400° F, is highly improbable.

3. Gasoline is easily spark ignited and oil is difficult to ignite by spark.

4. Stopping the engine before extinguishing a fire considerably reduces the possibility of fire re-ignition after extinguishment.

5. Faulty exhaust systems are probable sources of initial ignition, and very probable sources of fire re-ignition after extinguishment, unless the engine is stopped.

6. Ignition of gasoline and oil never occurred during the tests due solely to hot metal surfaces. However, hot metal surfaces, in combination with stagnant volumes of air and oil vapor could be a source of fire ignition, as stated in Conclusion 1.

TABLE 7

FIRE TEST STATISTICS

	NUMBER OF TESTS CONDUCTED			QUANTITIES OF AGENTS USED		
EXTINGUISHING AGENTS	FIRE TESTS	RATE TESTS	TOTAL TESTS	FIRES	RATE TESTS	TOTAL TESTS
Carbon Dioxide	635	228	863	11,580 lbs.	2,200 lbs.	13,780 lbs.
Carbon Tetrachloride	425	147	572	666 gals.	92 gals.	758 gals.
Methyl Bromide	107	9	116	69 gals.	3 gals.	72 gals.
Sodium Bicarbonate	80	14	94	1,383 lbs.	147 lbs.	1,530 lbs.
Mixture – (70% Carbon Tetrachloride (30% Methyl Bromide	24	9	33	22 gals.	4 gals.	26 gals.
Mixture – (70% Dichlormethane (30% Methyl Bromide	6	0	6	4 gals.	0	4 gals.
Potassium Carbonate	5	0	5	4 gals.	0	4 gals.
Mixture – (Carbon Tetrachloride (Carbon Dioxide	4	20	24	11 gals.	4 gals.	15 gals.
Water	4	1	5	8 gals.	2 gals.	10 gals.
Total Number of tests on Extinguishing Agents	1290	428	1718			
Detector	90	—	90			
Ignition Study Fire Tests	26	29	55			
Preliminary Fires	16	—	16			
TOTAL TESTS	1422	457	1879			

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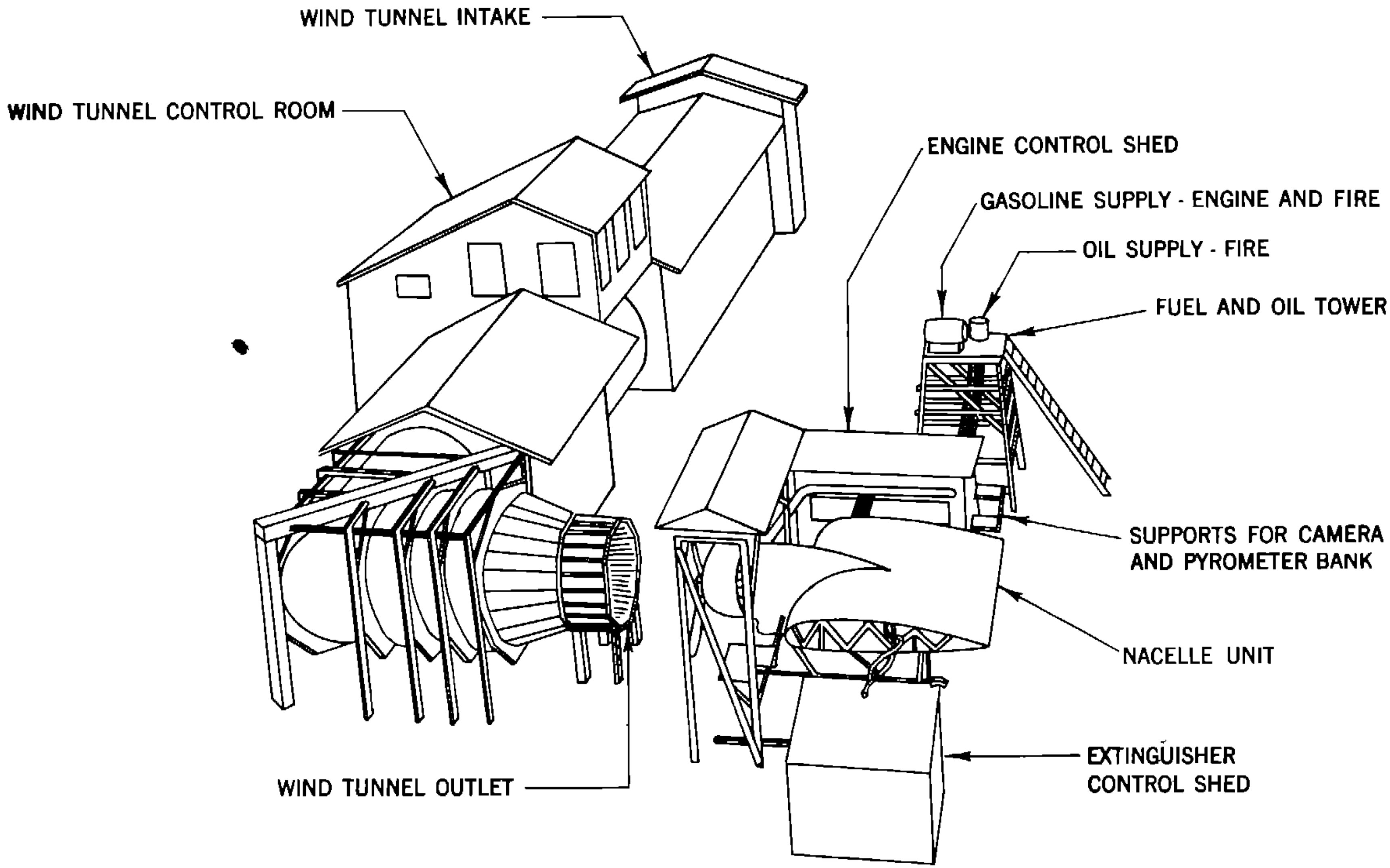


FIGURE 1. Test layout.

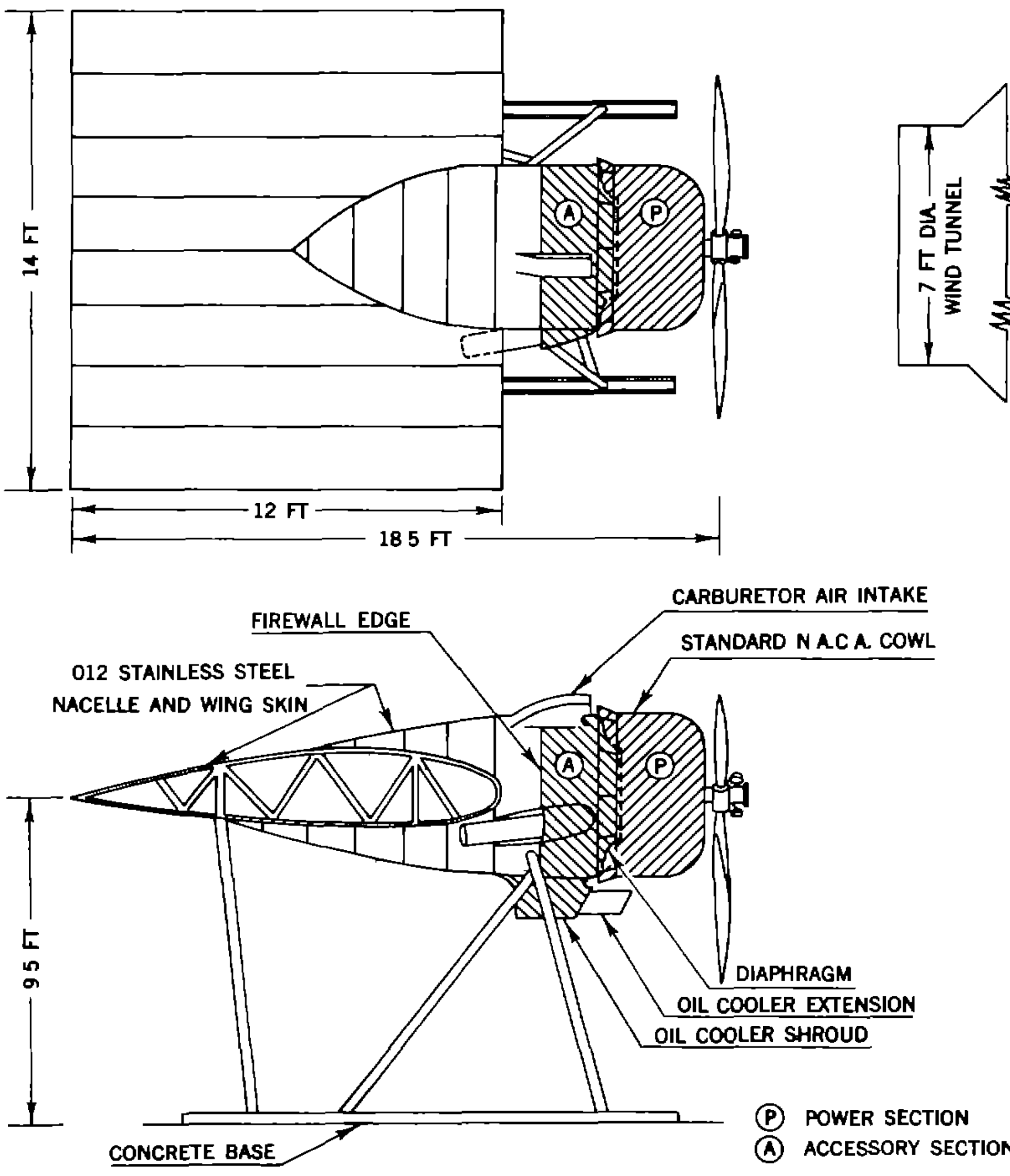


FIGURE 2. Nacelle unit.

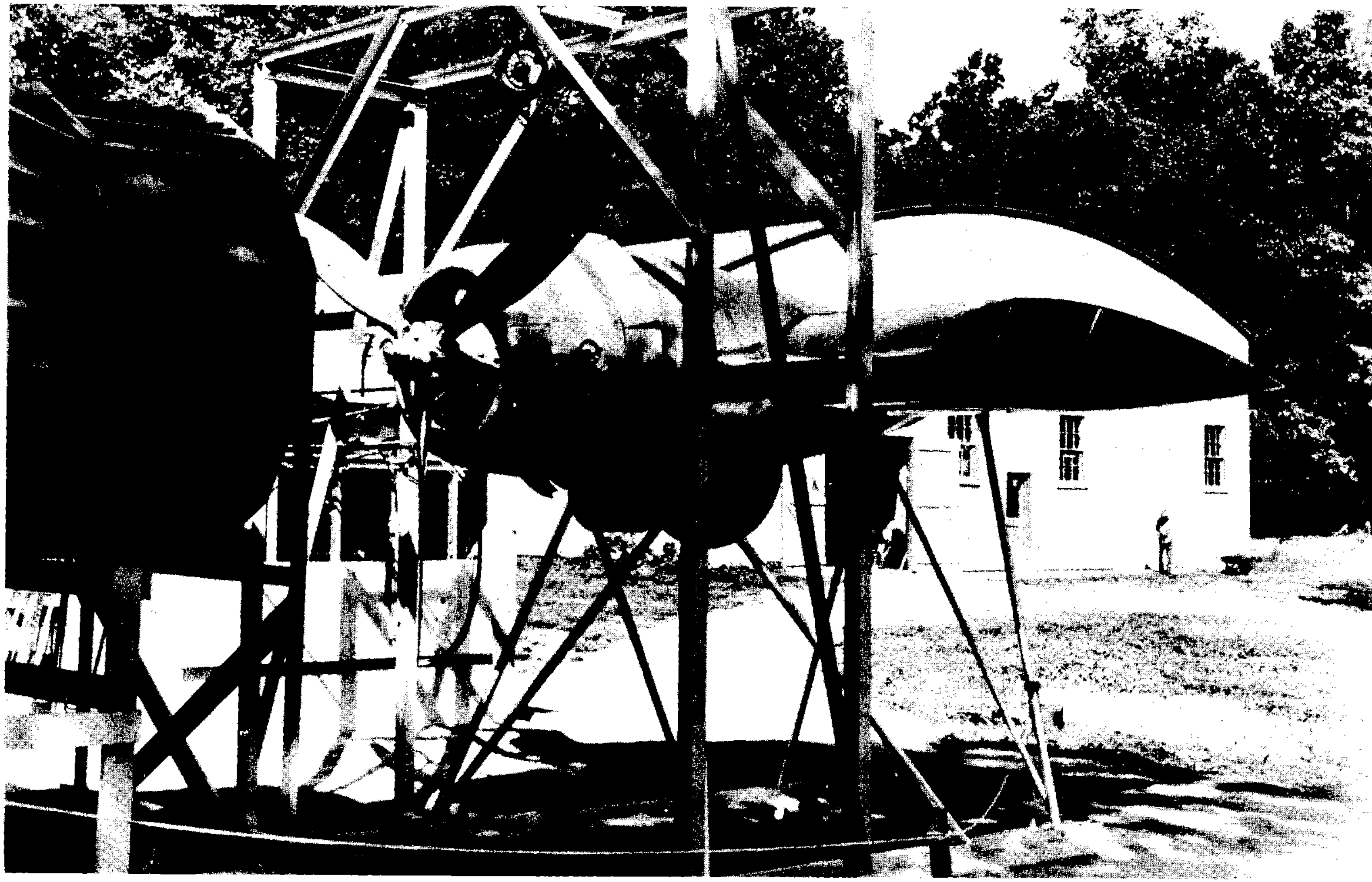


FIGURE 3. Three-quarter front view of Nacelle Unit.

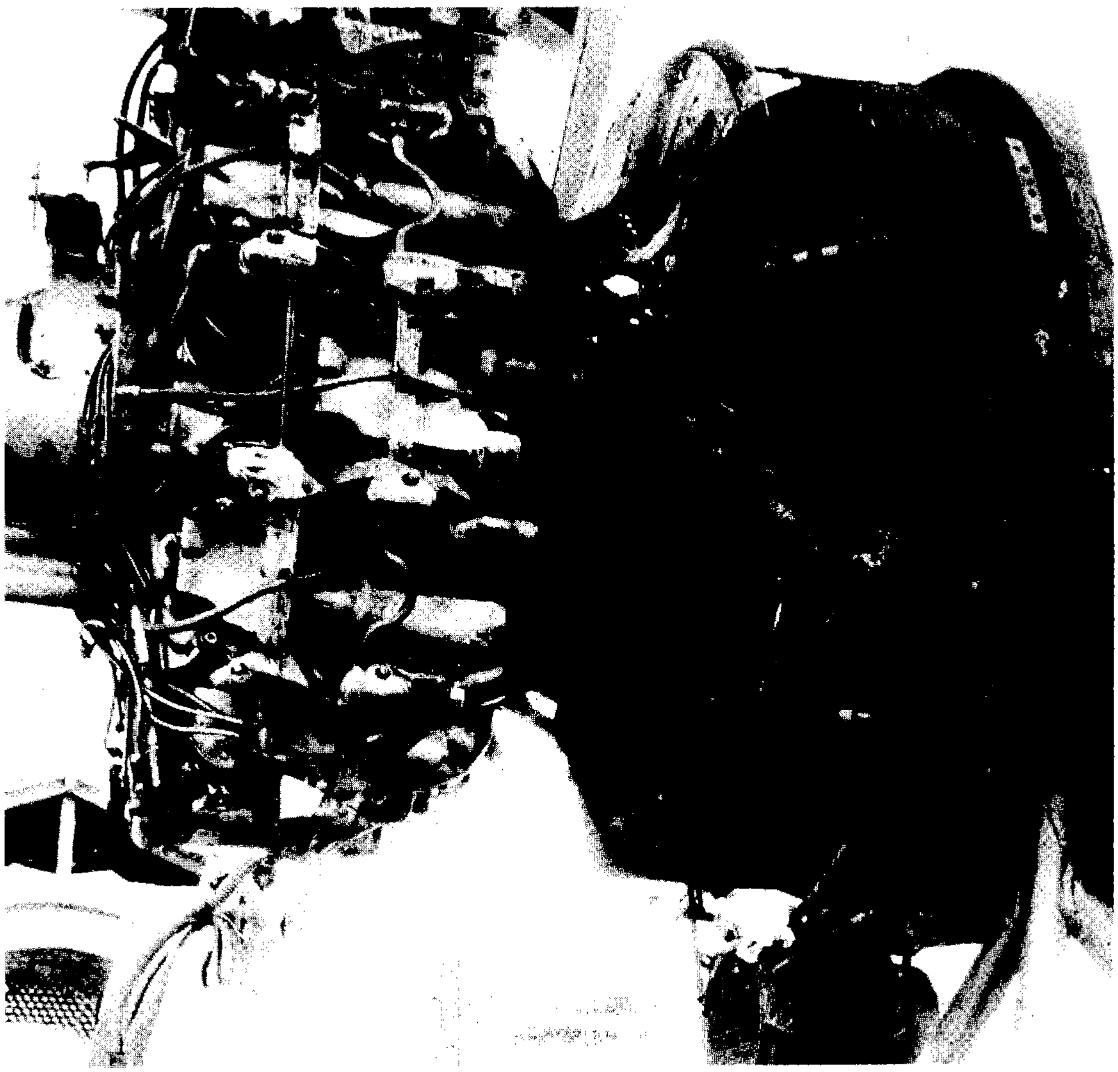


FIGURE 4. Powerplant installation (left side) after 1200 fires.

FIGURE 5. Powerplant installation (right side) after 1200 fires. Arrow shows opening between cylinders due to the removal of the intercylinder baffles as described under "General Test Procedure".

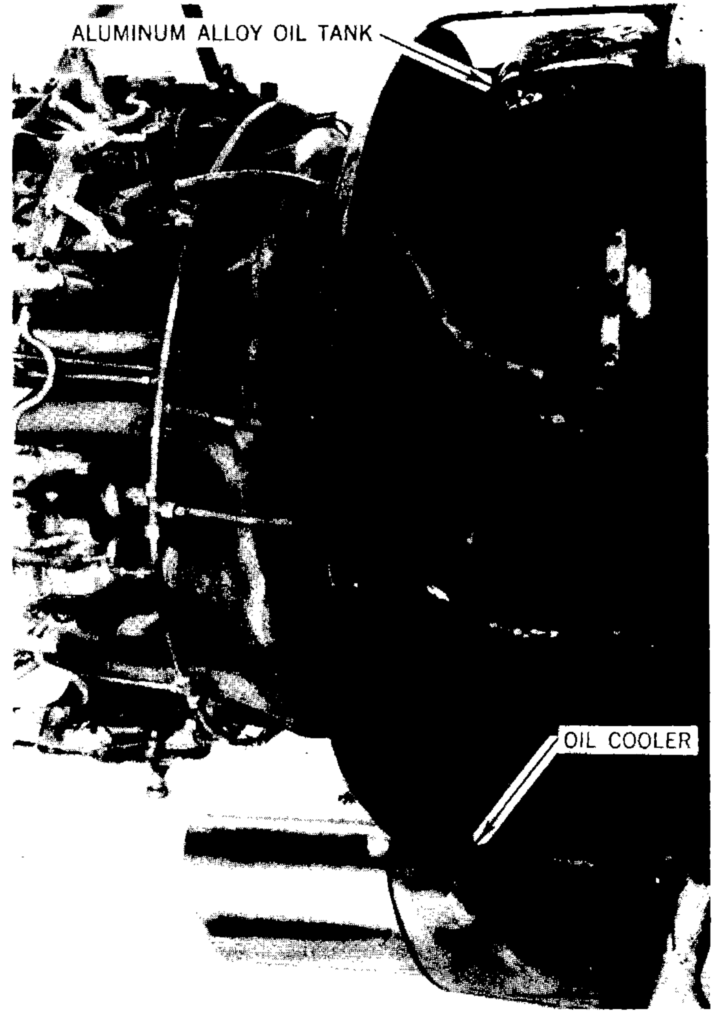


FIGURE 6. View of unprotected aluminum alloy oil tank.

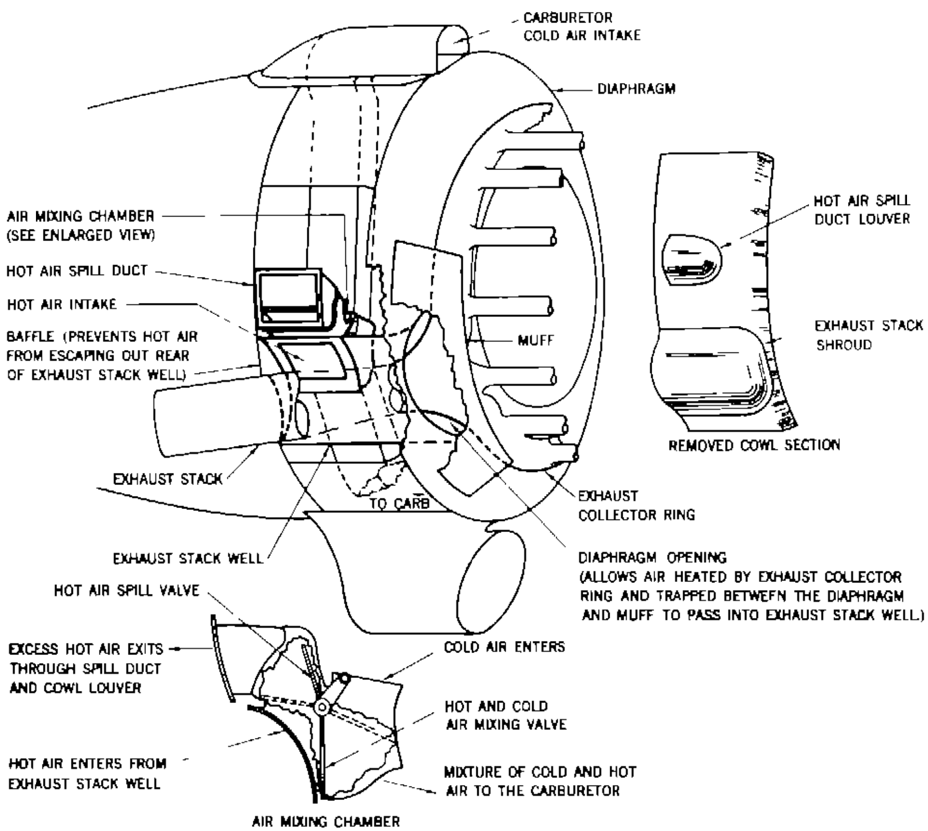


FIGURE 7 Carburetor air heating system

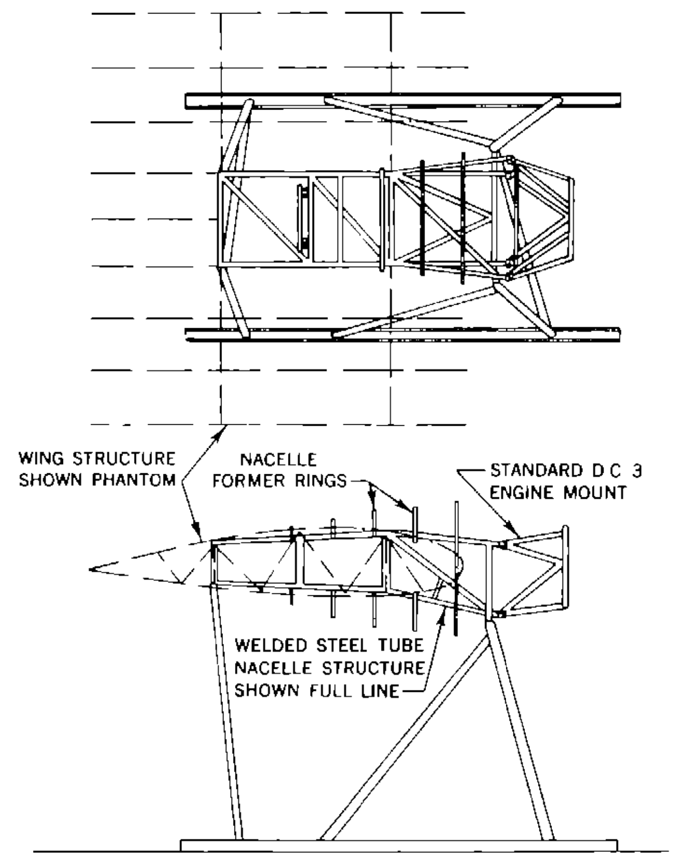


FIGURE 8 Nacelle unit skeleton structure

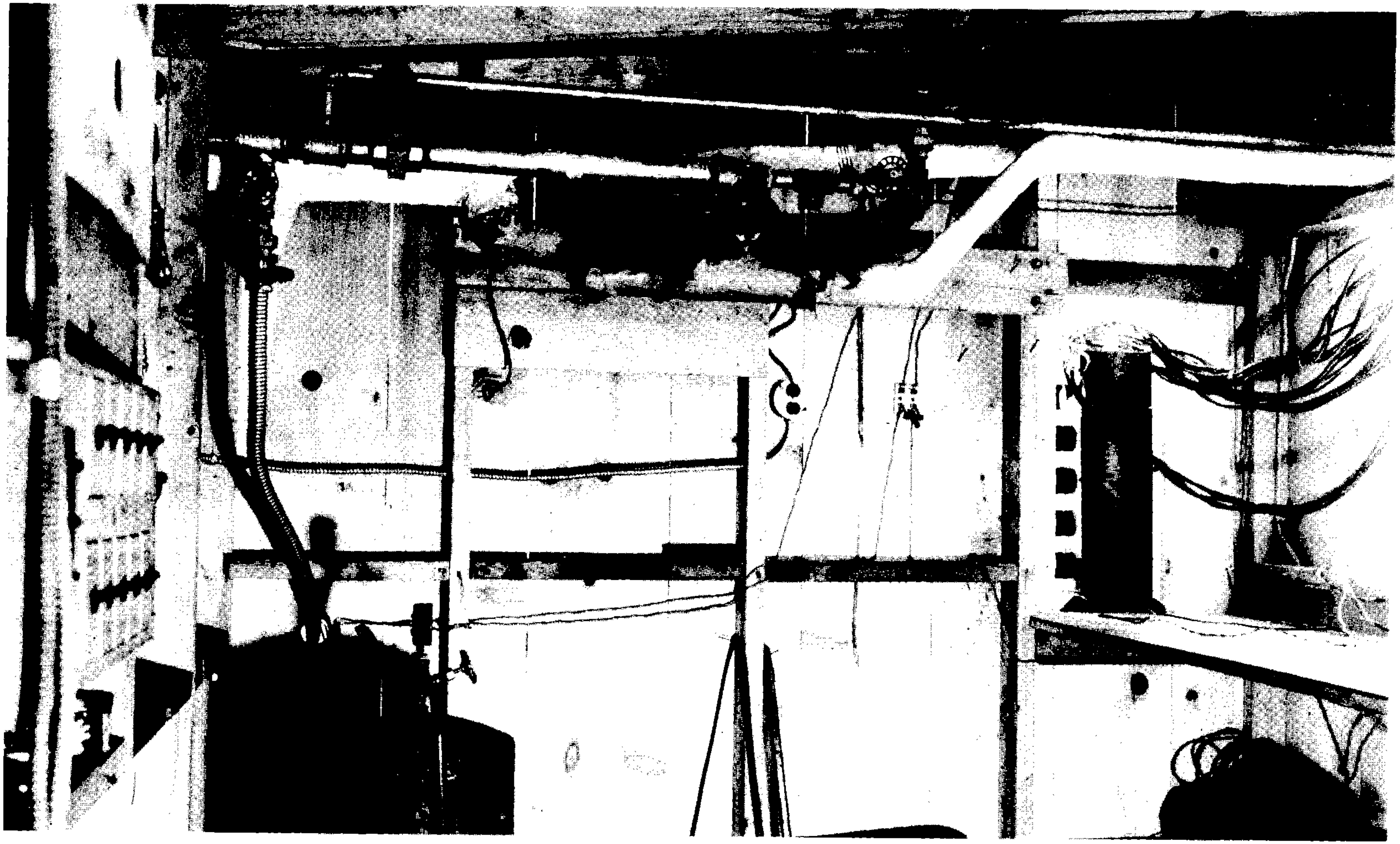


FIGURE 9. Control shed interior showing gasoline and oil control valves.

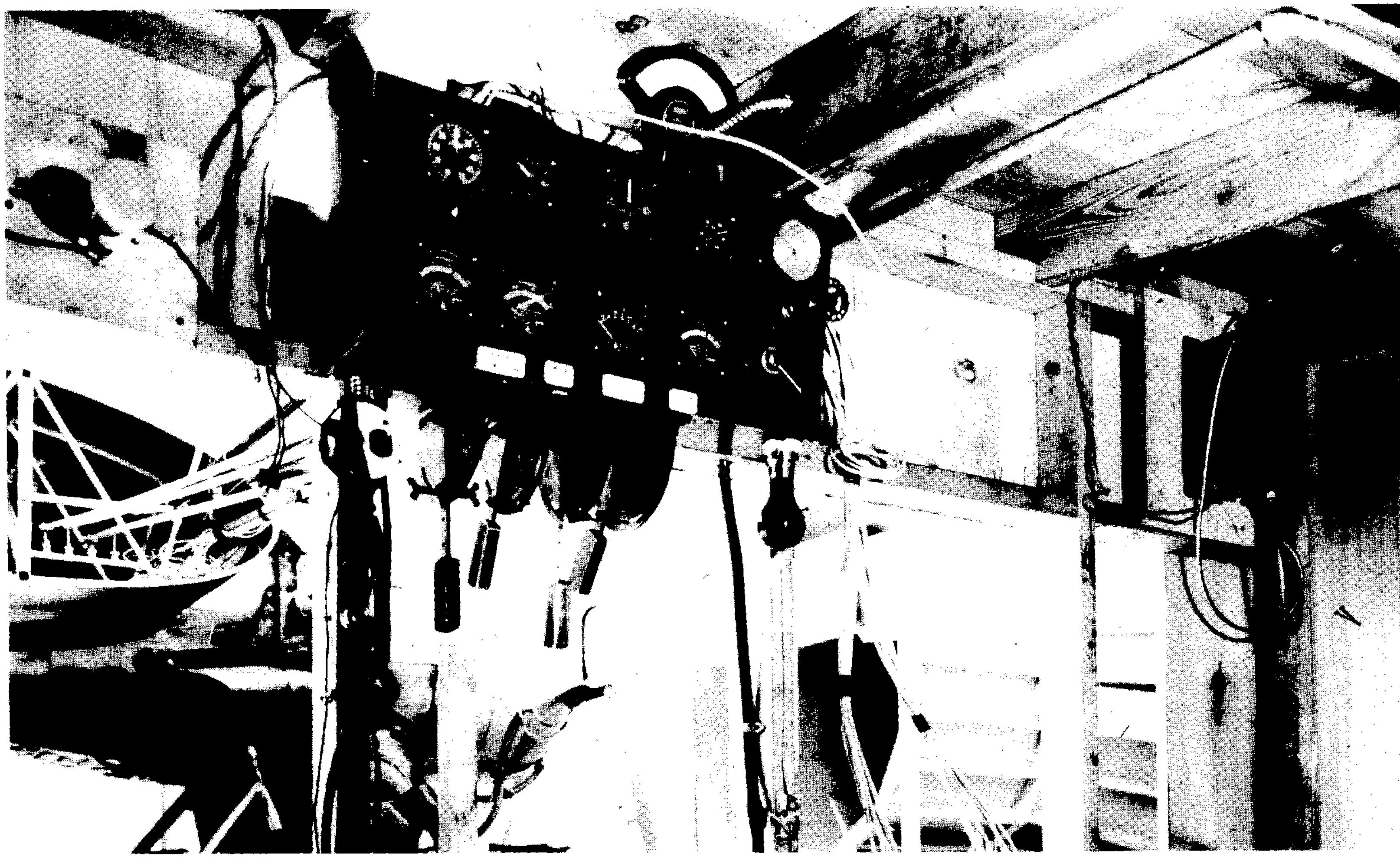


FIGURE 10. Control shed interior showing engine instruments and operating controls.

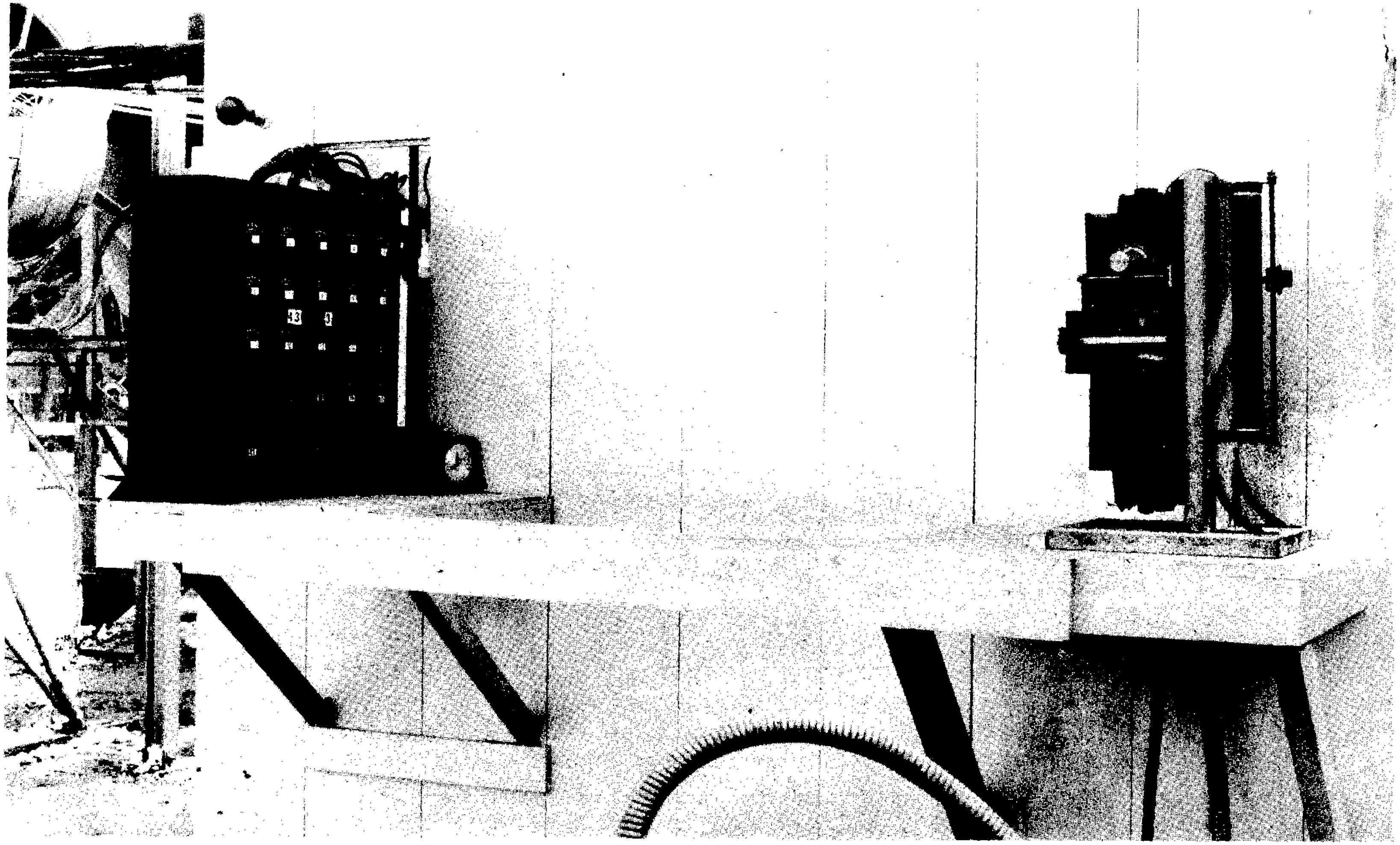


FIGURE 11. Control shed exterior showing pyrometer bank and recording camera.

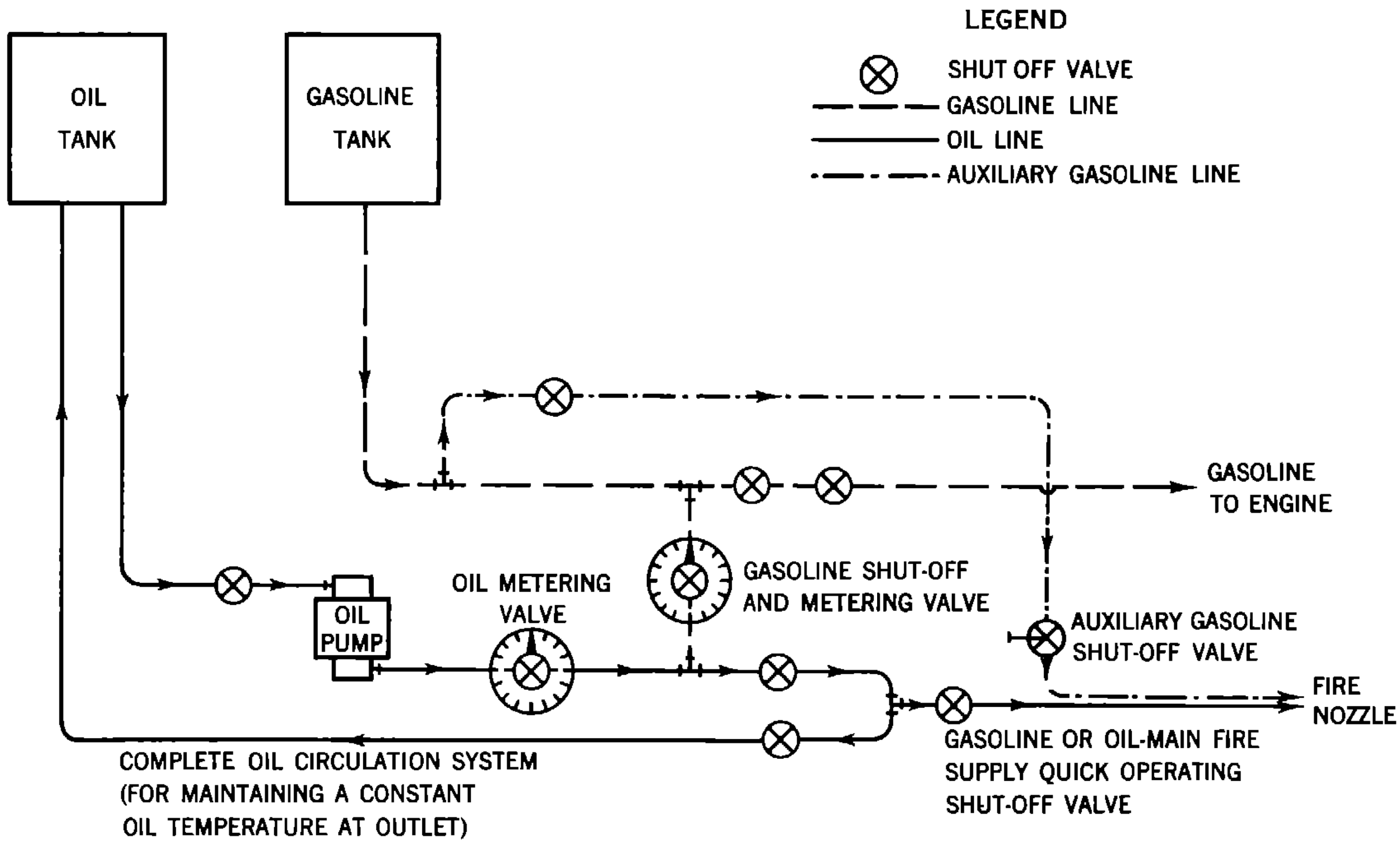


FIGURE 12 Gasoline and oil piping diagram

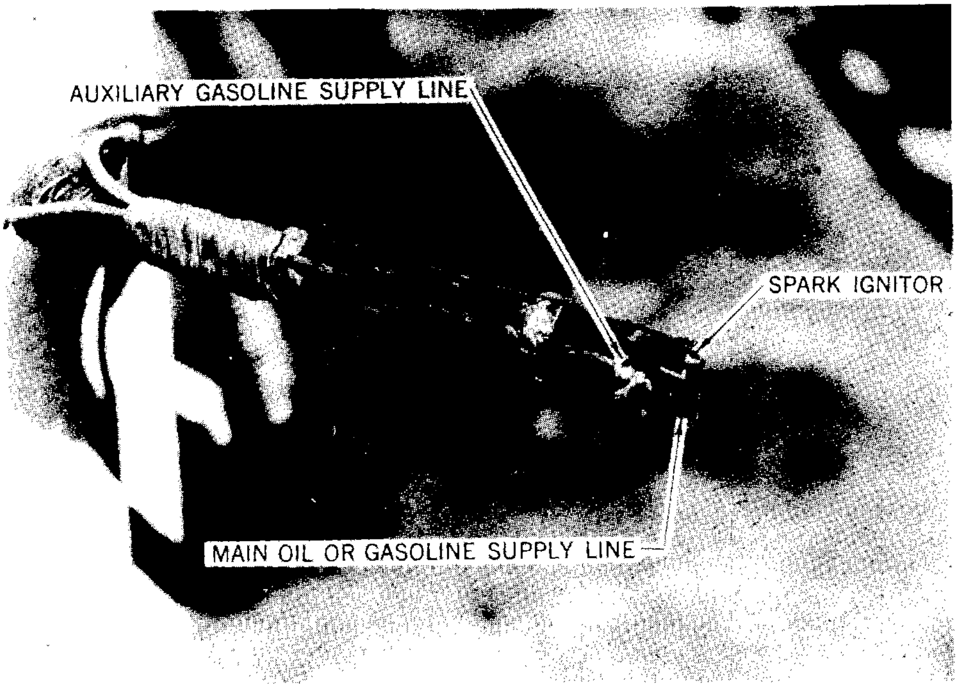


FIGURE 13. Fire nozzle.

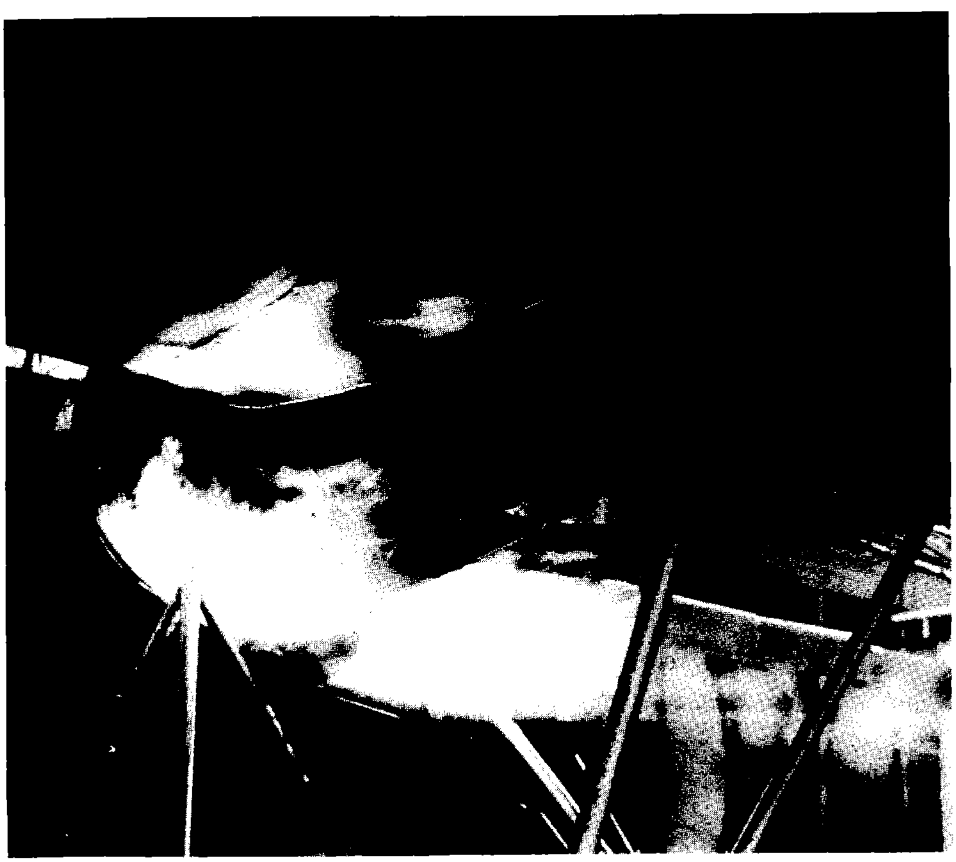


FIGURE 14. 5 gallons per minute power section oil fire.

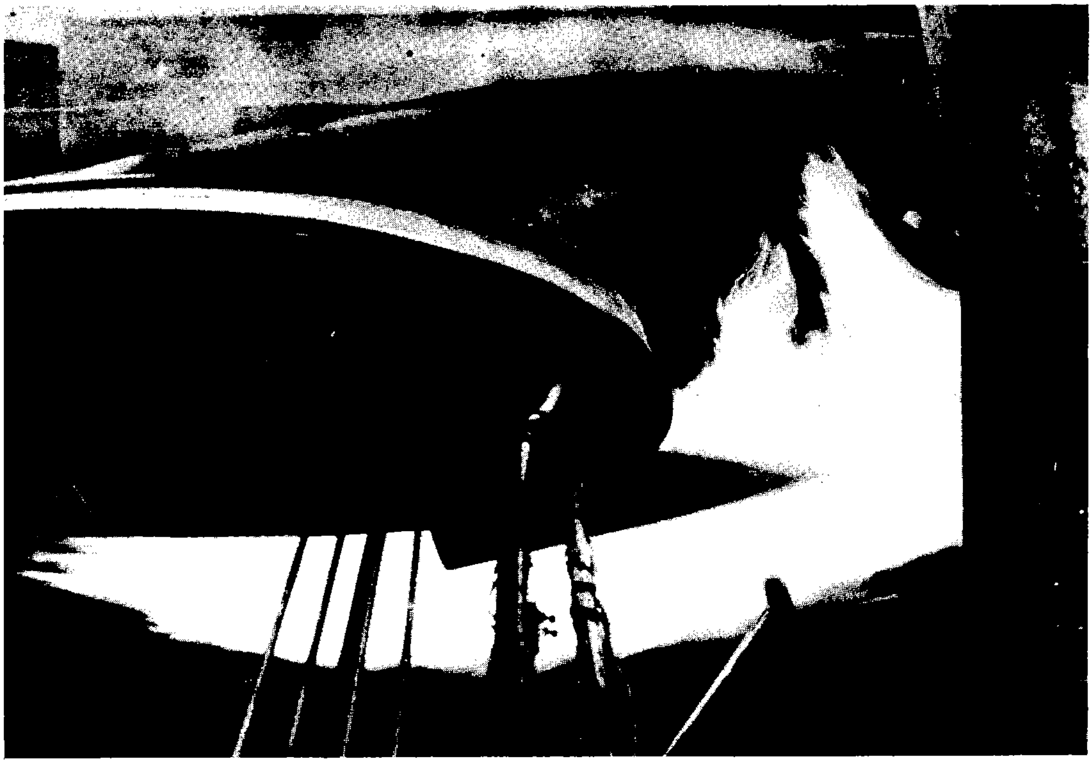


FIGURE 15. 5 gallons per minute power section oil fire.

FIGURE 16. 5 gallons per minute power section oil fire.

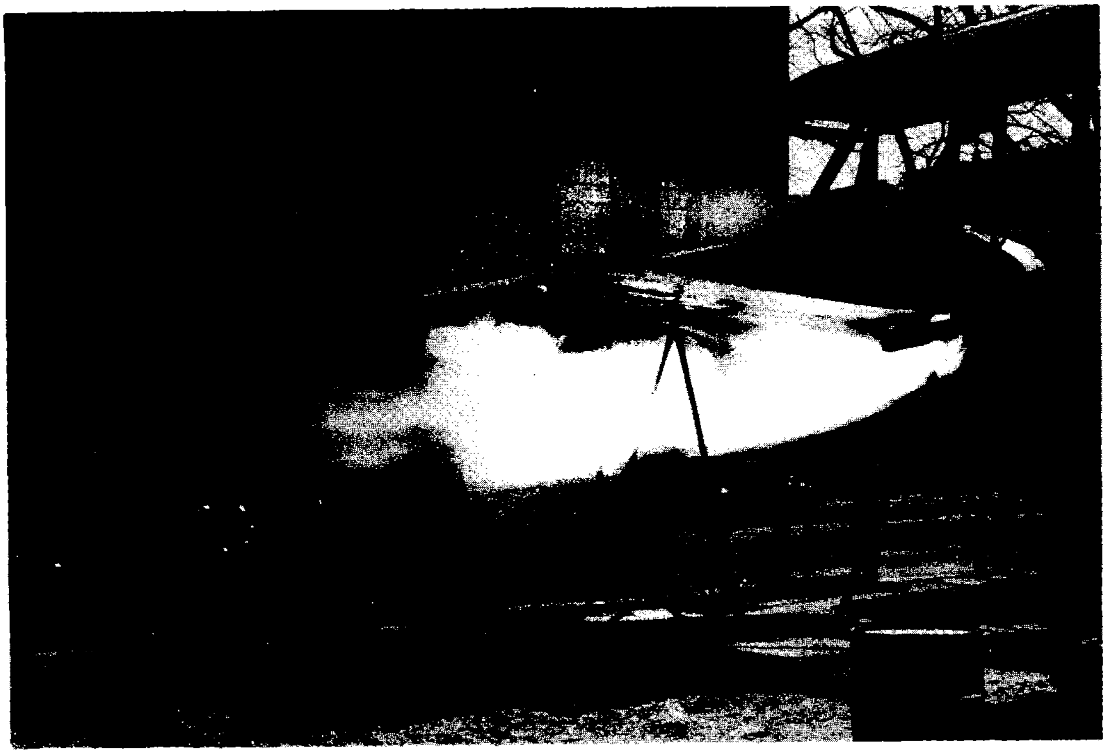


FIGURE 17. 11 gallons per minute accessory section oil fire.

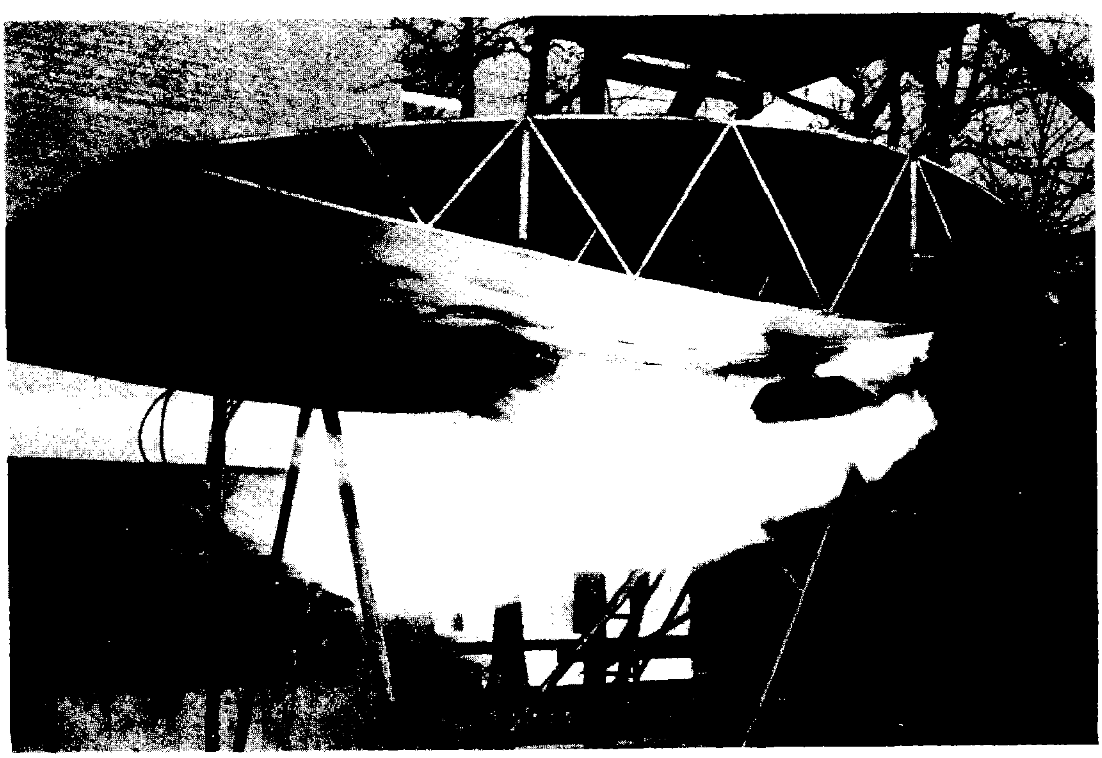


FIGURE 18. 6.5 gallons per minute accessory section gasoline fire.

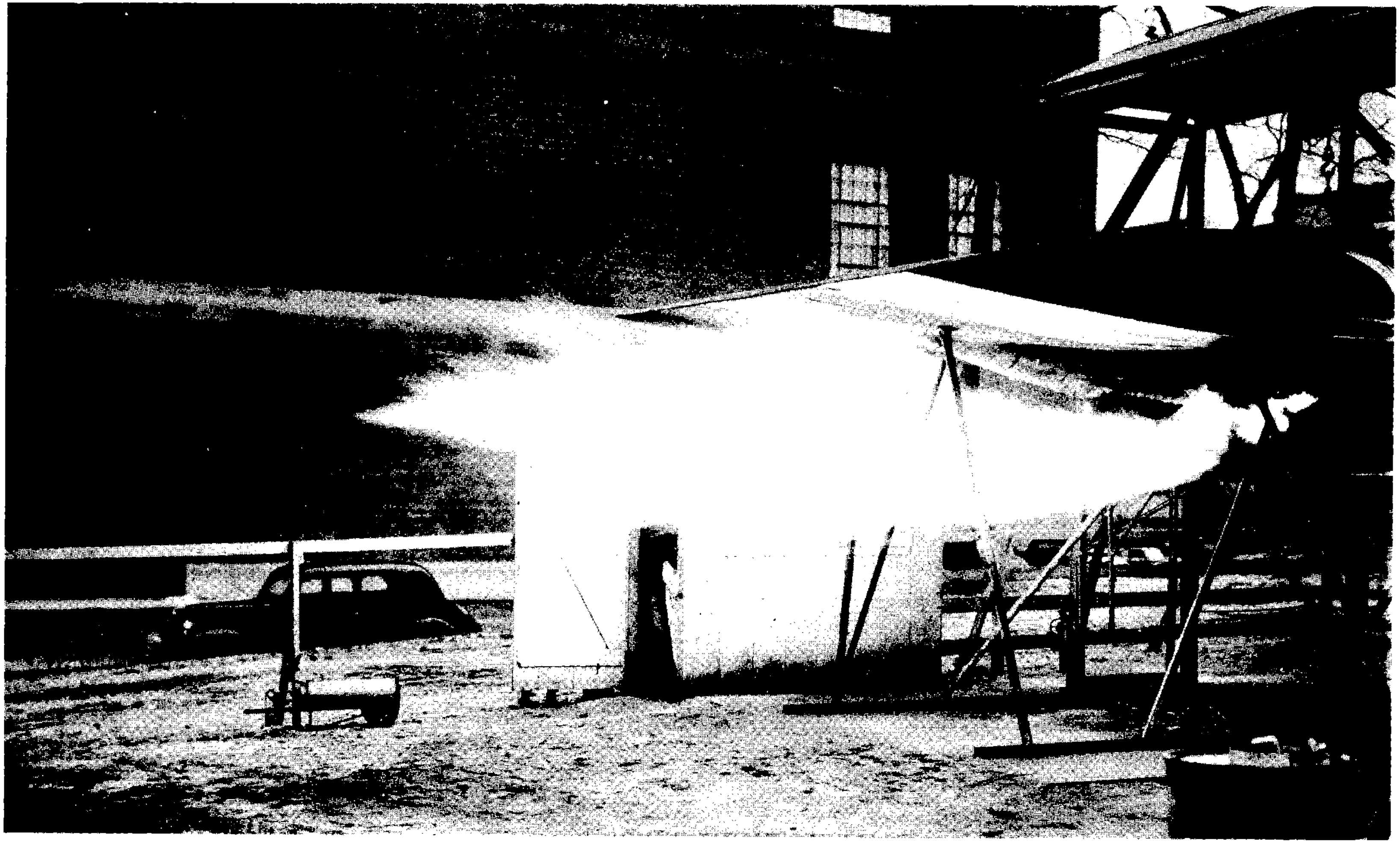


FIGURE 19. 6.5 gallons per minute accessory section gasoline fire.

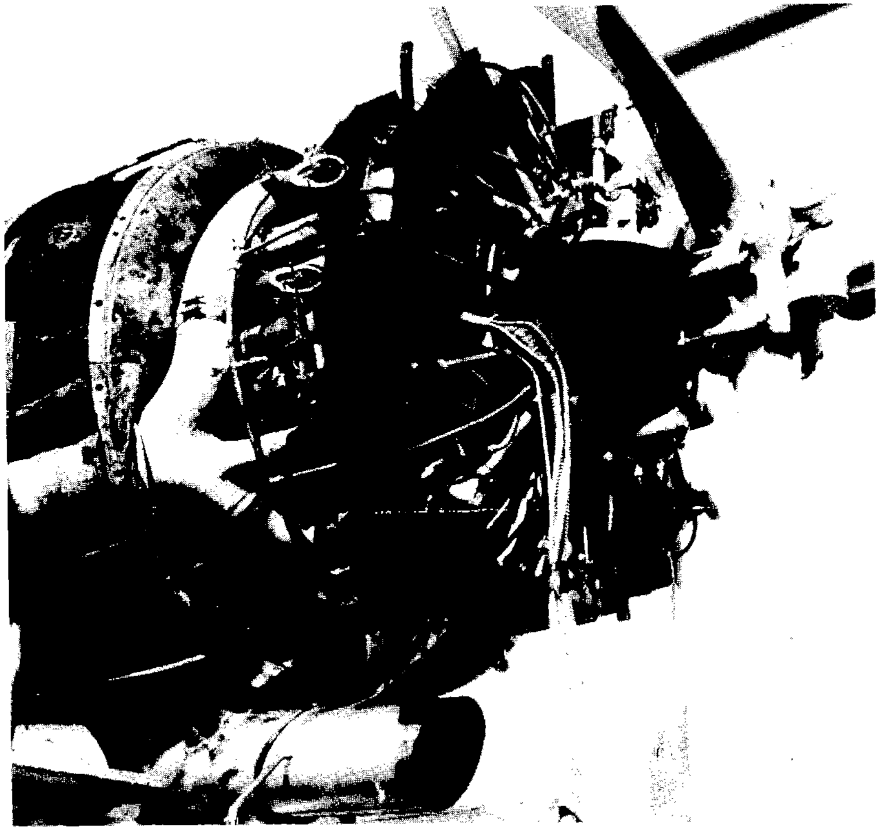


FIGURE 20. Fire nozzle in position in the power section.

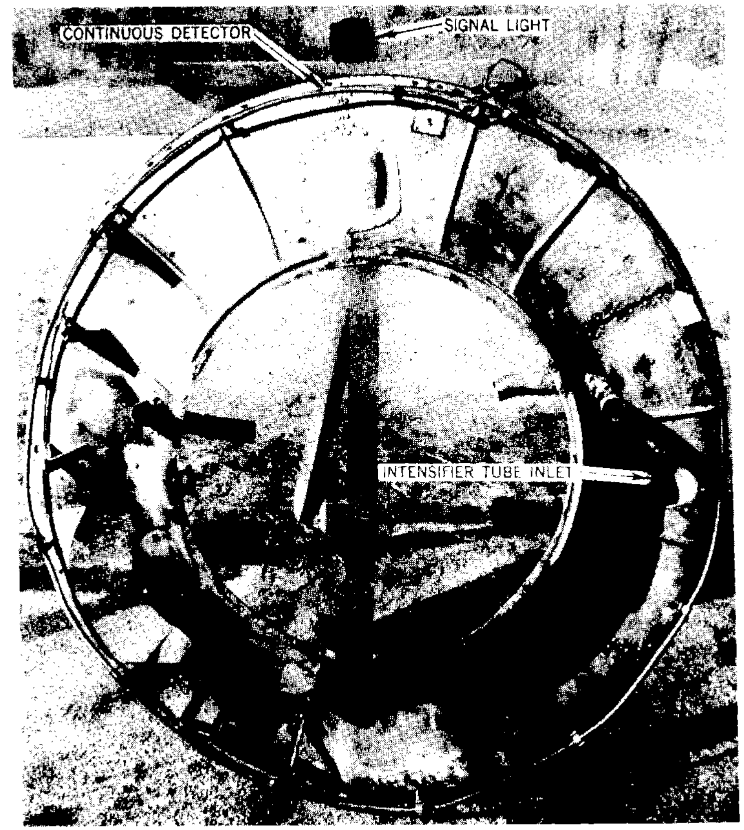


FIGURE 21. Diaphragm showing continuous detector installed.

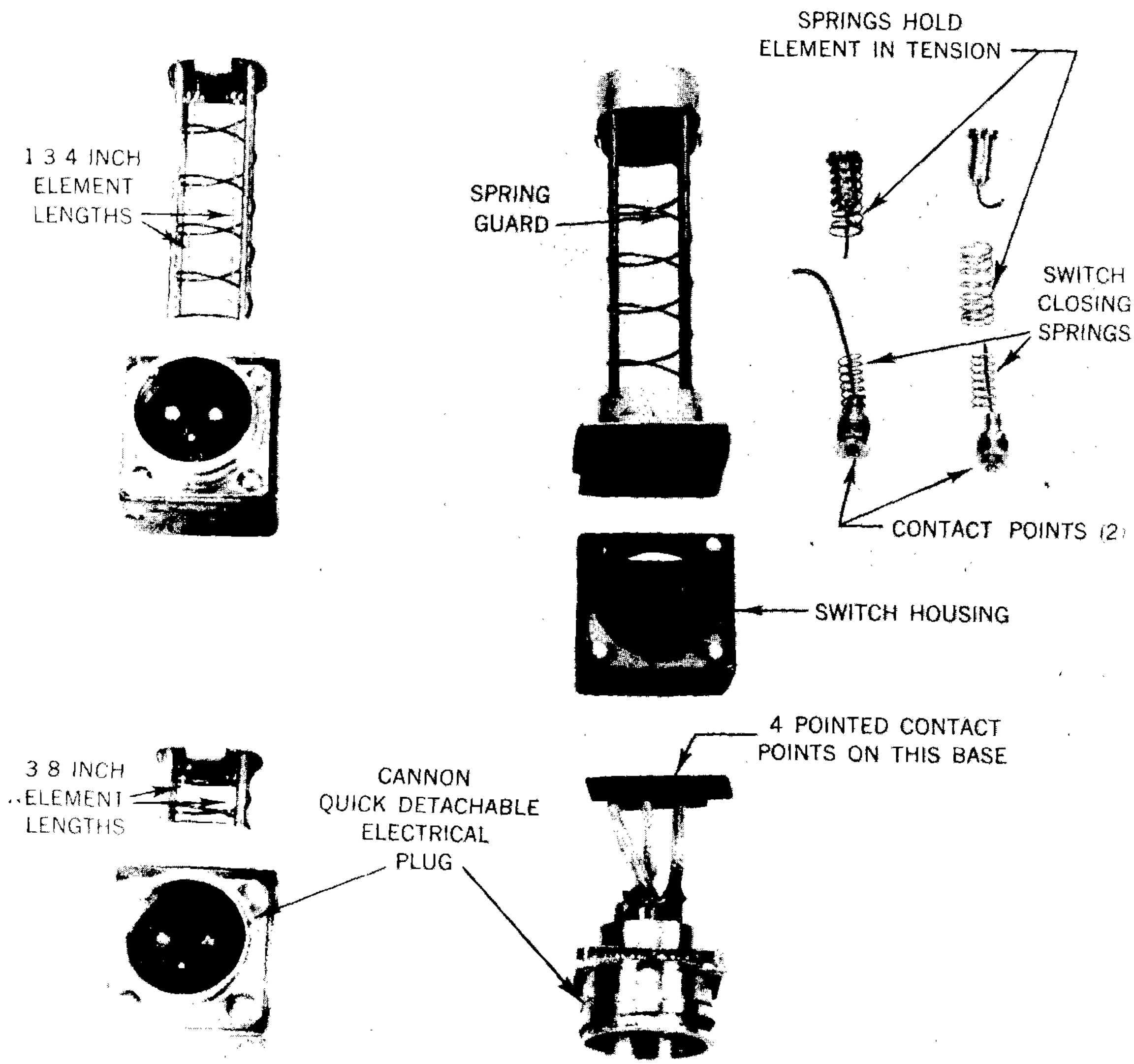


FIGURE 22. Flame type detector (Walter Kidde & Co.)

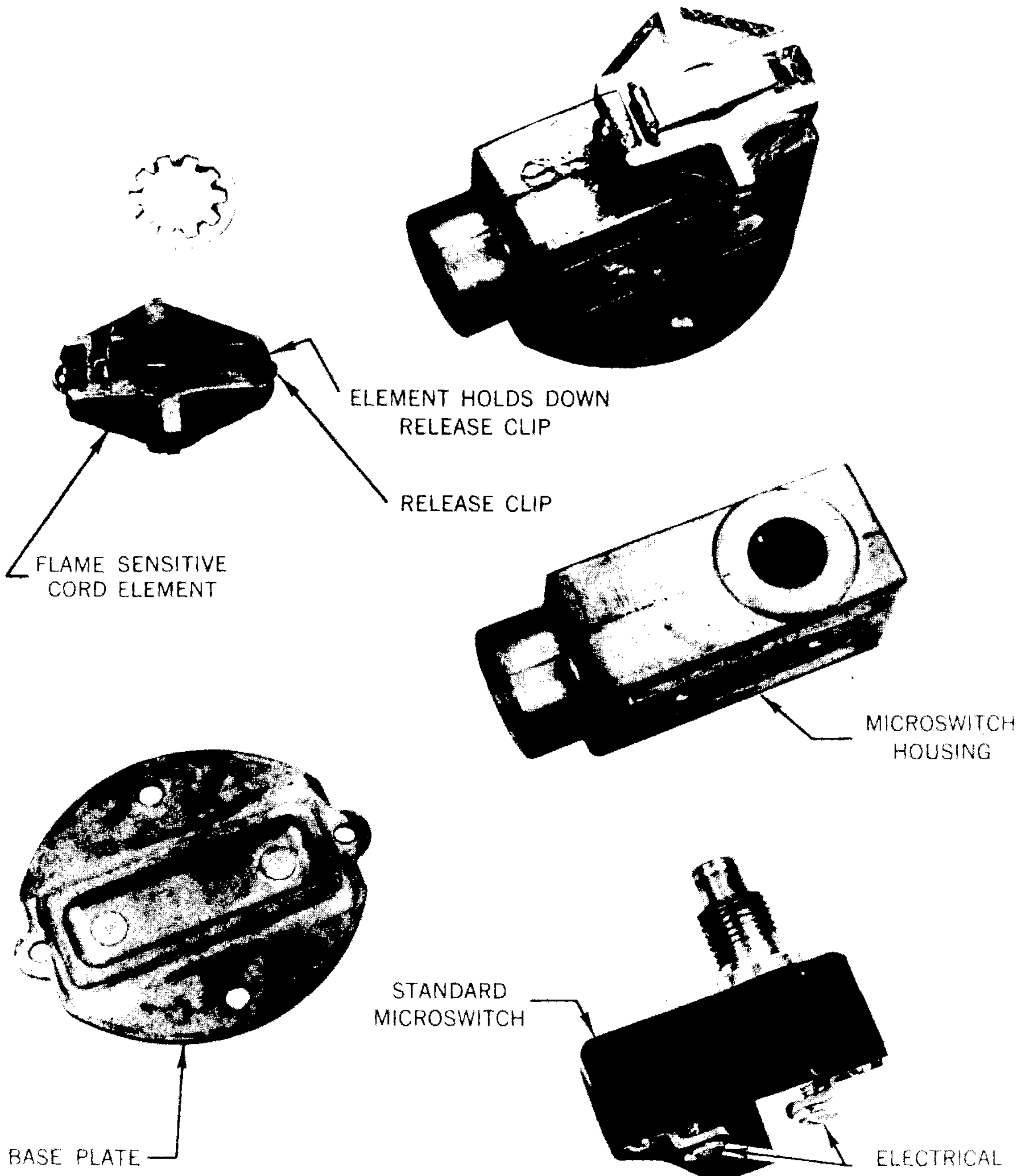


FIGURE 23. Flame type detector (Dugas Engineering Corp.)

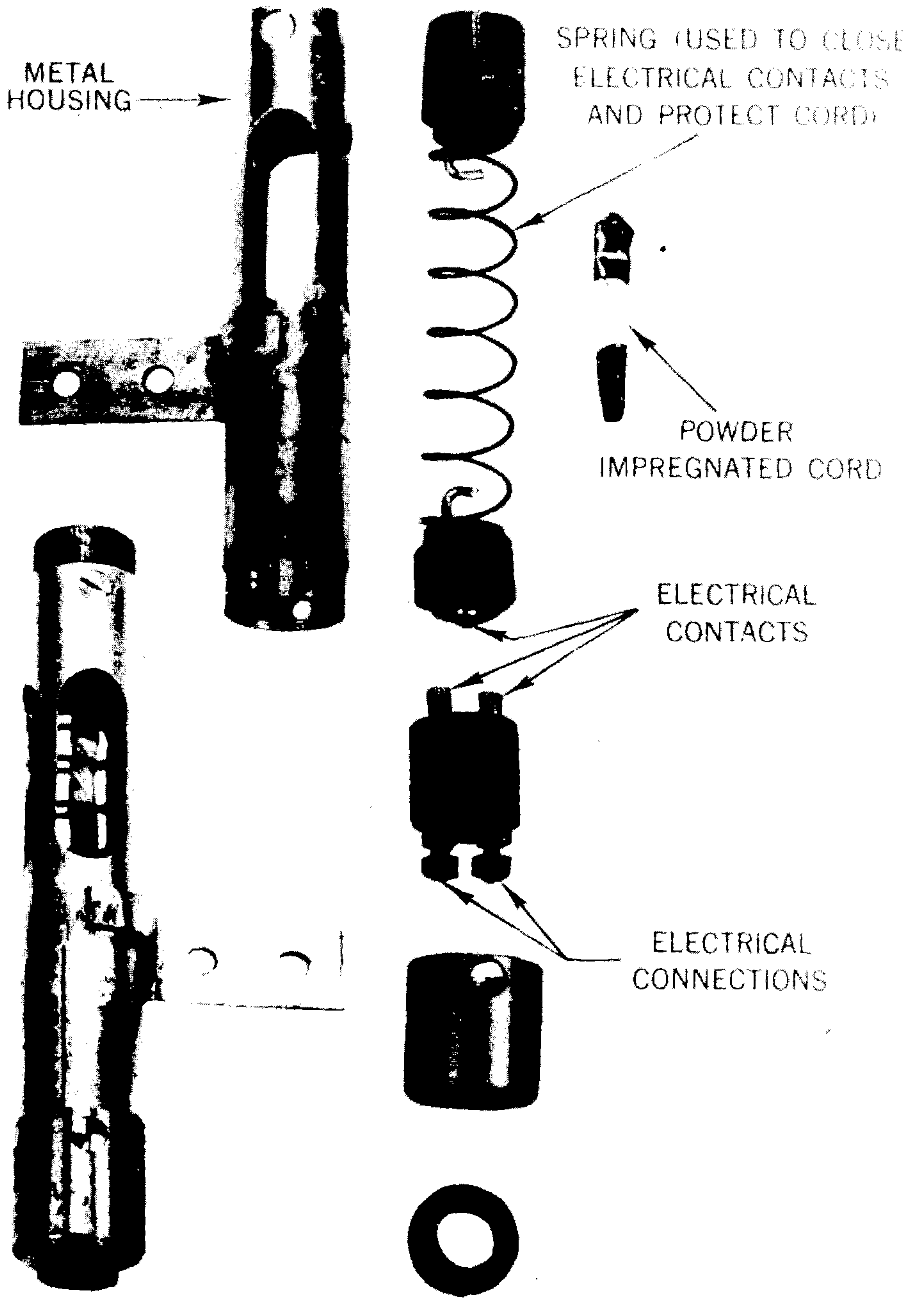


FIGURE 24. Flame type detector (Graviner Mfg. Co., Ltd.)

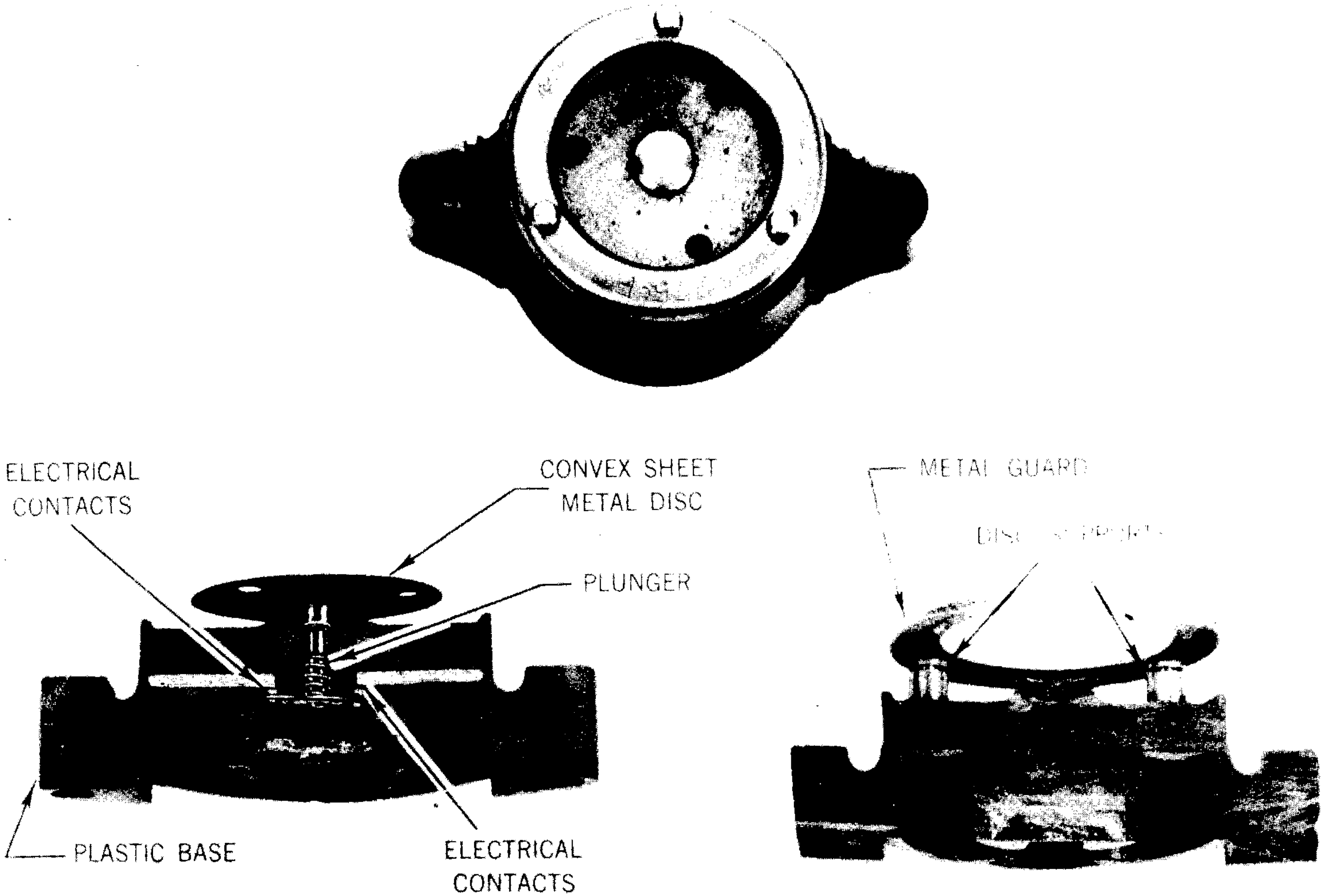


FIGURE 25. Metal expansion type detector (American District Telegraph Co.)

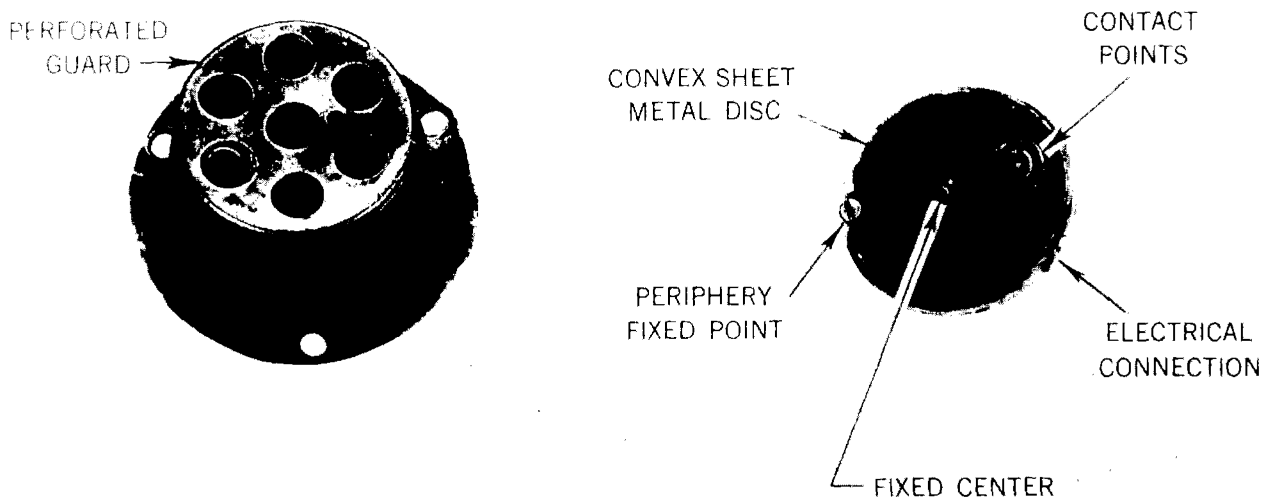


FIGURE 26. Metal expansion type detector (American-La France-Foamite Corp.)

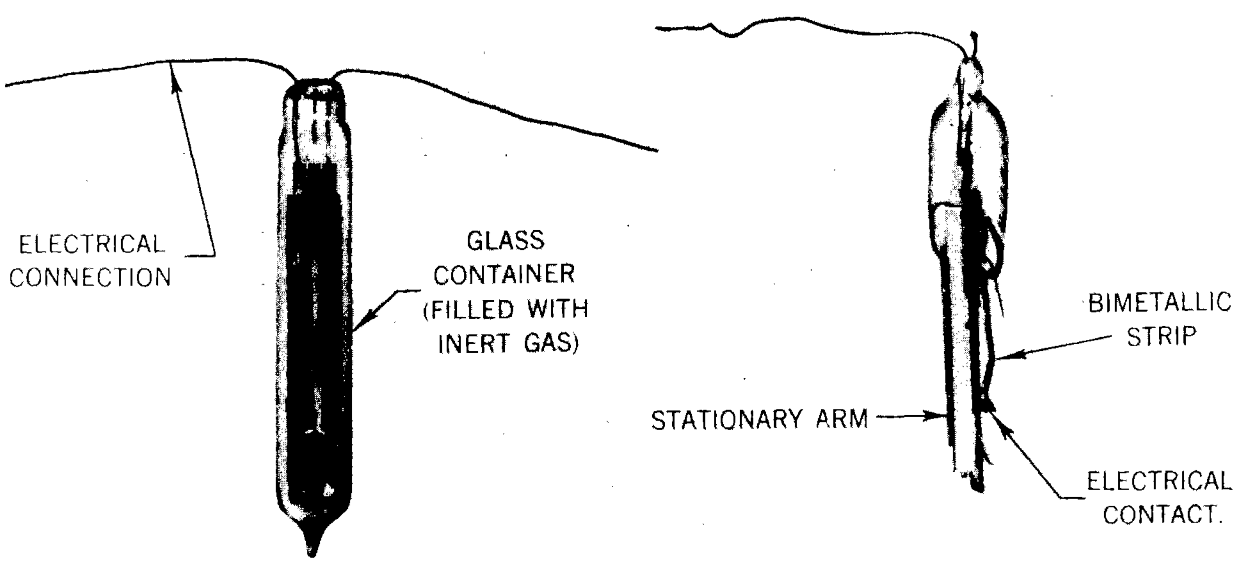


FIGURE 27. Metal expansion type detector (Thomas A. Edison, Inc.)

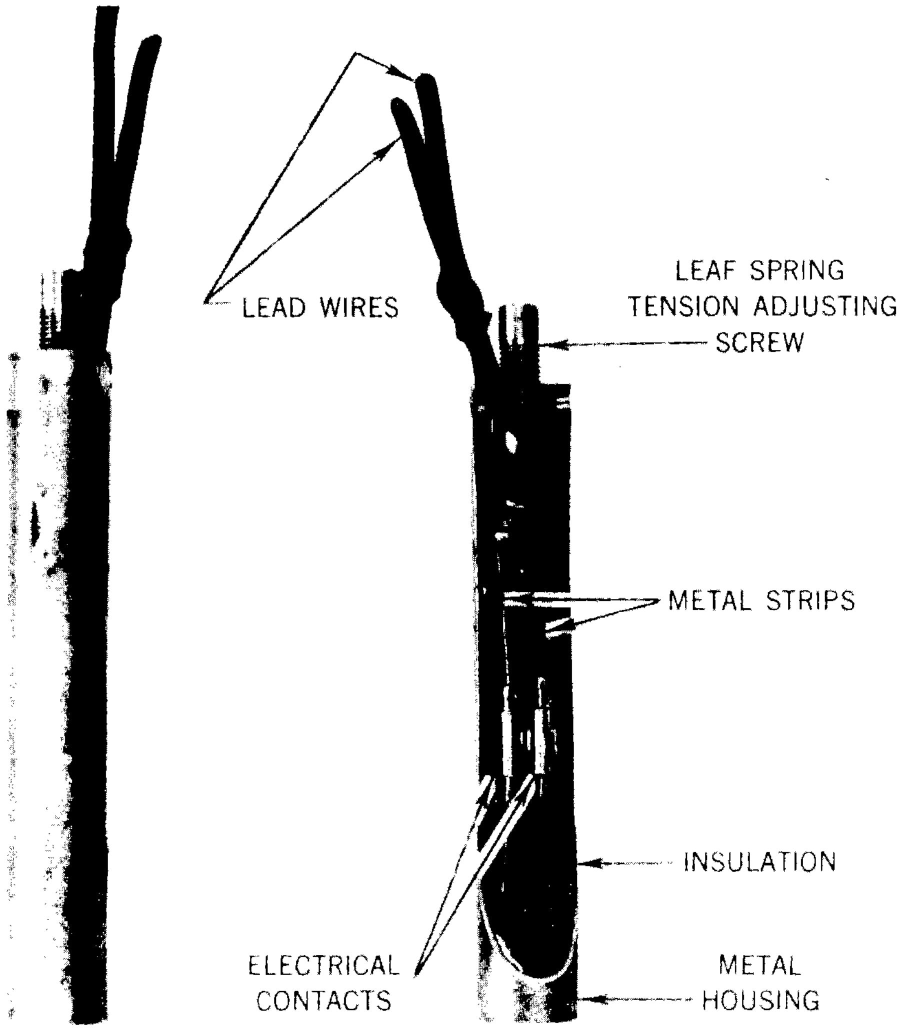


FIGURE 28. Metal expansion type detector (Fenwal, Inc.)

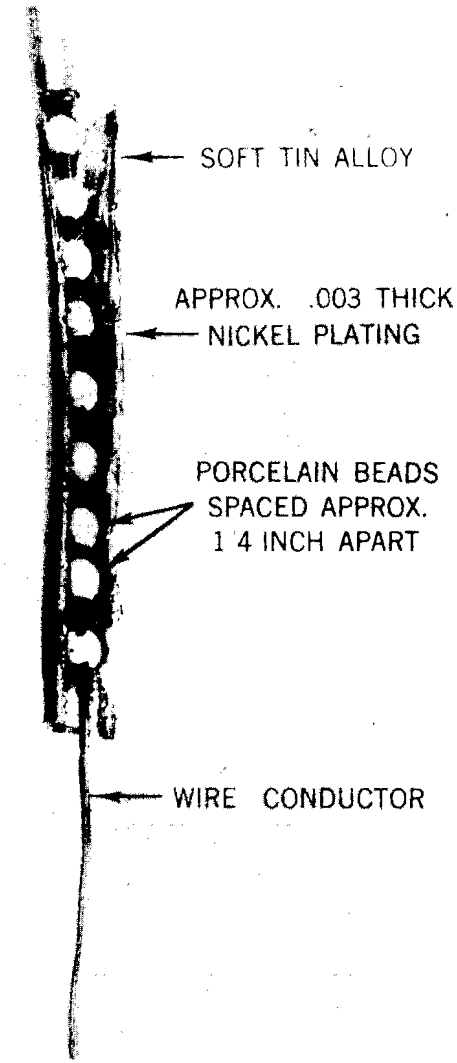


FIGURE 29. Fusible alloy type detector (Fenwal, Inc.)

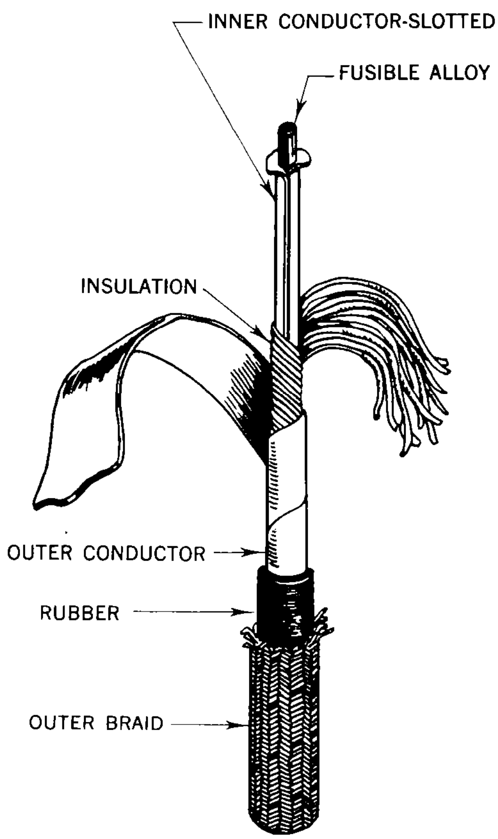


FIGURE 30. Fusible alloy type detector (Sealand Corp.)

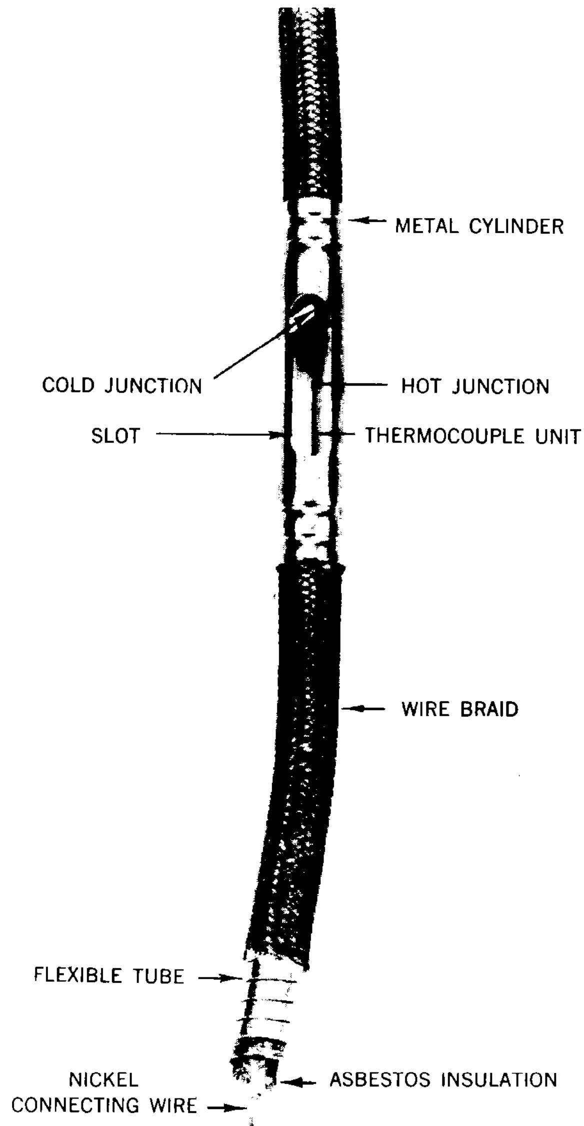


FIGURE 31. Thermocouple type detector (Thomas A. Edison, Inc.) (See also figure 21)

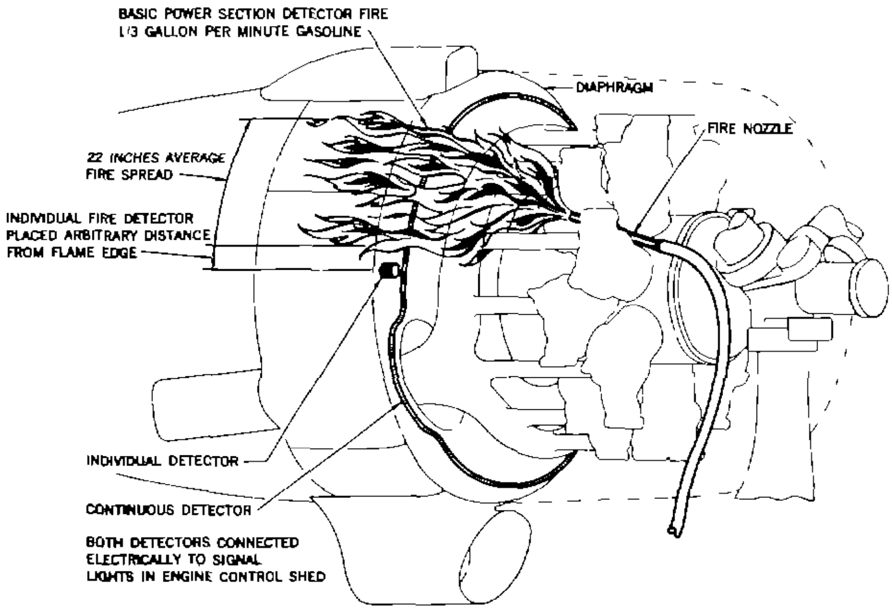


FIGURE 32 Method used to determine optimum fire detector locations and number of detectors required in the power section (Detector locations were varied with respect to the fire until detector flashed fire alarm within 3 seconds of fire start.)

DETECTOR TYPE	MAXIMUM SPACING INCHES BETWEEN DETECTORS	
	POWER SECTION	ACCESSORY SECTION
FLAME	27	5
METAL EXPANSION	21	5

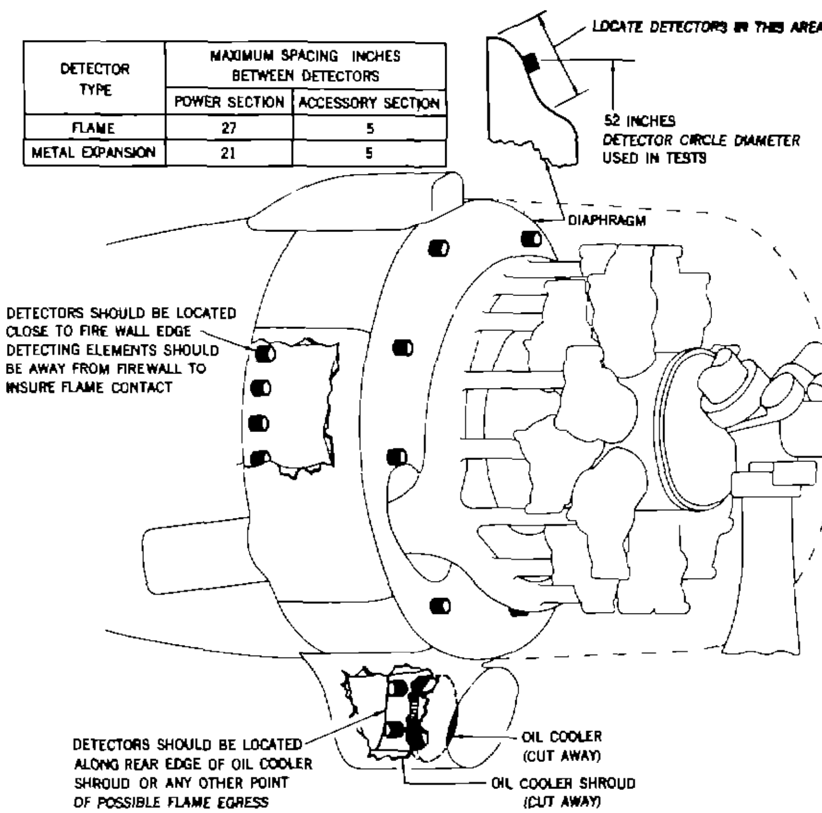


FIGURE 33 Optimum locations for unit type fire detectors in the power and accessory sections.

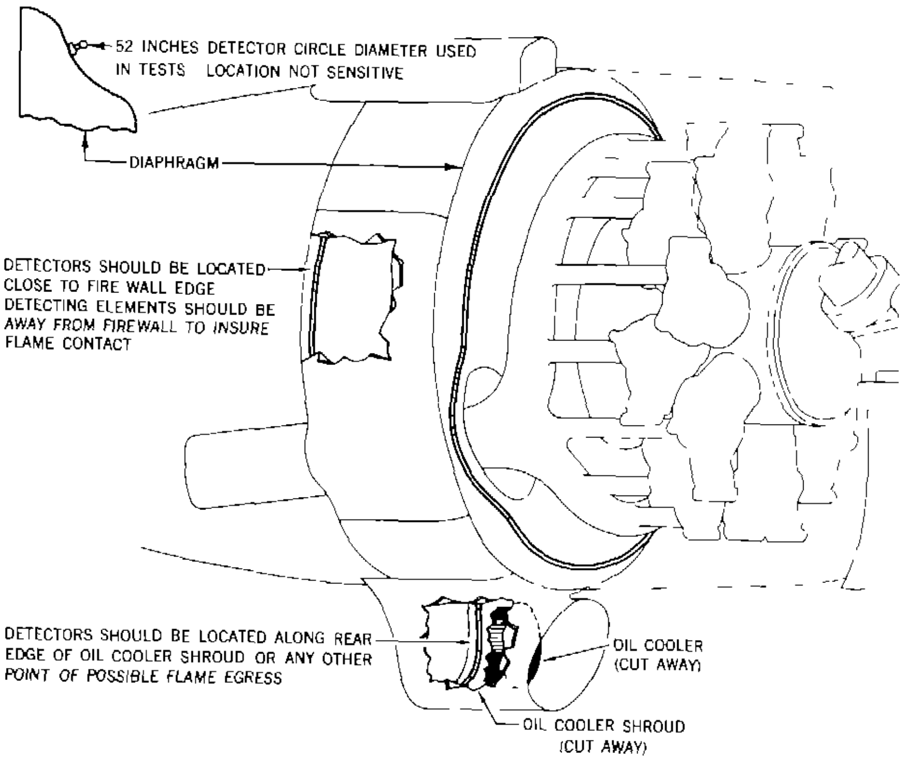


FIGURE 34 Optimum locations for continuous type fire detectors in the power and accessory sections

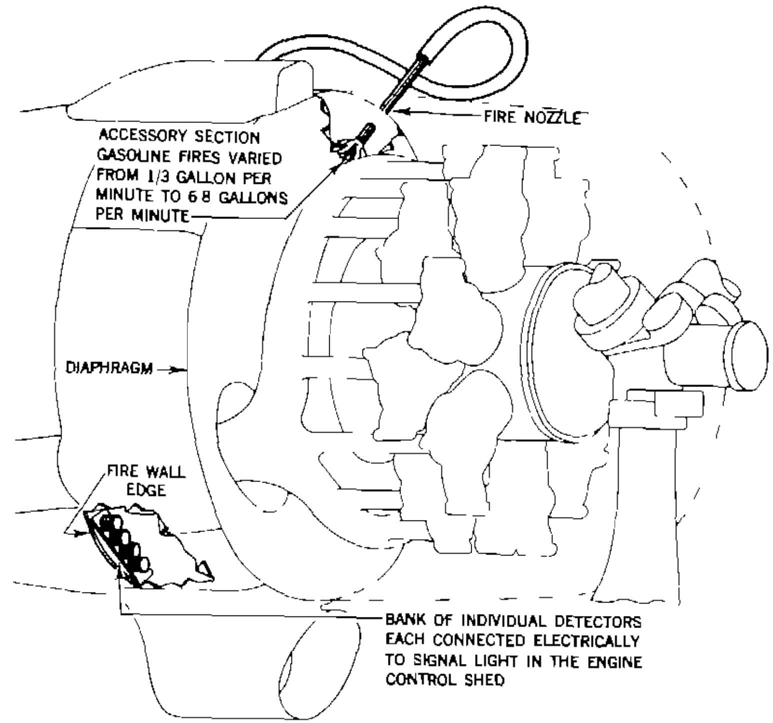


FIGURE 35 One method used to determine optimum fire detector locations and number of detectors required in the accessory section (Unsuccessful as the fire never reached the detector bank vicinity)

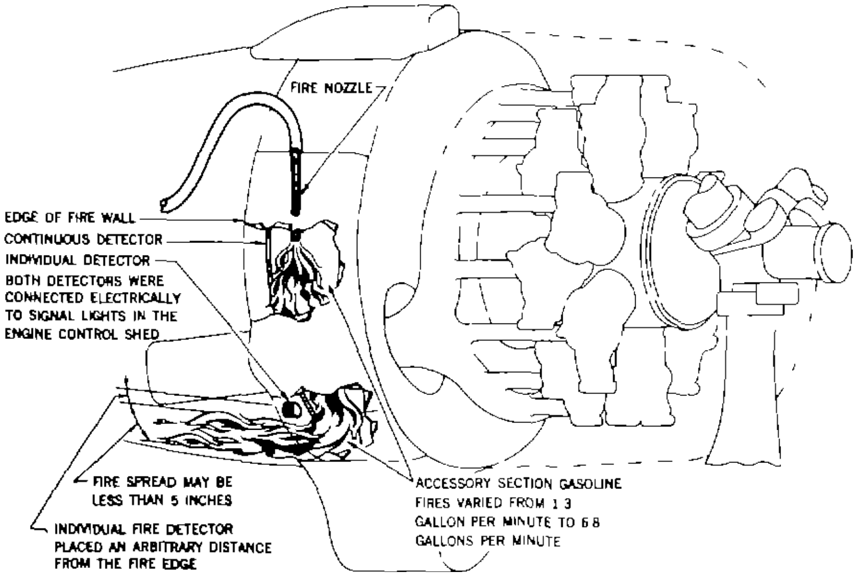


FIGURE 36 Final method used to determine optimum fire detector location and number of detectors required in the accessory section (Detector locations were varied with respect to the fire until detector flashed fire alarm within 3 seconds of fire start)

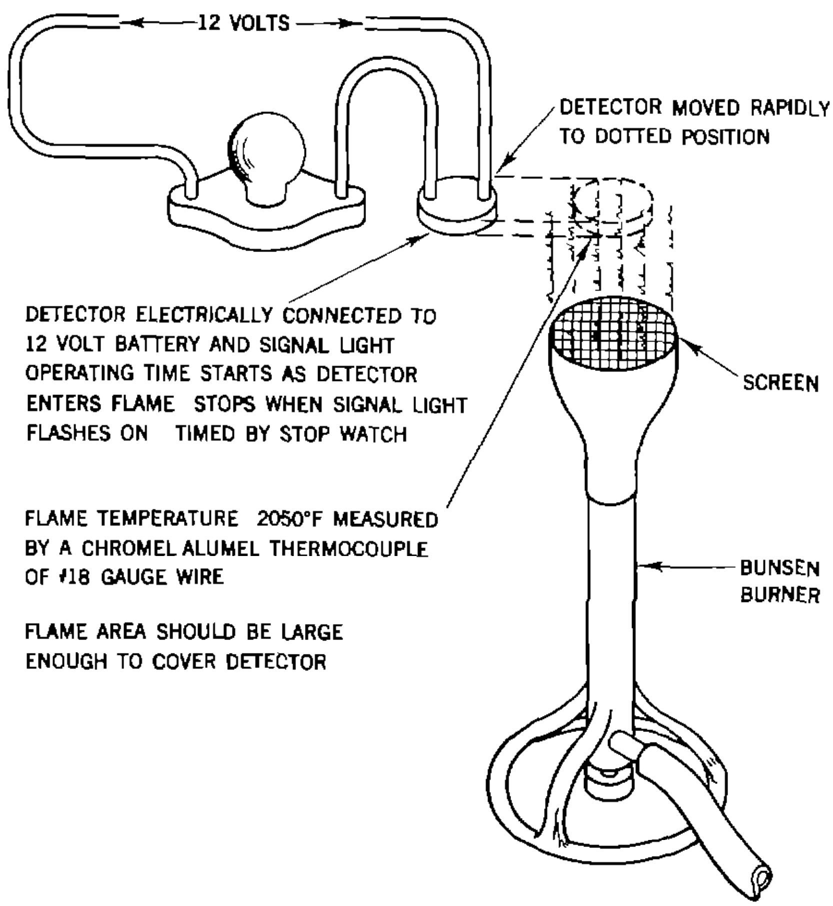


FIGURE 37. Method for determining detector operating time

4 EXTINGUISHING SYSTEMS TESTED AT THIS LOCATION

A (a) 28 1/16″ DIA HOLES DISCHARGED FORWARD
(b) 28 1/16″ DIA HOLES DISCHARGED AWAY FROM CRANKCASE

B (a) 56 1/16″ DIA HOLES DISCHARGED TOWARD CRANKCASE
(b) NO DISCHARGE FROM FORWARD RING

C (a) NO DISCHARGE FROM REAR RING
(b) 28 1/16″ DIA HOLES DISCHARGED AWAY FROM CRANKCASE

D SAME AS C EXCEPT
(b) 56 1/16″ DIA HOLES DISCHARGED AWAY FROM CRANKCASE

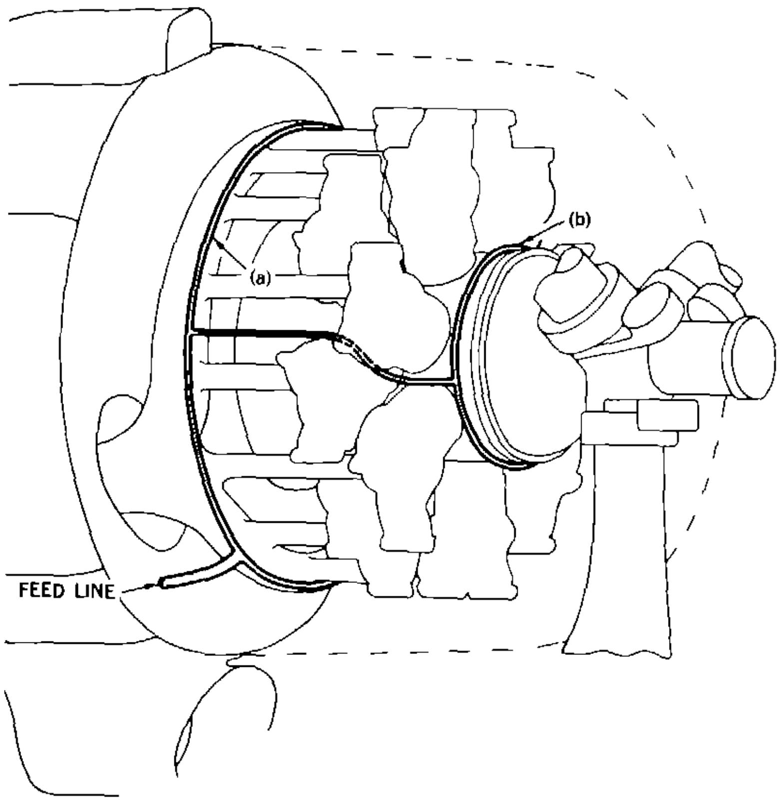


FIGURE 38. Power section distribution system (general type).

3 EXTINGUISHING SYSTEMS TESTED AT THIS LOCATION

A (a) 28 1/16″ DIA HOLES DISCHARGED 45° FORWARD AND AWAY FROM CRANKCASE
(b) 28 1/16″ DIA HOLES DISCHARGED AWAY FROM CRANKCASE

B SAME AS A EXCEPT
(b) 28 1/16″ DIA HOLES DISCHARGED 45° AFT AND AWAY FROM CRANKCASE

C SAME AS A EXCEPT
(b) NO DISCHARGE FROM FORWARD RING

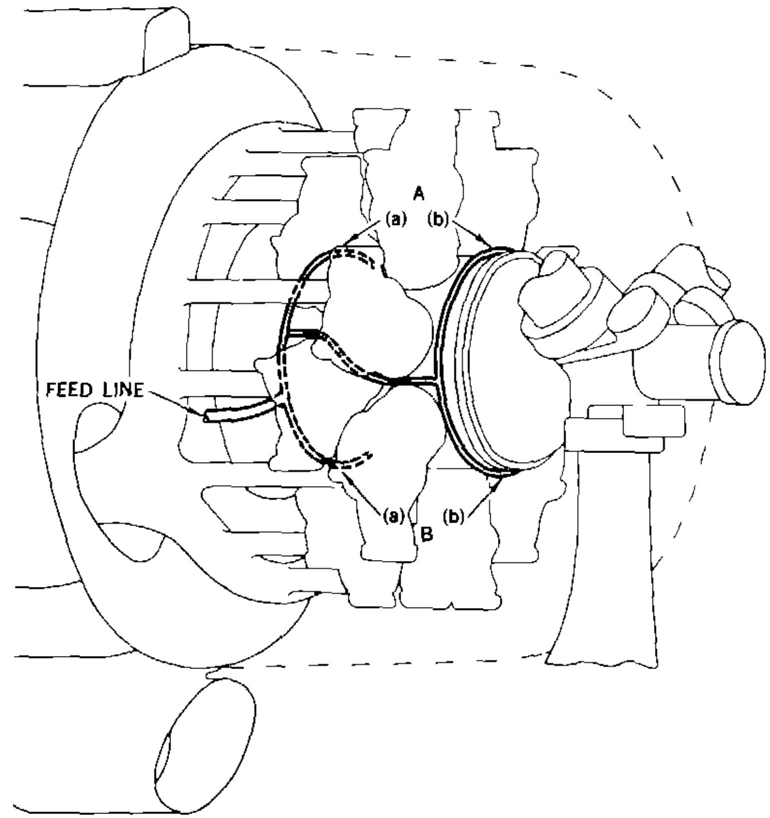


FIGURE 39. Power section distribution system (general type).

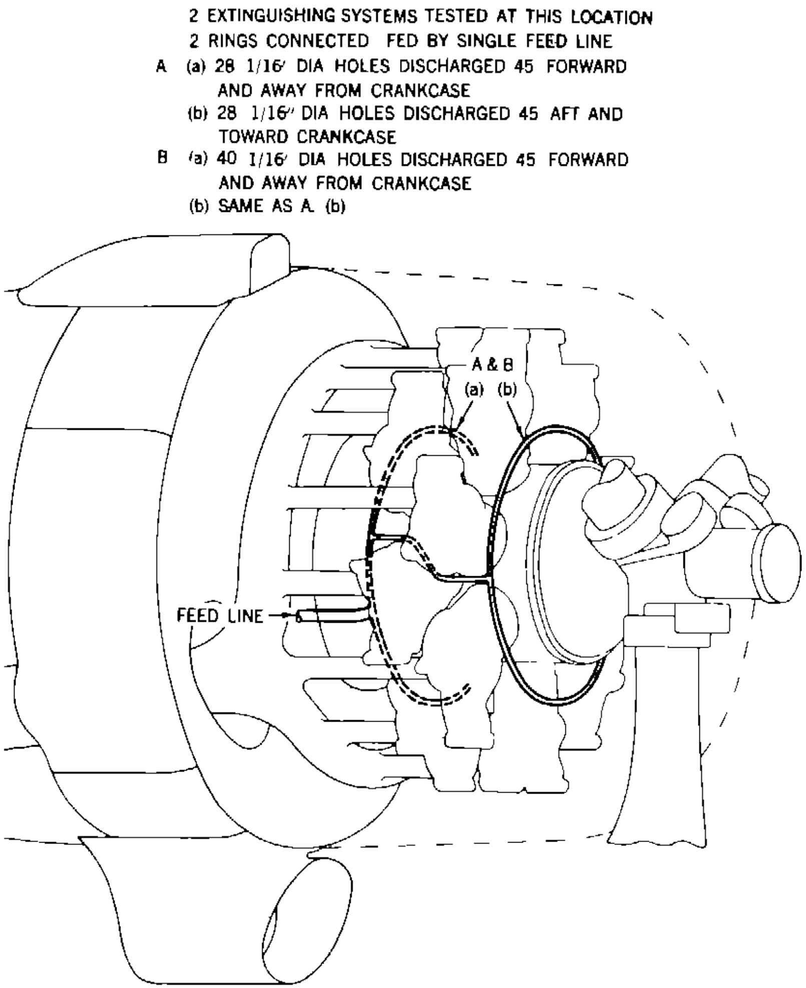


FIGURE 40 Power section distribution system (general type).

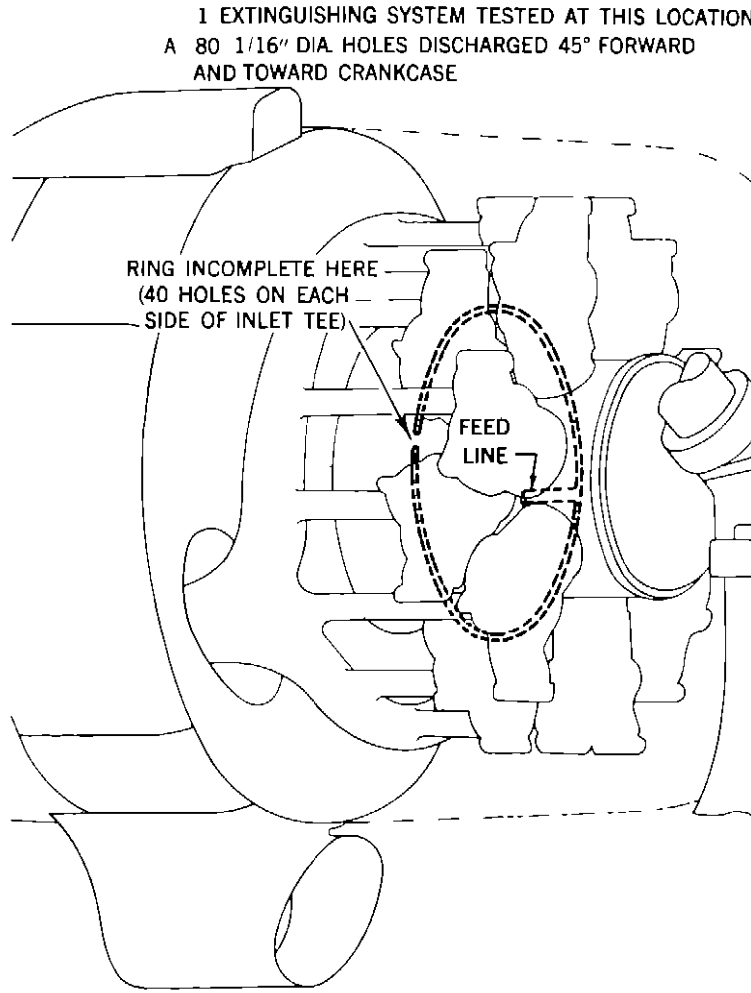


FIGURE 41. Power section distribution system (general type).

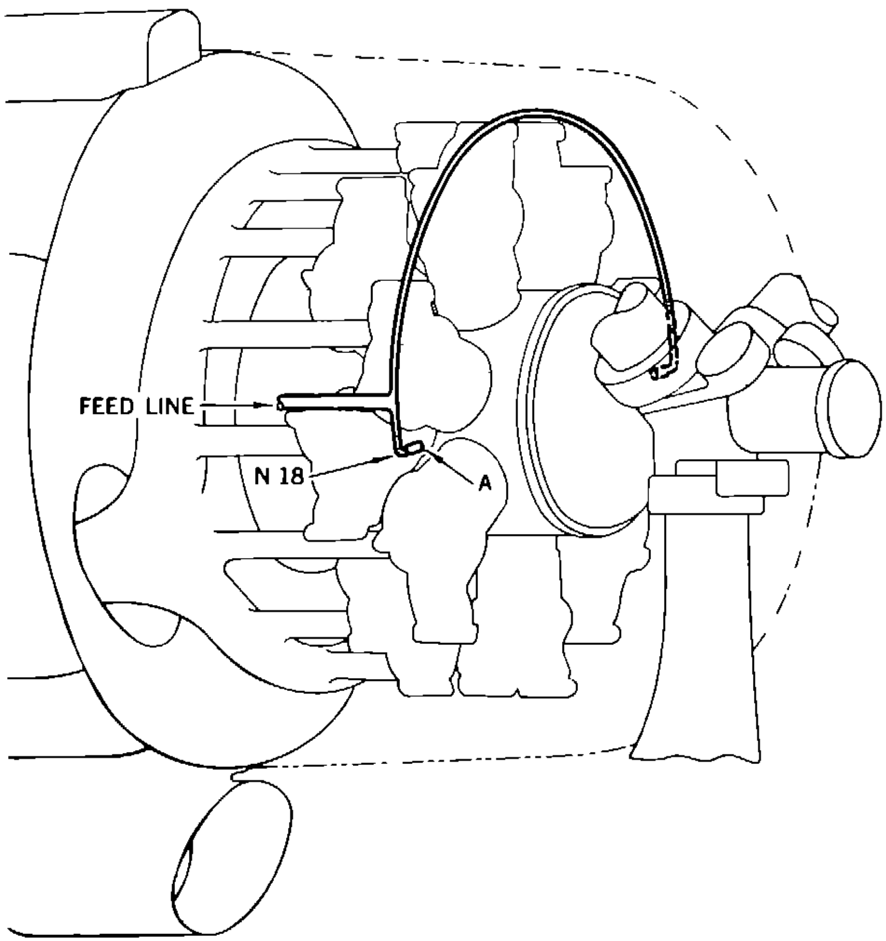


FIGURE 42 Power section distribution system (general type).

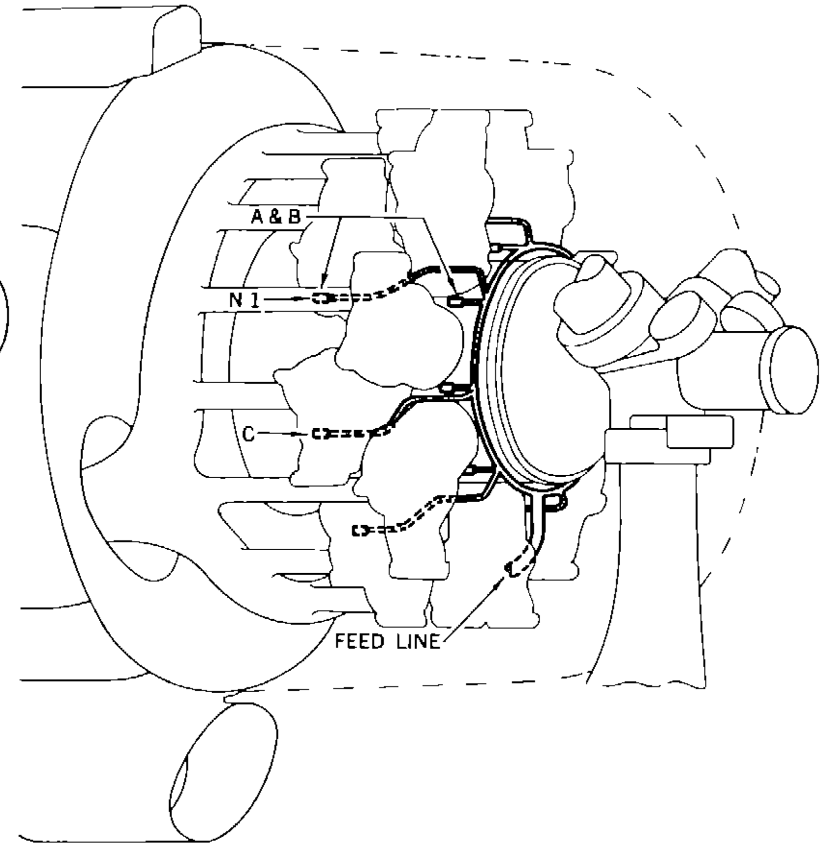


FIGURE 43. Power section distribution system (specific type).

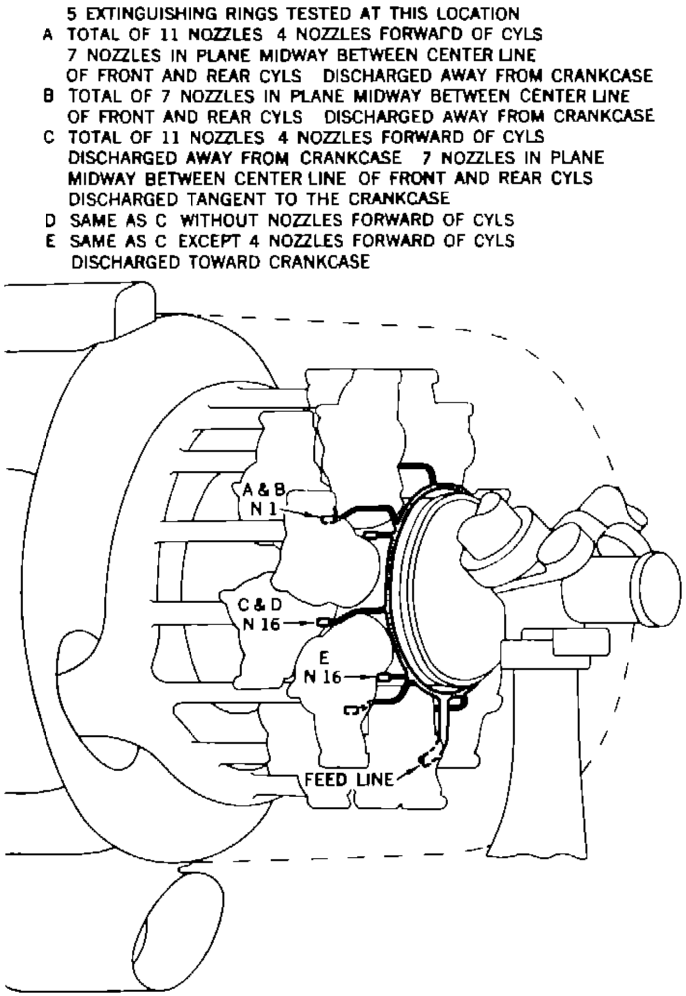


FIGURE 44. Power section distribution system (specific type).

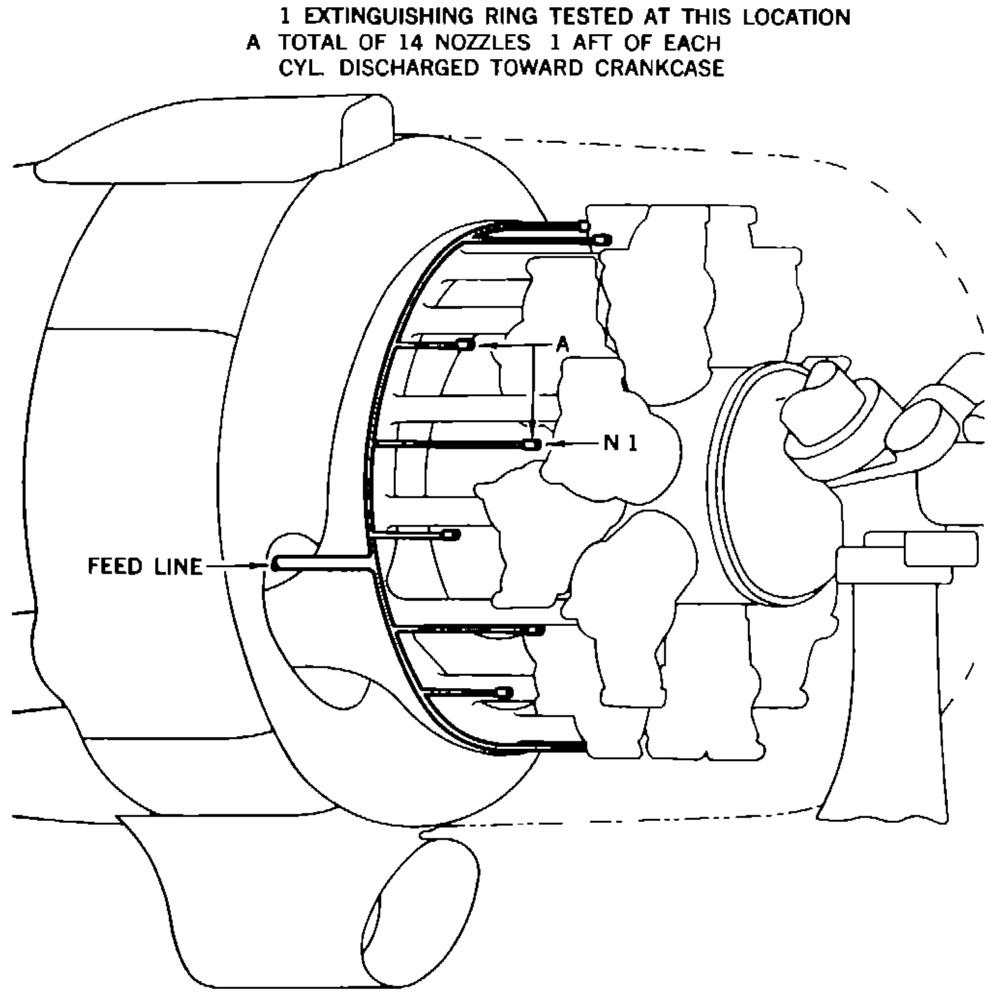


FIGURE 45. Power section distribution system (specific type).

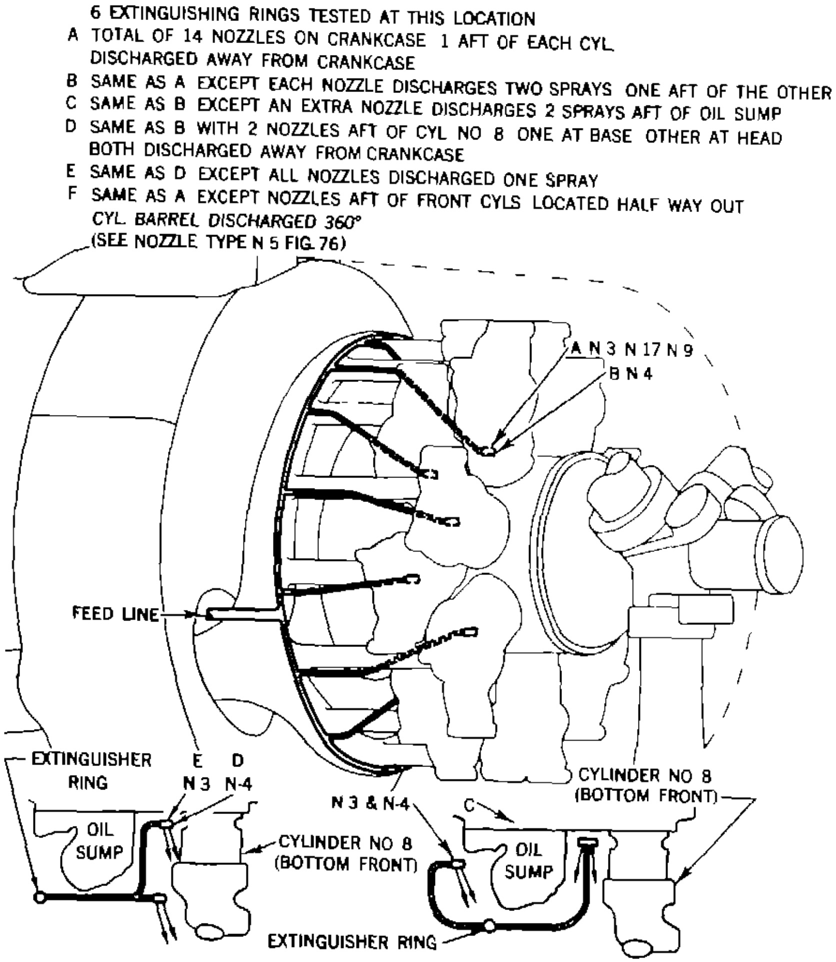


FIGURE 46 Power section distribution system (specific type)

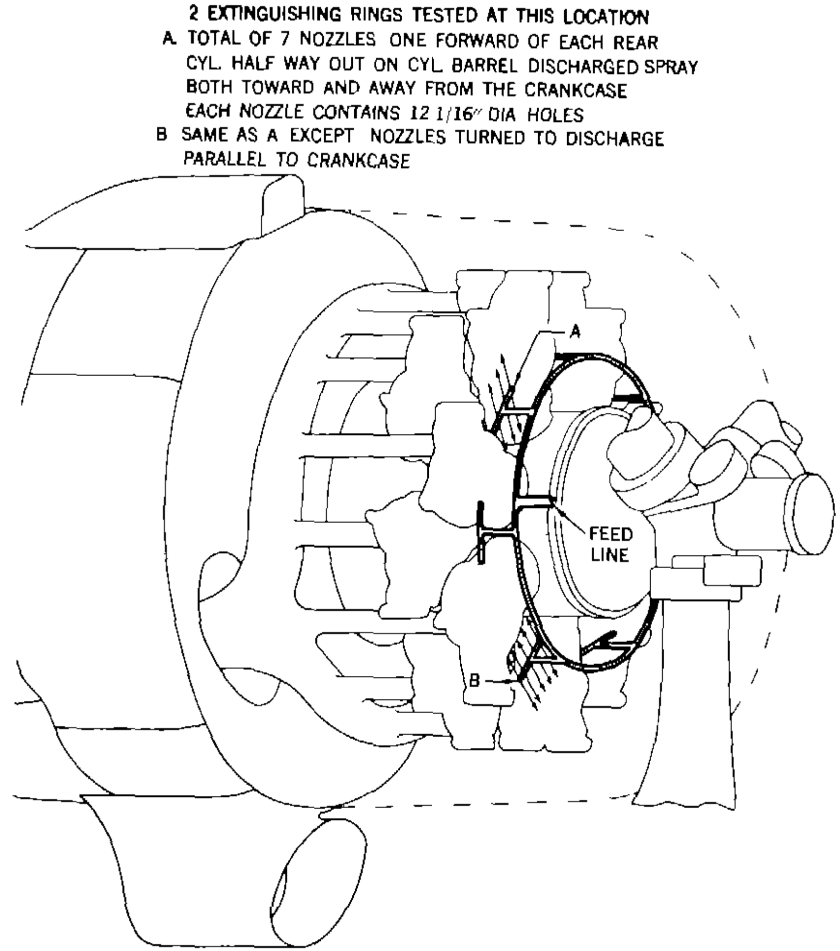


FIGURE 47 Power section distribution system (specific type)

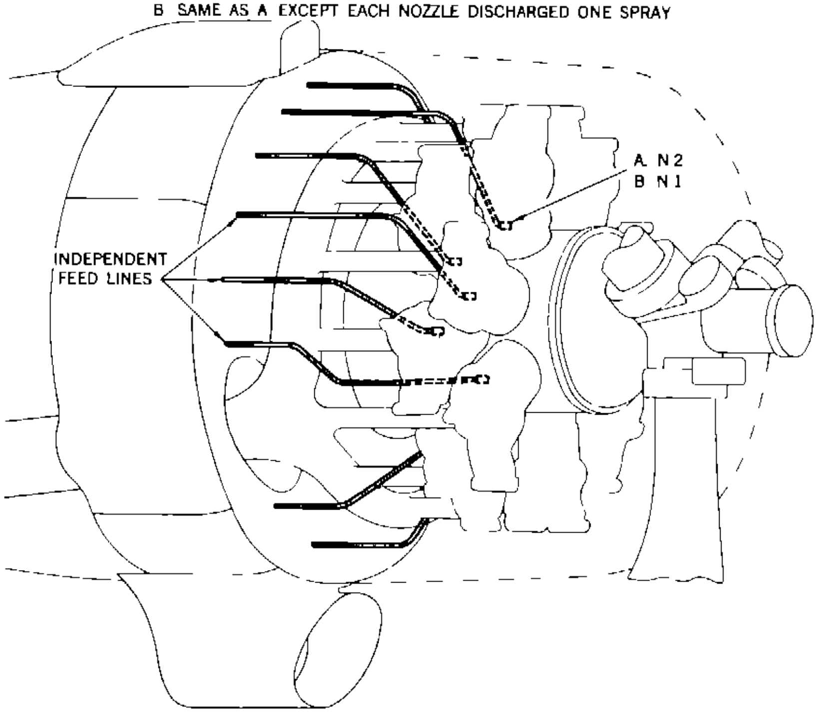


FIGURE 48 Power section distribution system (specific type)

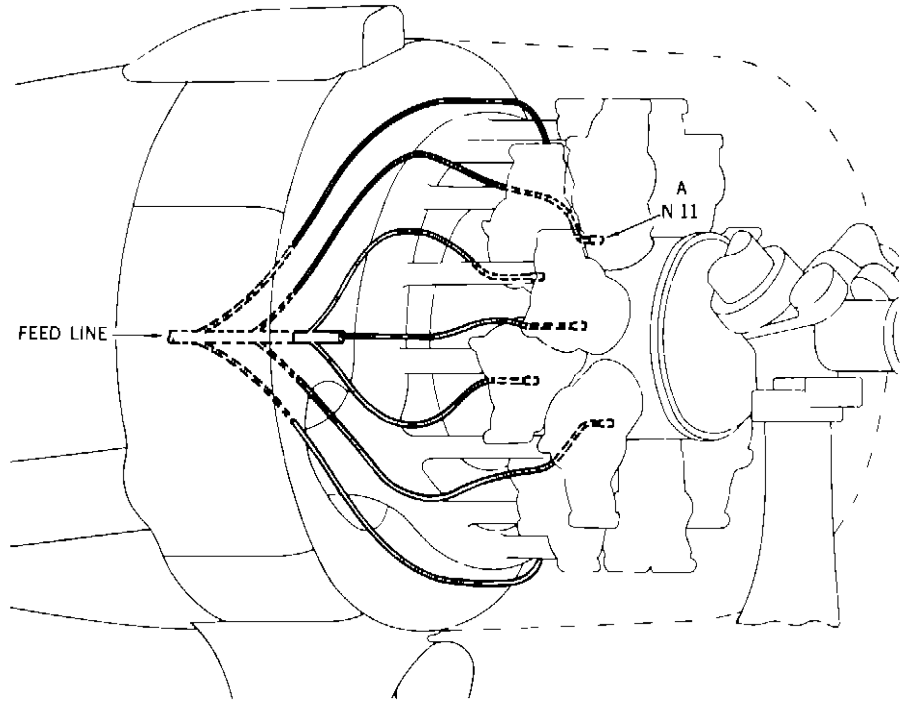


FIGURE 49 Power section distribution system (specific type)

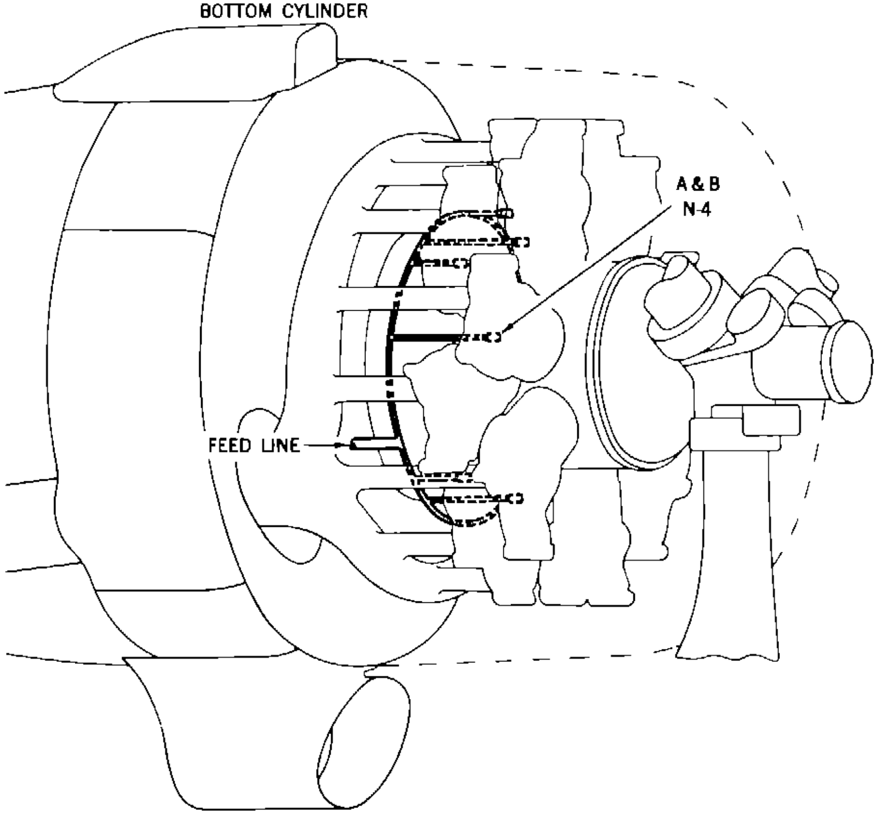


FIGURE 50. Power section distribution system (specific type).

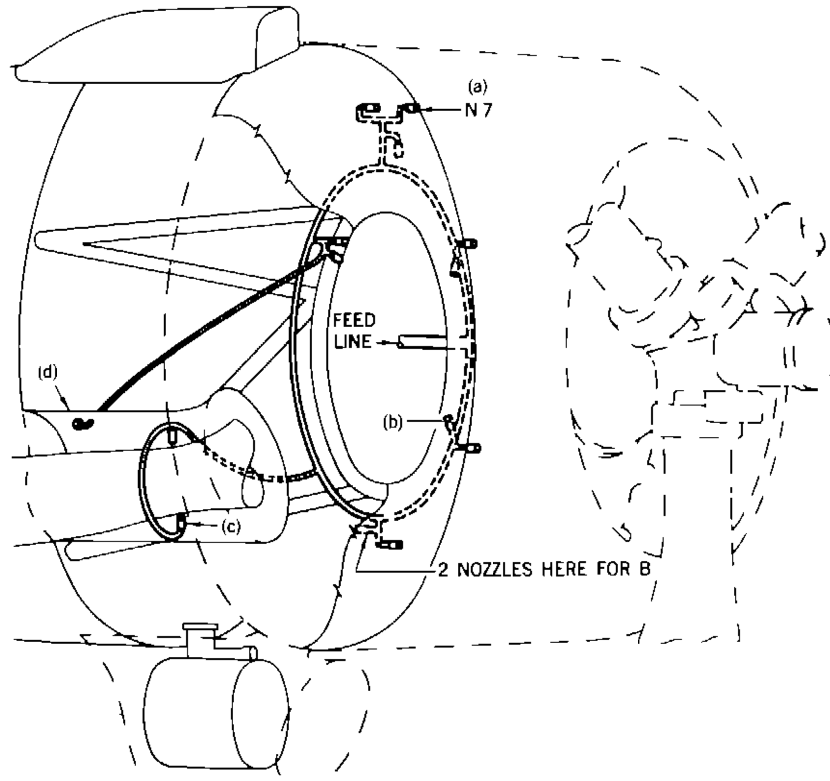


FIGURE 51. Power and accessory section distribution system (general type).

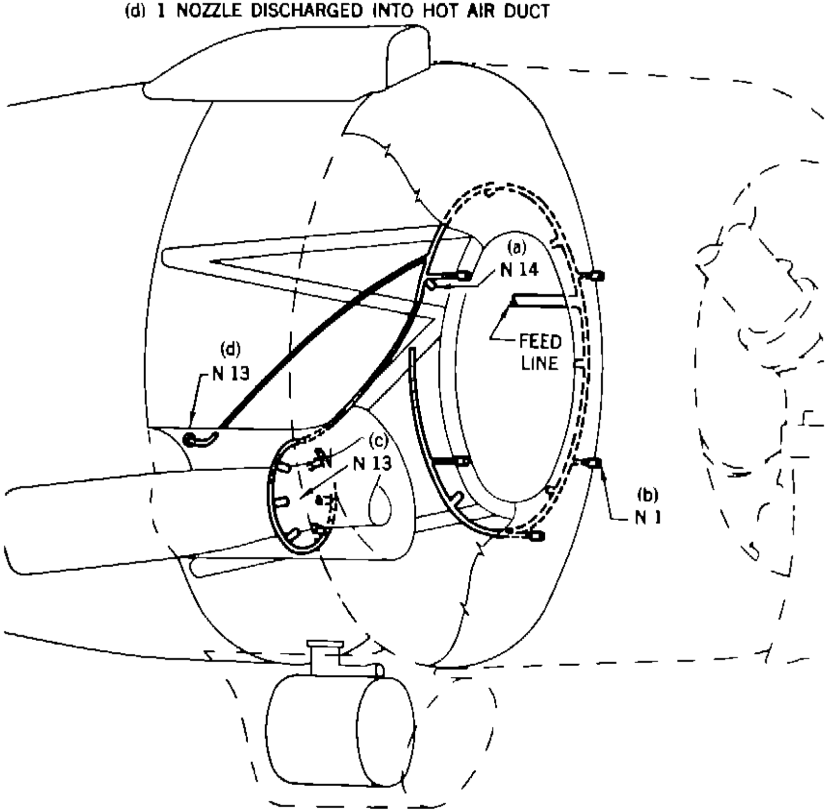


FIGURE 52. Power and accessory section distribution system (general type).

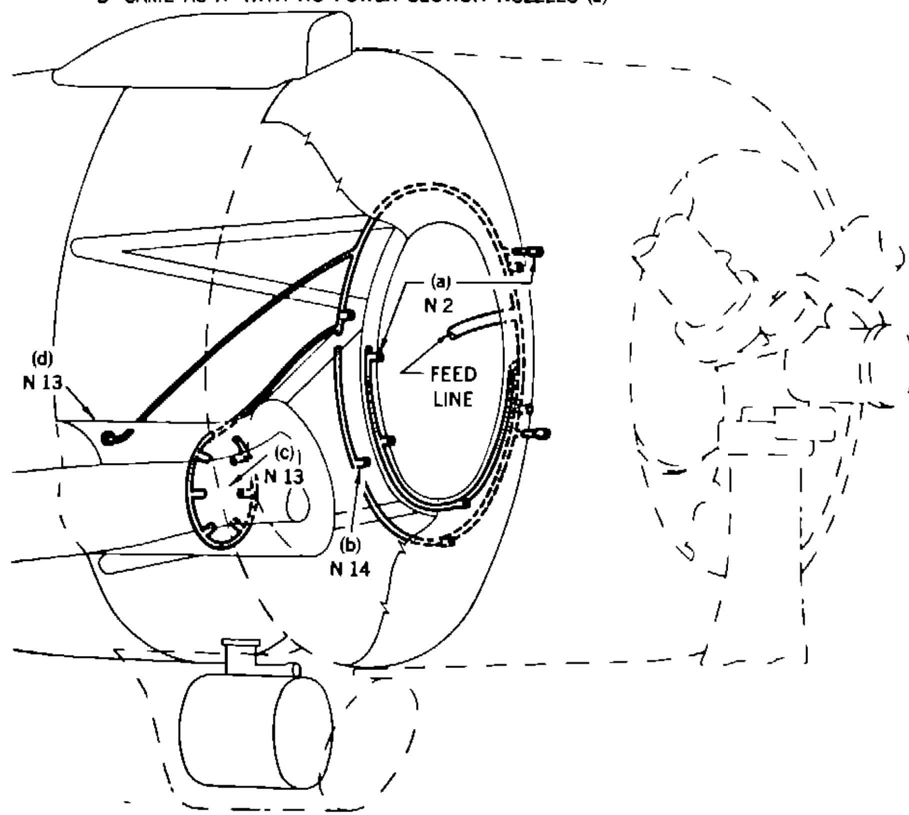


FIGURE 53. Power and accessory section distribution system (general type).

5 EXTINGUISHING SYSTEMS TESTED AT THIS LOCATION

A. (a) 5 NOZZLES TO ACCESSORY SECTION DISCHARGED AFT AND AWAY FROM CRANKCASE
   (b) 3 NOZZLES TO POWER SECTION DISCHARGED AWAY FROM CRANKCASE
   (c) 6 SLOTS DISCHARGED TOWARD EXHAUST STACK
   (d) 1 NOZZLE DISCHARGED OVER OIL COOLER

B SAME AS A. EXCEPT
   (d) 2 NOZZLES DISCHARGED OVER OIL COOLER

C SAME AS A EXCEPT
   (d) NO NOZZLES DISCHARGED OVER OIL COOLER

D SAME AS A. EXCEPT
   (b) NO NOZZLES DISCHARGED TO POWER SECTION
   (d) 2 NOZZLES DISCHARGED OVER OIL COOLER

E. SAME AS A. EXCEPT
   (a) 8 NOZZLES TO ACCESSORY SECTION DISCHARGED AFT AND AWAY FROM CRANKCASE
   (d) NO NOZZLES DISCHARGED OVER OIL COOLER

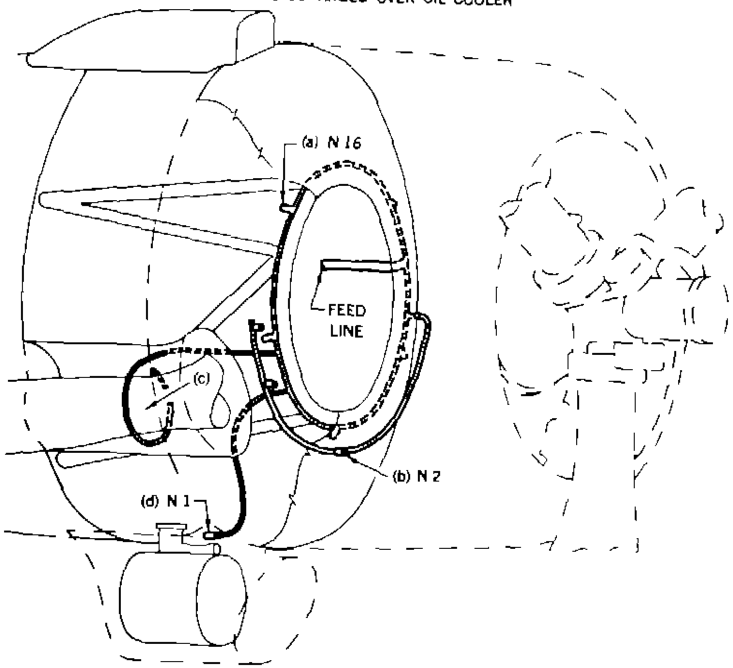


FIGURE 54 Power and accessory section distribution system (general type)

4 EXTINGUISHING SYSTEMS TESTED AT THIS LOCATION

A (a) 28 1/16″ DIA. HOLES DISCHARGED FORWARD
   (b) 6 1/16″ DIA HOLES DISCHARGED TOWARD EXHAUST STACK
   (c) 6-1/16″ DIA HOLES DISCHARGED INBOARD (HOT AIR SPILL DUCT)

B SAME AS A EXCEPT
   (b) NO HOLES DISCHARGED TOWARD EXHAUST STACK

C SAME AS A. EXCEPT
   (c) NO HOLES DISCHARGED INBOARD (HOT AIR SPILL DUCT)

D SAME AS C EXCEPT
   (a) 34 1/16″ DIA. HOLES DISCHARGED FORWARD

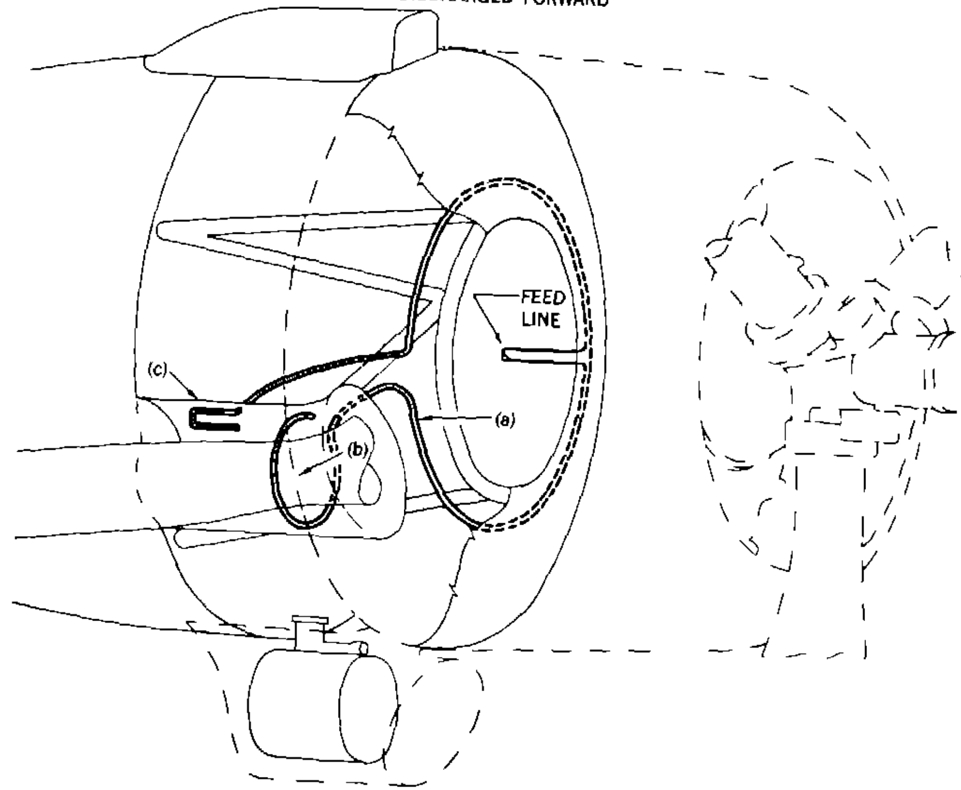


FIGURE 55 Accessory section distribution system (general type).

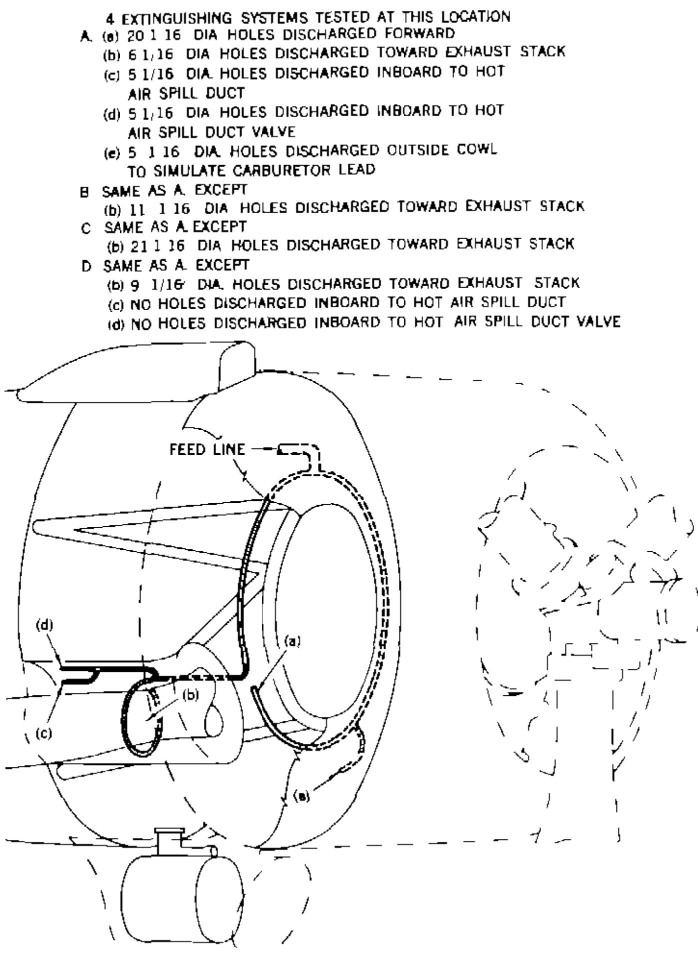


FIGURE 56 Accessory section distribution system (general type)

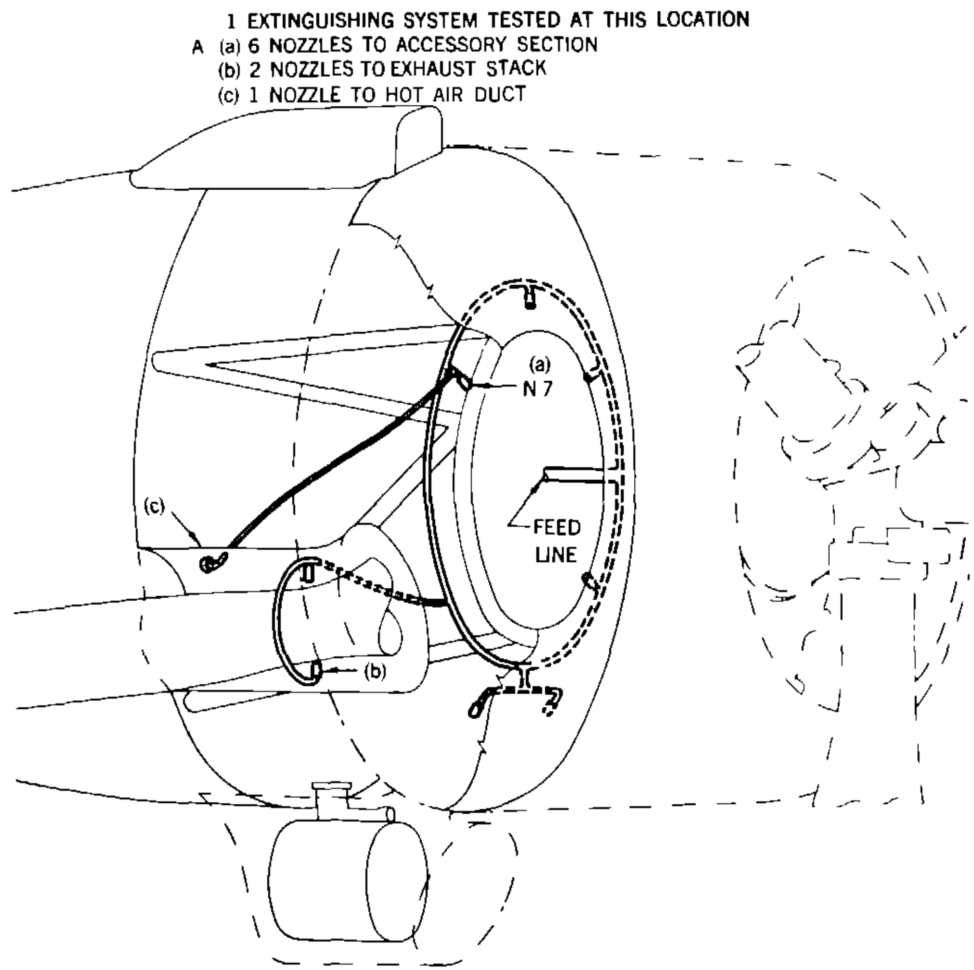


FIGURE 57. Accessory section distribution system (general type).

2 EXTINGUISHING SYSTEMS TESTED AT THIS LOCATION
A (a) 6 NOZZLES TO ACCESSORY SECTION DISCHARGED TOWARD CRANKCASE
(b) 1 NOZZLE DISCHARGED TOWARD OIL COOLER
(c) 1 NOZZLE DISCHARGED INTO HOT AIR DUCT
(d) 6 SLOTS DISCHARGED TOWARD EXHAUST STACK
B (a) 6 NOZZLES TO ACCESSORY SECTION DISCHARGED 45°
AFT AND TOWARD CRANKCASE
(b) NO NOZZLE DISCHARGED TOWARD OIL COOLER
(c) 1 NOZZLE DISCHARGED INTO HOT AIR DUCT
(d) 9 1/16″ DIA. HOLES DISCHARGED TOWARD EXHAUST STACK

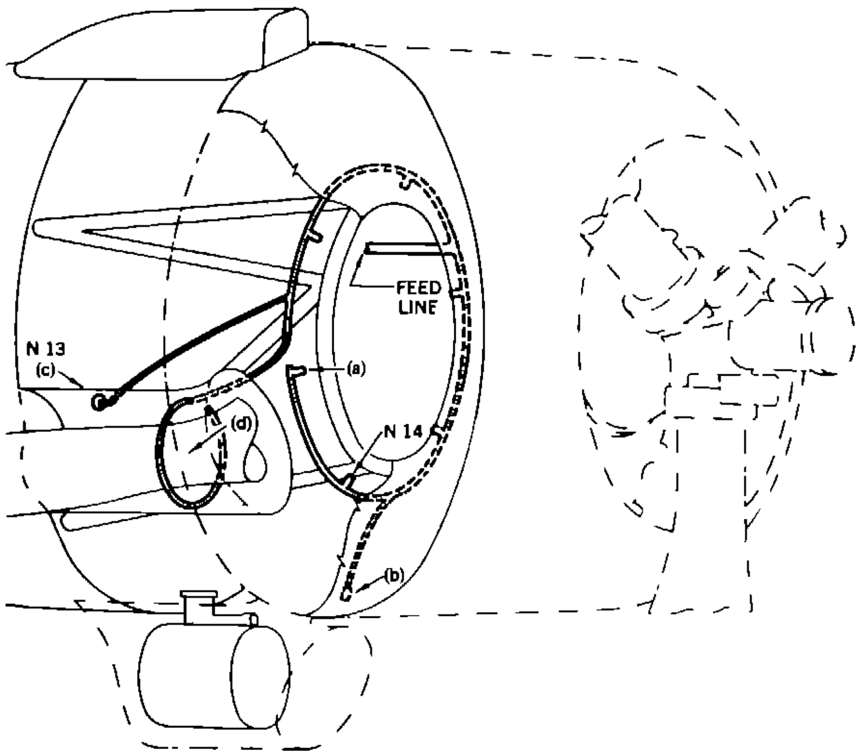


FIGURE 58. Accessory section distribution system (general type).

2 EXTINGUISHING SYSTEMS TESTED AT THIS LOCATION
A (a) 5 NOZZLES TO ACCESSORY SECTION DISCHARGED
AFT AND AWAY FROM CRANKCASE
(b) 3 NOZZLES DISCHARGED INTO EXHAUST STACK WELL
(c) 1 NOZZLE DISCHARGED FORWARD AND DOWN ON OIL COOLER
B SAME AS A EXCEPT
(c) 2 NOZZLES DISCHARGED DOWN ON EITHER SIDE OF OIL COOLER

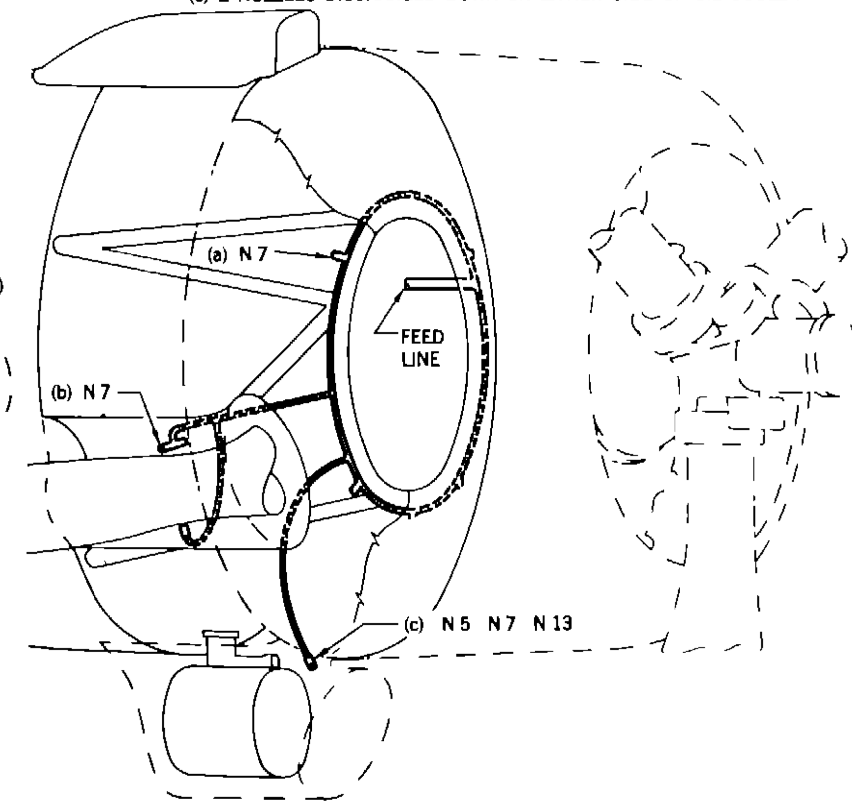


FIGURE 59. Accessory section distribution system (general type).

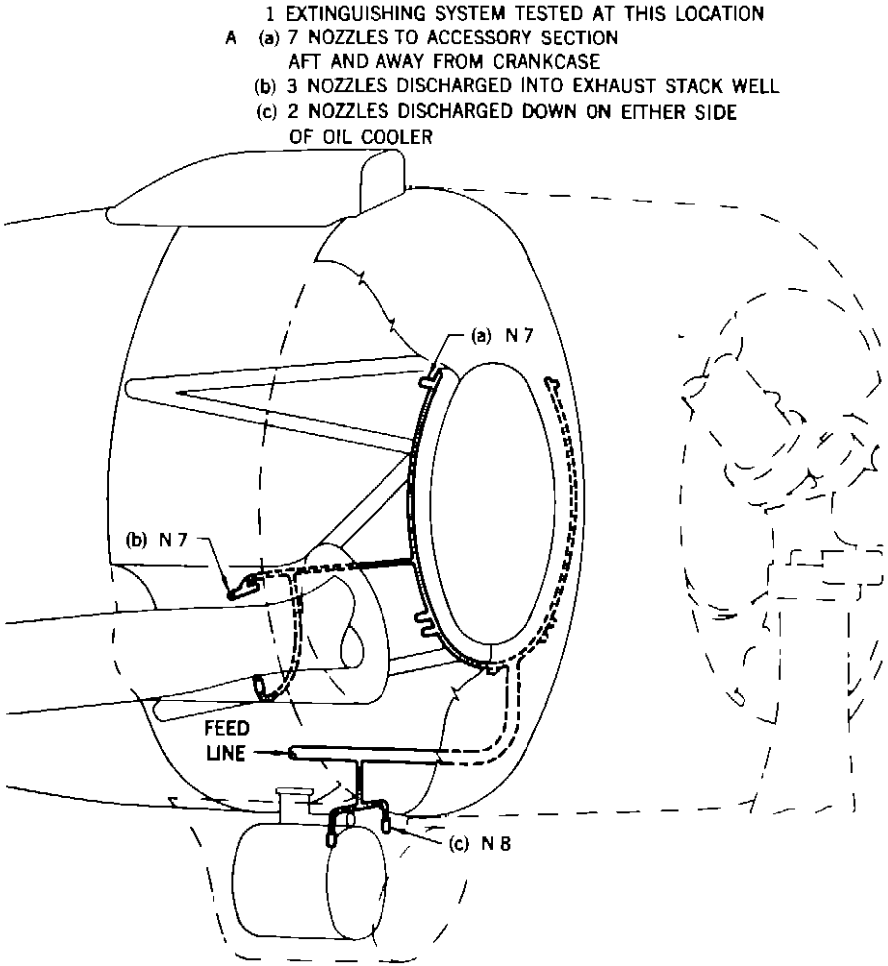


FIGURE 60. Accessory section distribution system (general type).

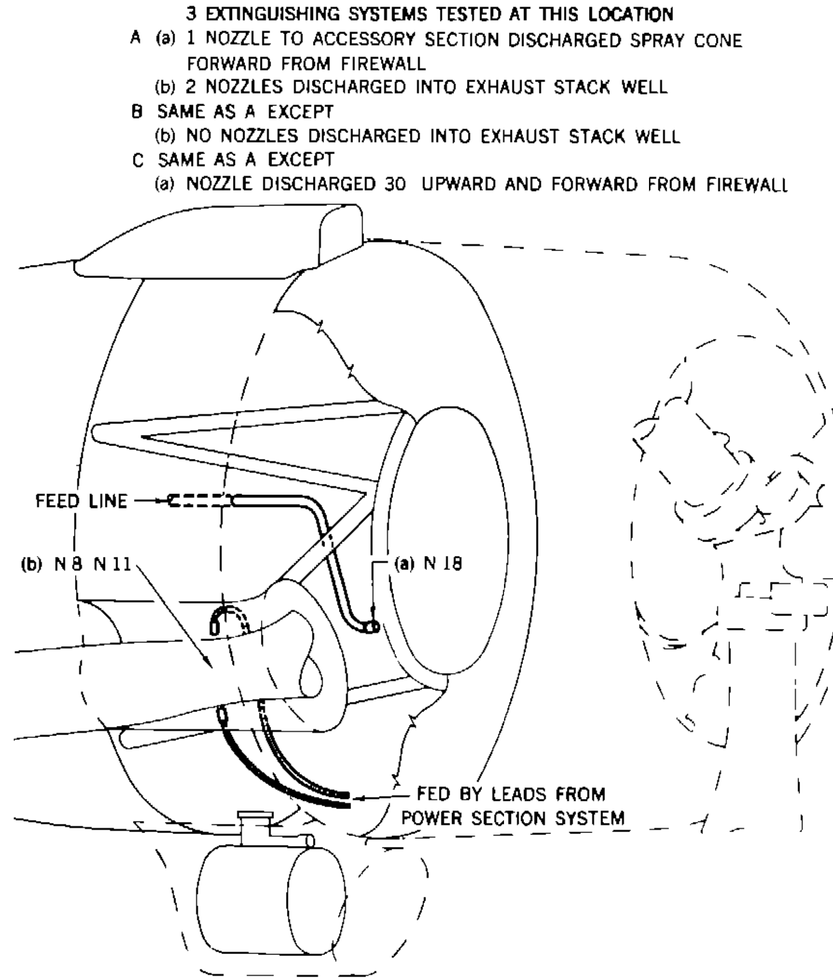


FIGURE 61. Accessory section distribution system (general type).

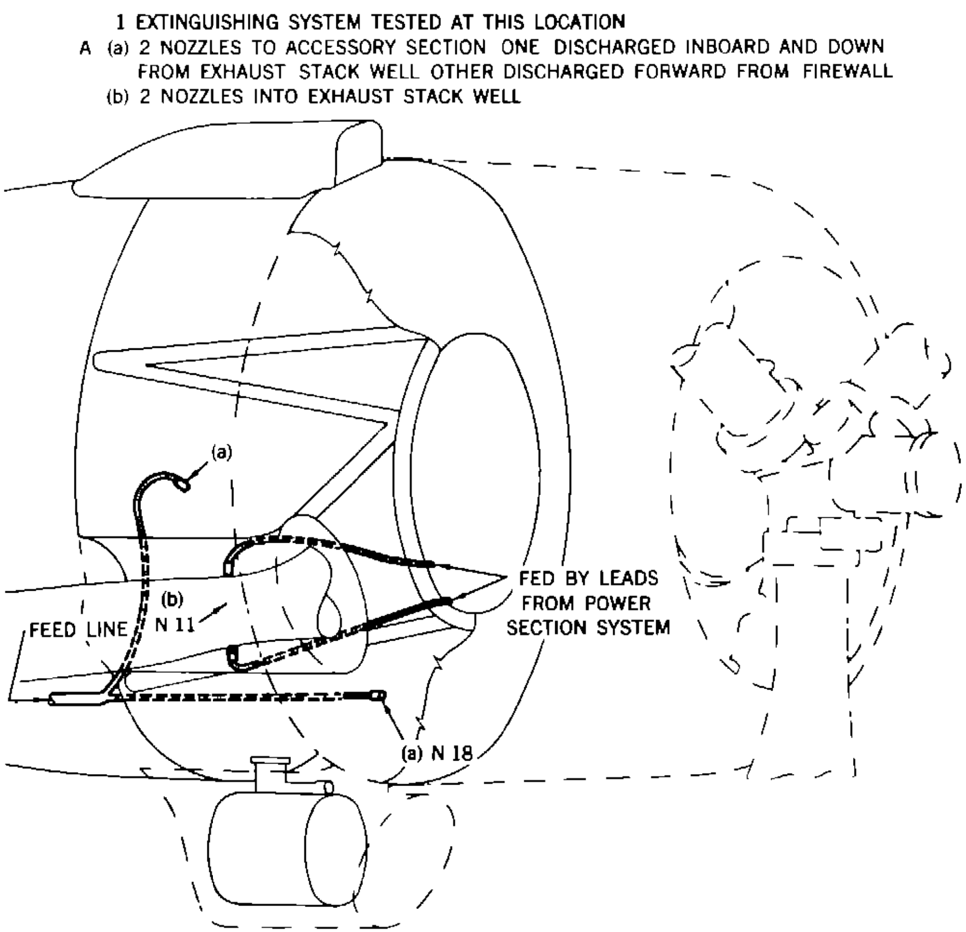


FIGURE 62 Accessory section distribution system (general type)

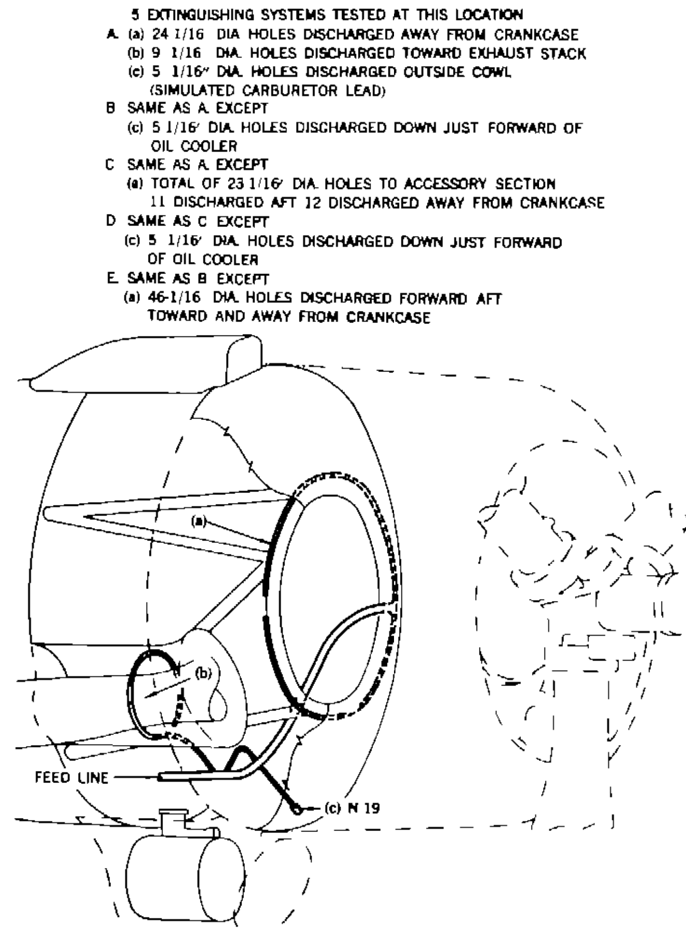


FIGURE 63 Accessory section distribution system (general type).

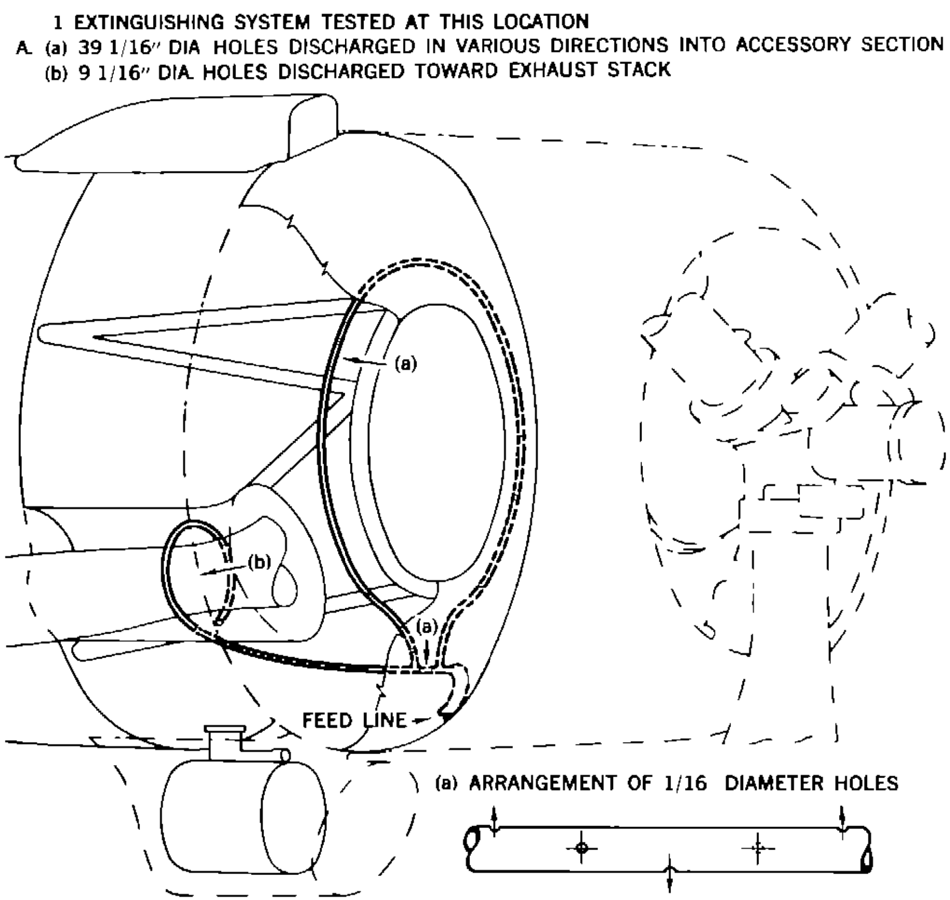


FIGURE 64. Accessory section distribution system (general type)

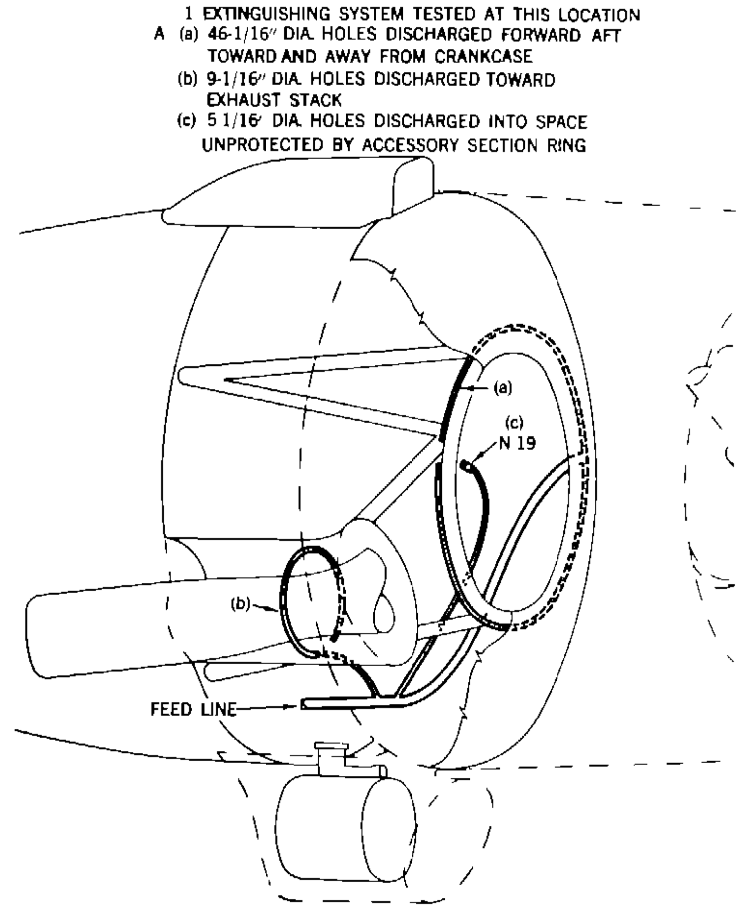


FIGURE 65 Accessory section distribution system (general type)

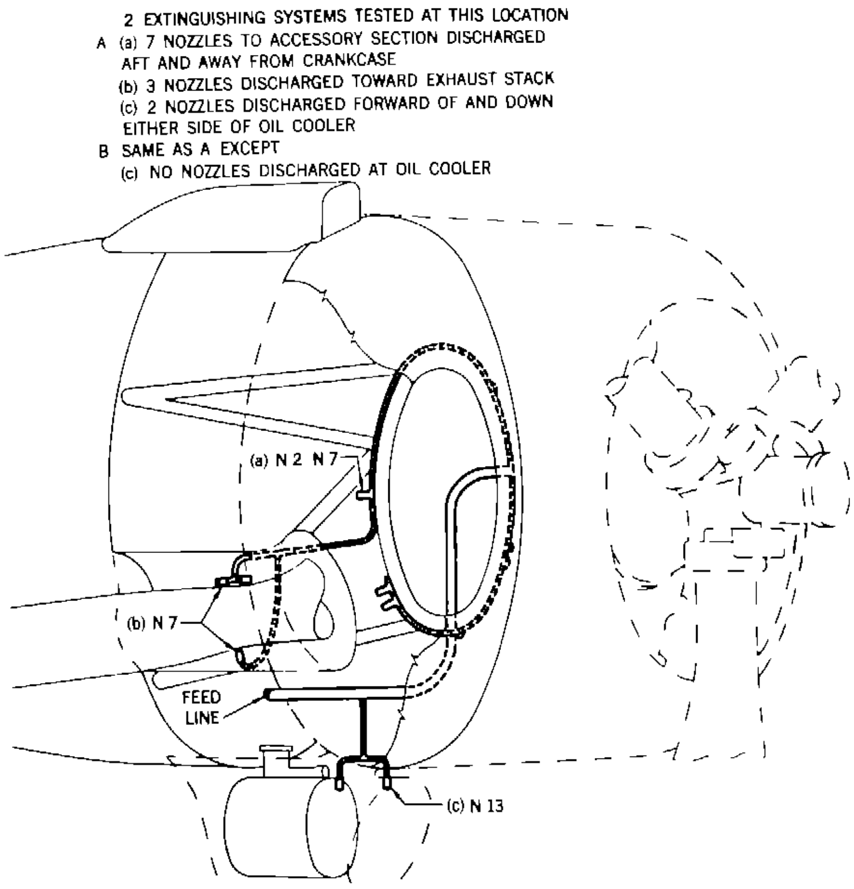


FIGURE 66. Accessory section distribution system (general type)

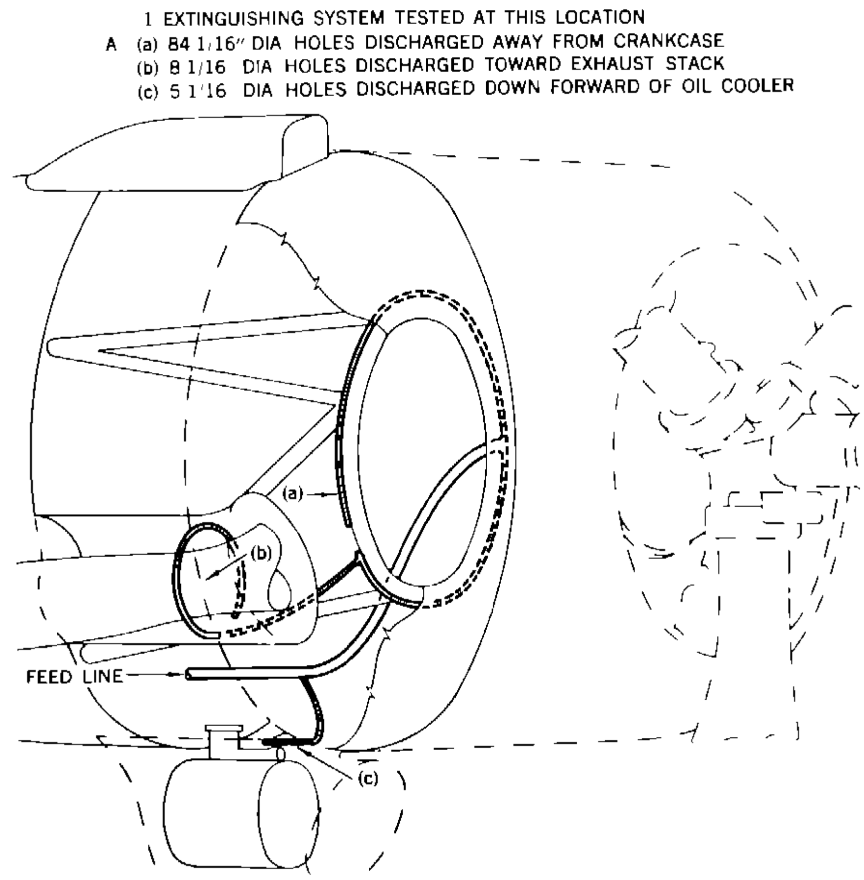


FIGURE 67. Accessory section distribution system (general type).

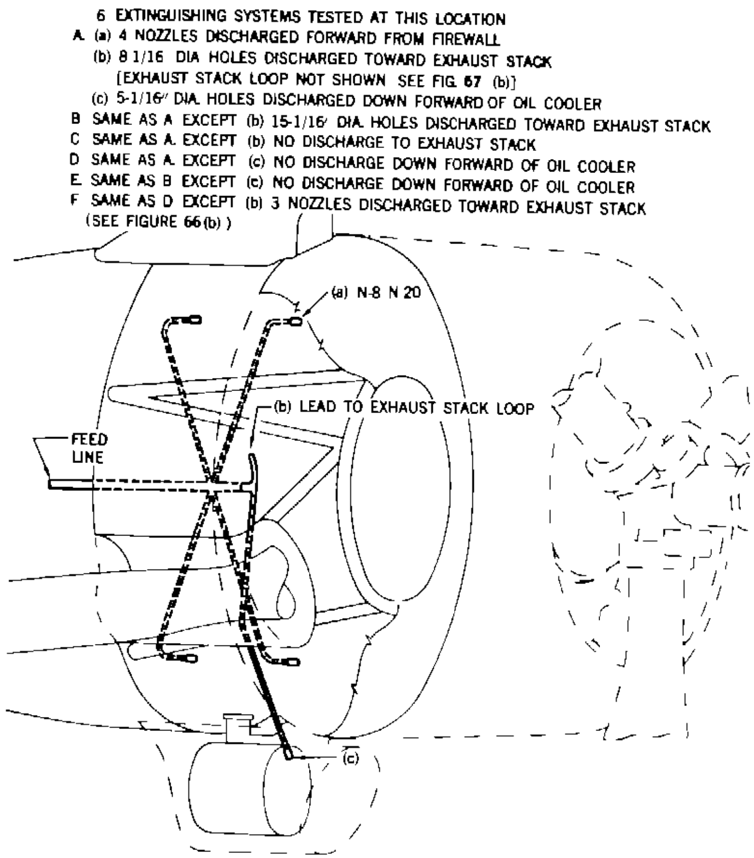


FIGURE 68 Accessory section distribution system (general type)

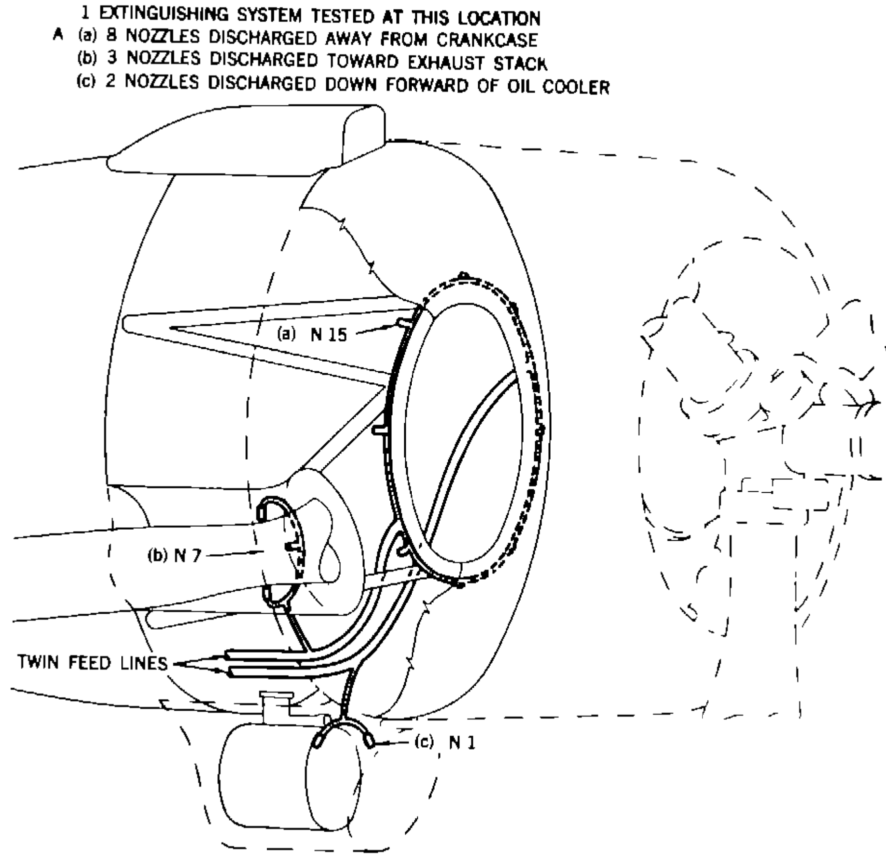


FIGURE 69 Accessory section distribution system (general type)

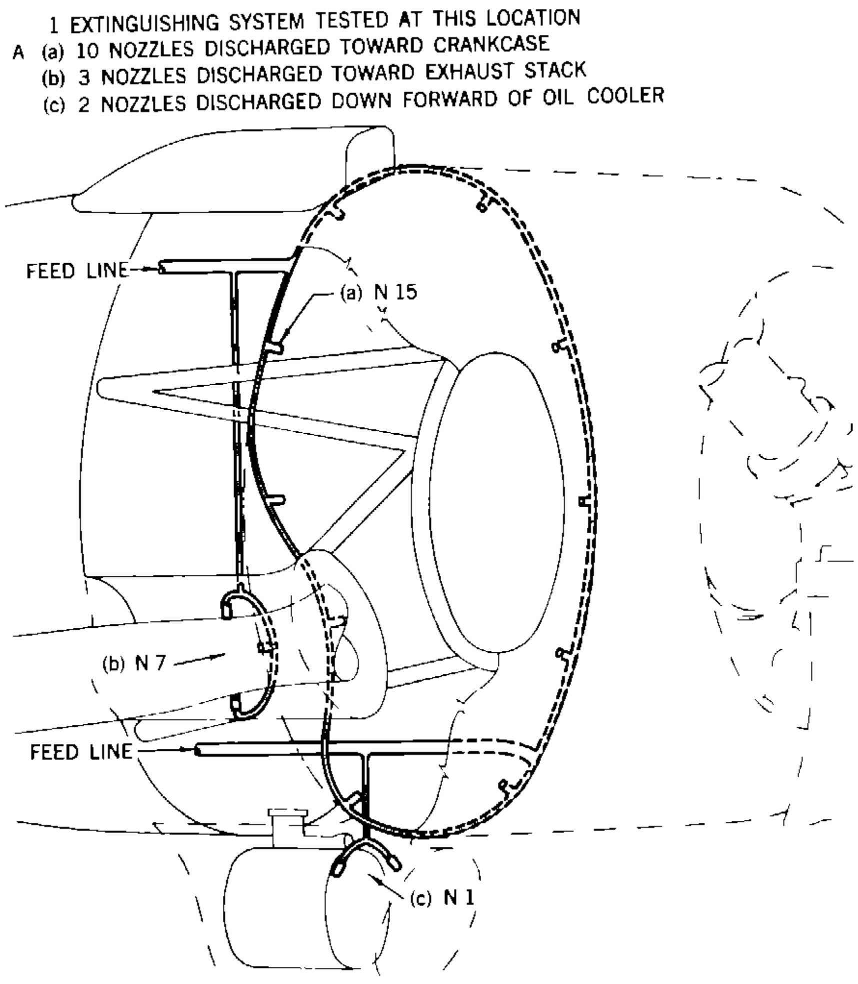


FIGURE 70. Accessory section distribution system (general type)

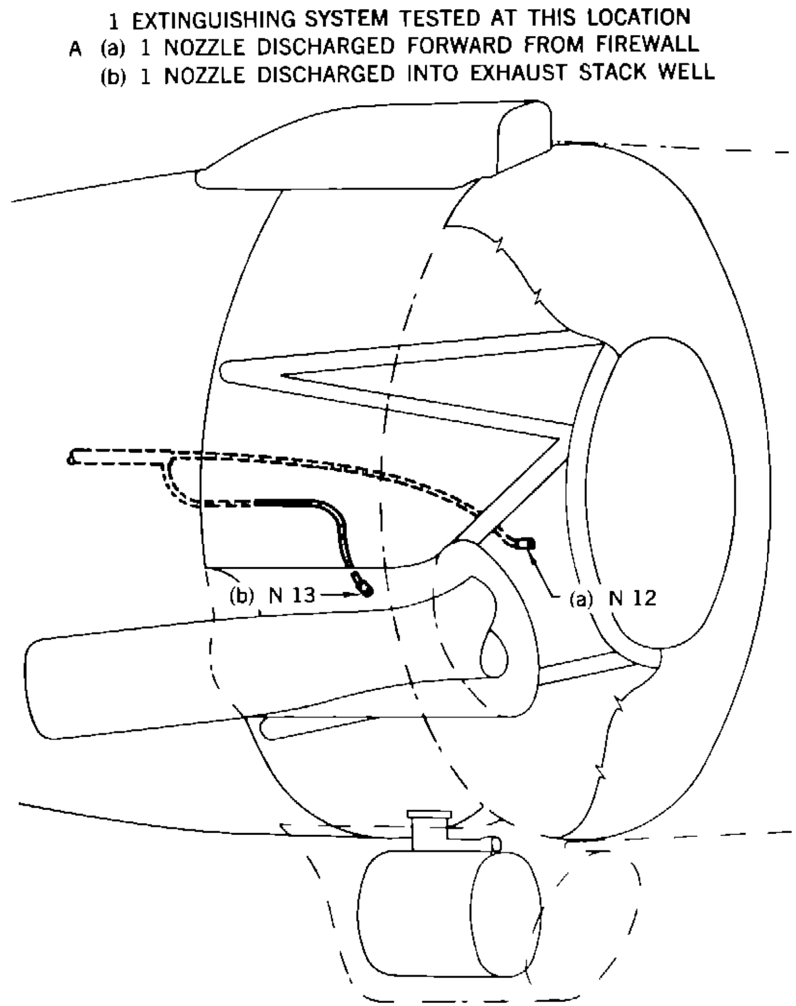


FIGURE 71 Accessory section distribution system (general type).

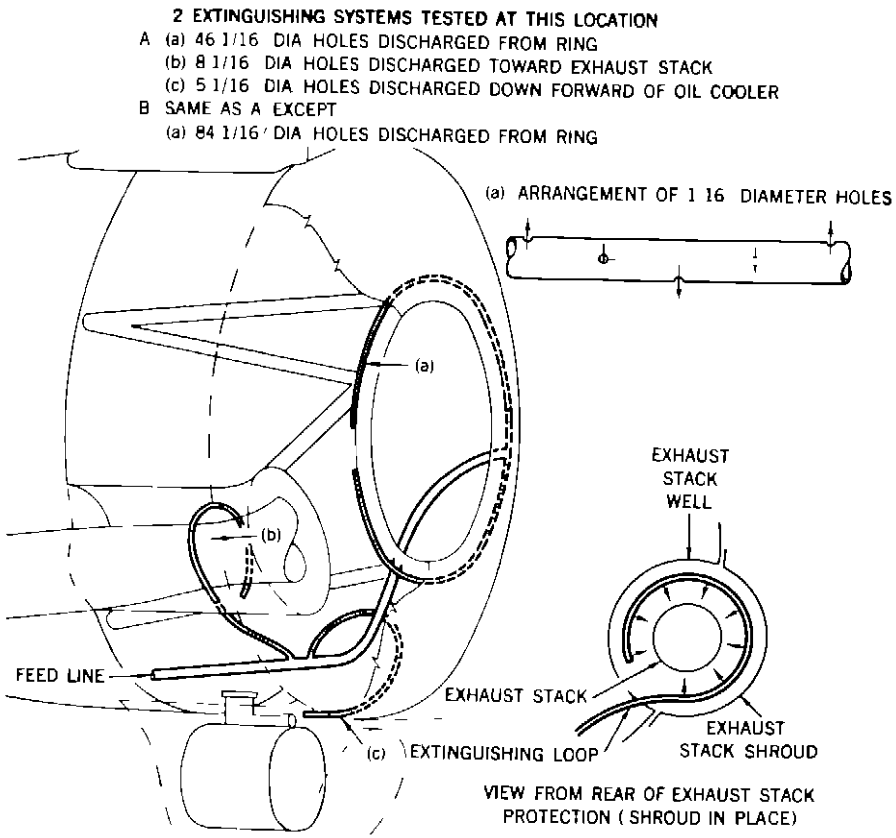


FIGURE 72 Distribution system used for extinguishing accessory section fires with gaseous extinguishing agents

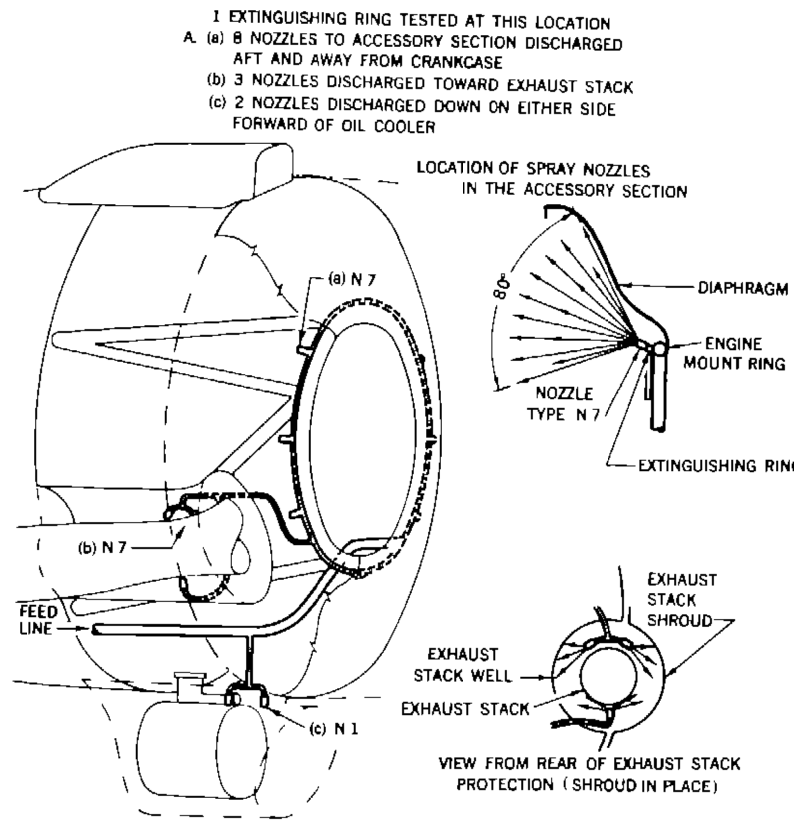


FIGURE 73 Distribution system used for extinguishing accessory section fires with liquid extinguishing agents.

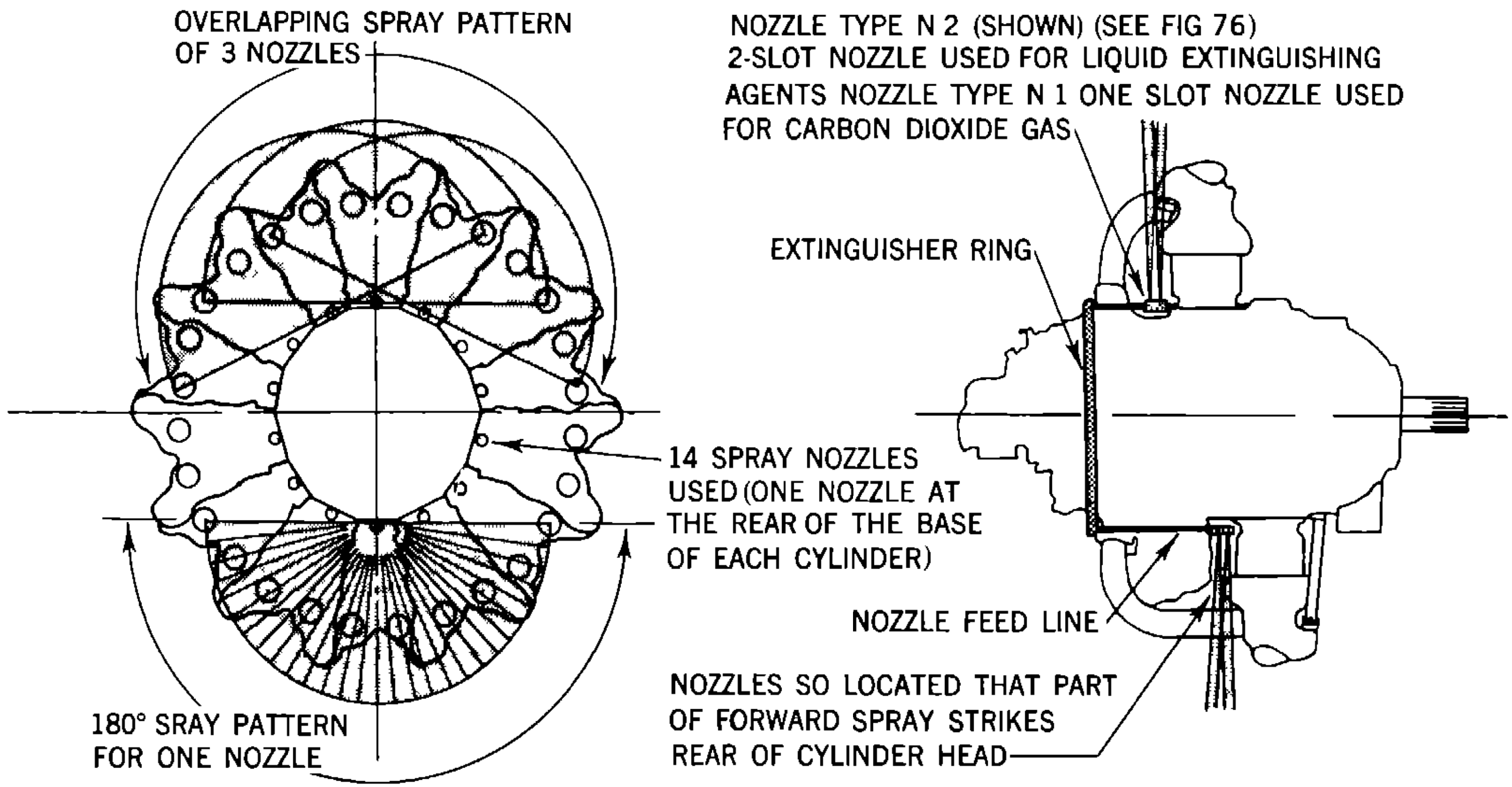


FIGURE 74. Spray nozzle locations used for extinguishing power section fires.

FIGURE 75. Example of fire spillage over front of N. A. C. A. cowl from fire source forward of cylinders.

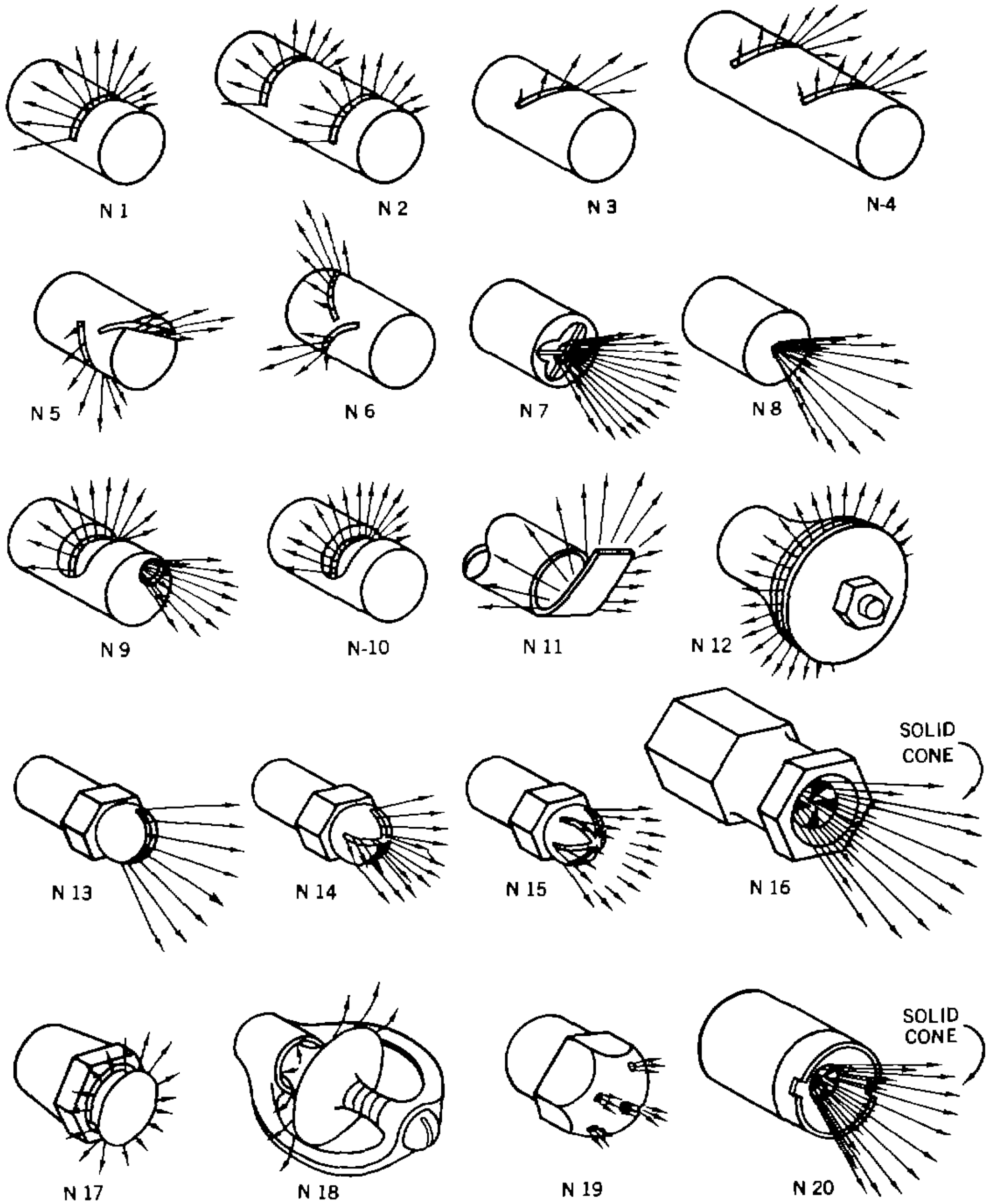


FIGURE 76. Nozzle types used in tests. Arrows indicate spray direction

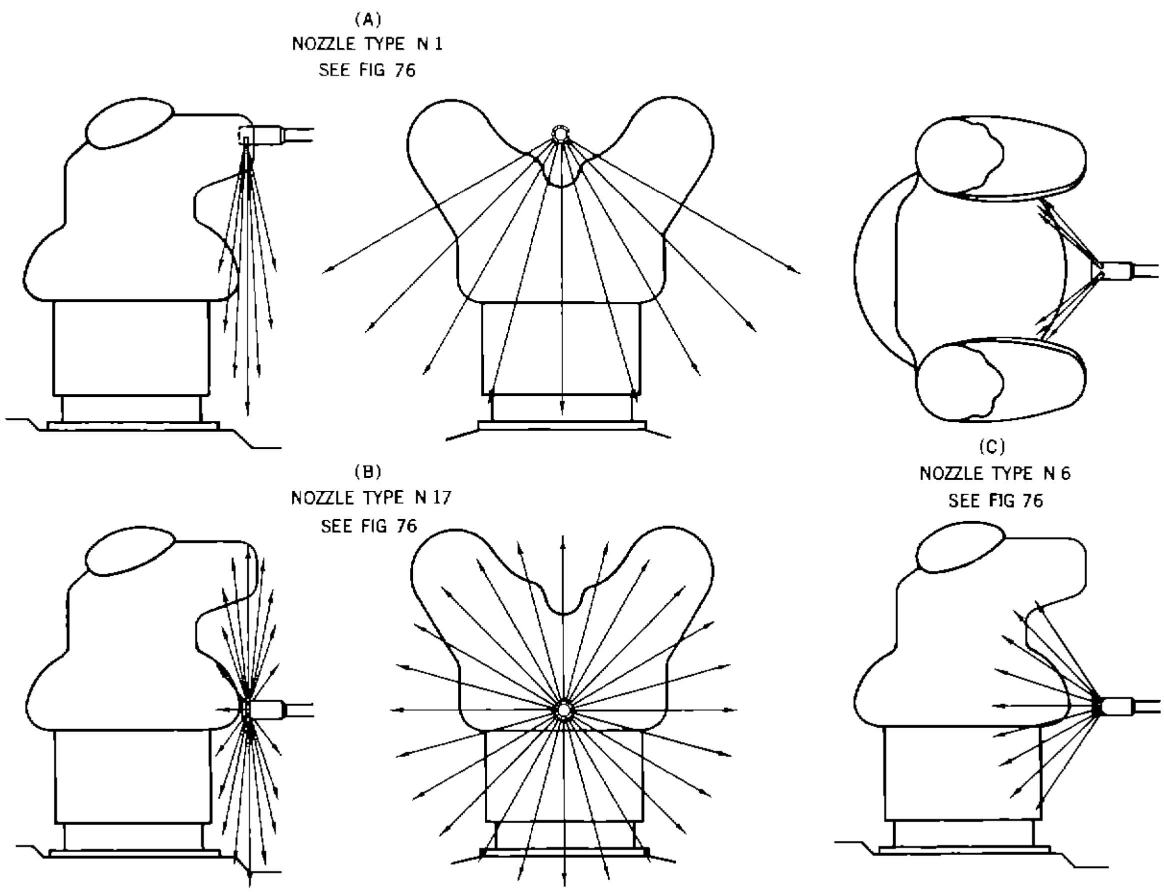


FIGURE 77 Three methods of individual cylinder treatment

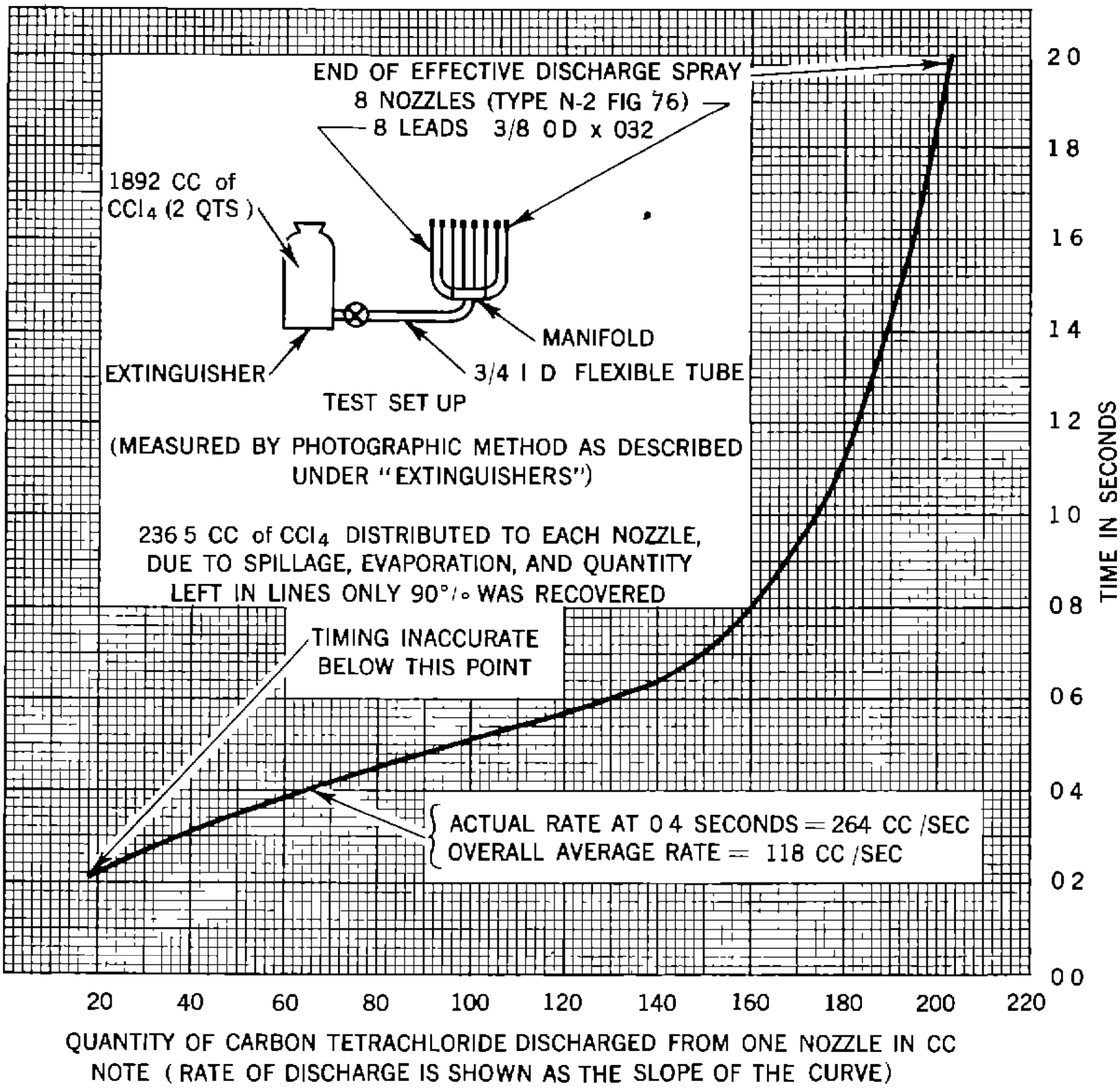
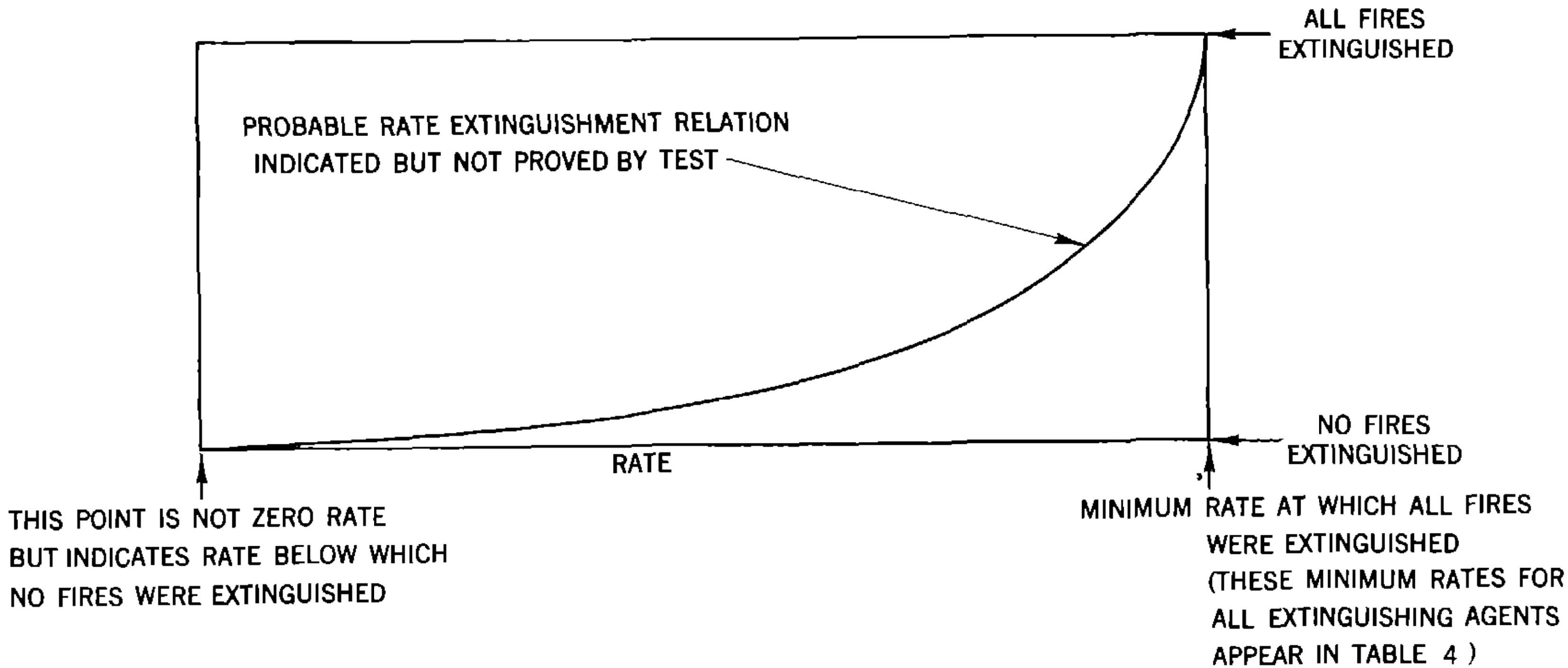


FIGURE 78 Rate of carbon tetrachloride discharge from one power section nozzle.



NOTE: This curve is not to be used as a quantitive relationship. It is merely a method of illustrating the probable qualitative relationship existing between the rate of agent application and the extinguishment efficiency.

No two fires tested were identical and each fire burned according to the set of conditions existing at the time of the fire. As the rate of application of the agent was increased it became possible to extinguish more and more of such fires, until the increase in rate became adequate to extinguish all fires This point is noted on the curve as the minimum rate at which all fires were extinguished.

FIGURE 79. Power section extinguishment efficiency vs. rate of extinguishing agent discharge.

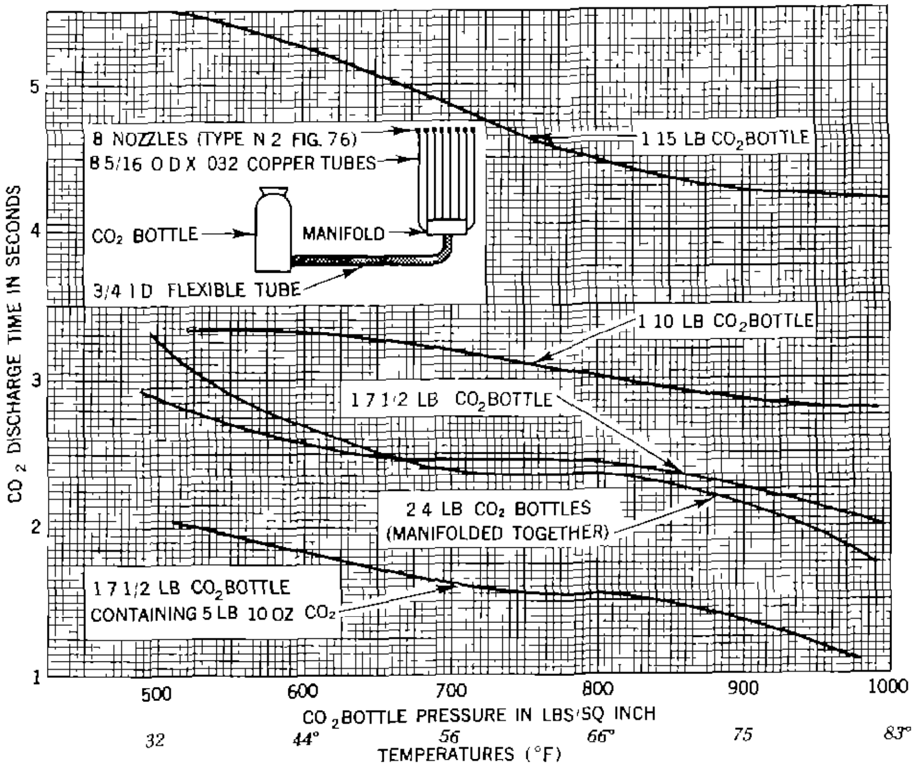


FIGURE 80 Typical curves of discharge tire vs bottle pressure for various size carbon dioxide bottles

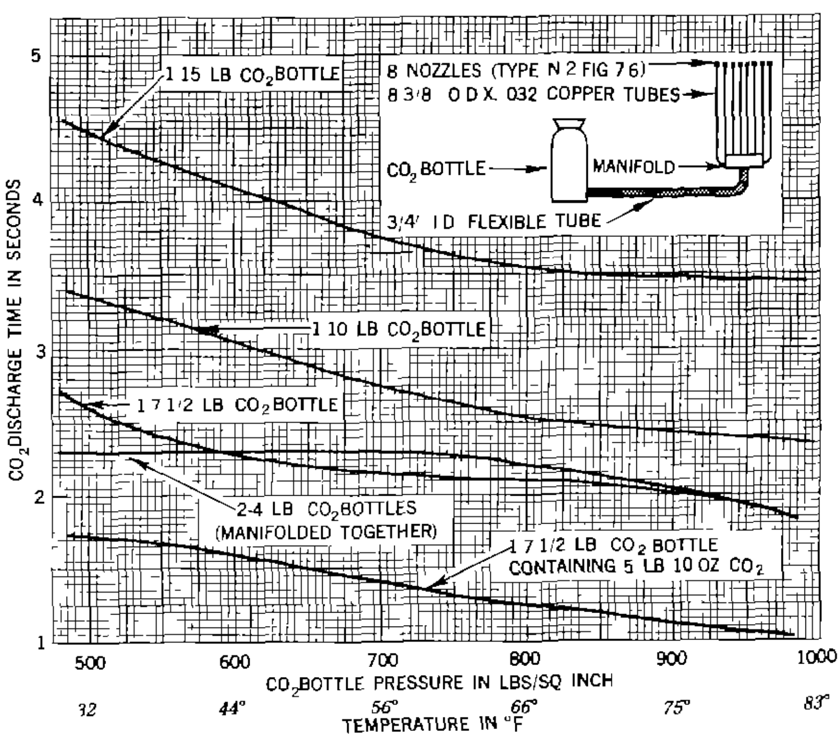


FIGURE 81 Typical curves of discharge time vs bottle pressure for various size carbon dioxide bottles.

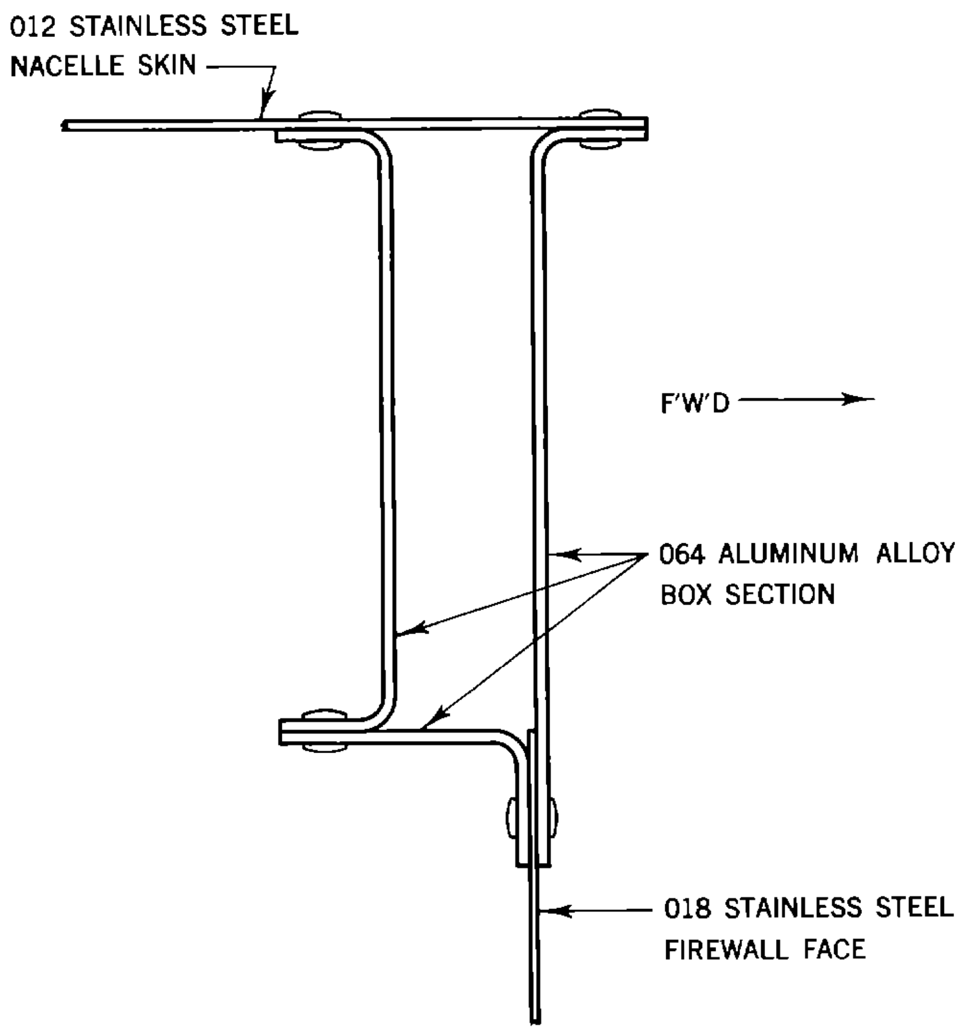


FIGURE 82. Aluminum alloy box section periphery of firewall.

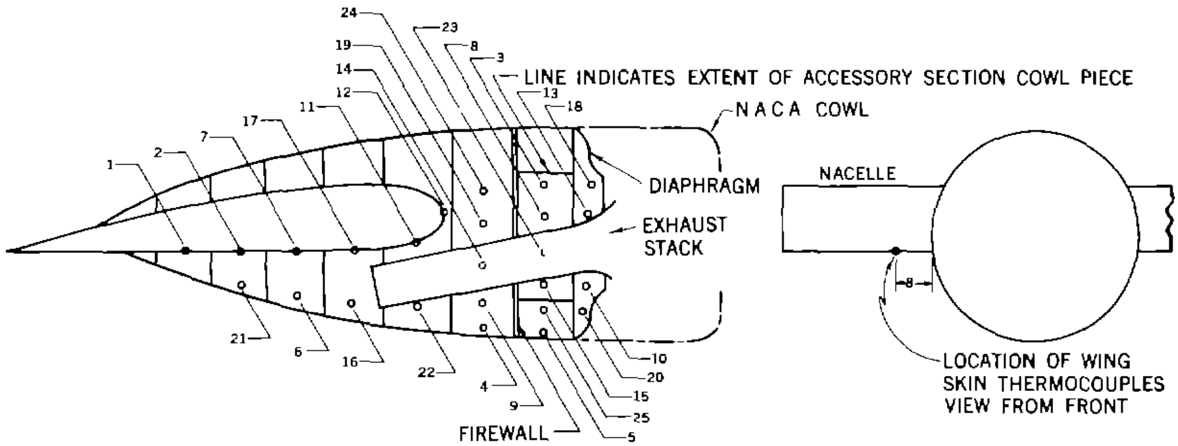


FIGURE 83. Locations of thermocouples for determination of skin temperatures under various fire conditions

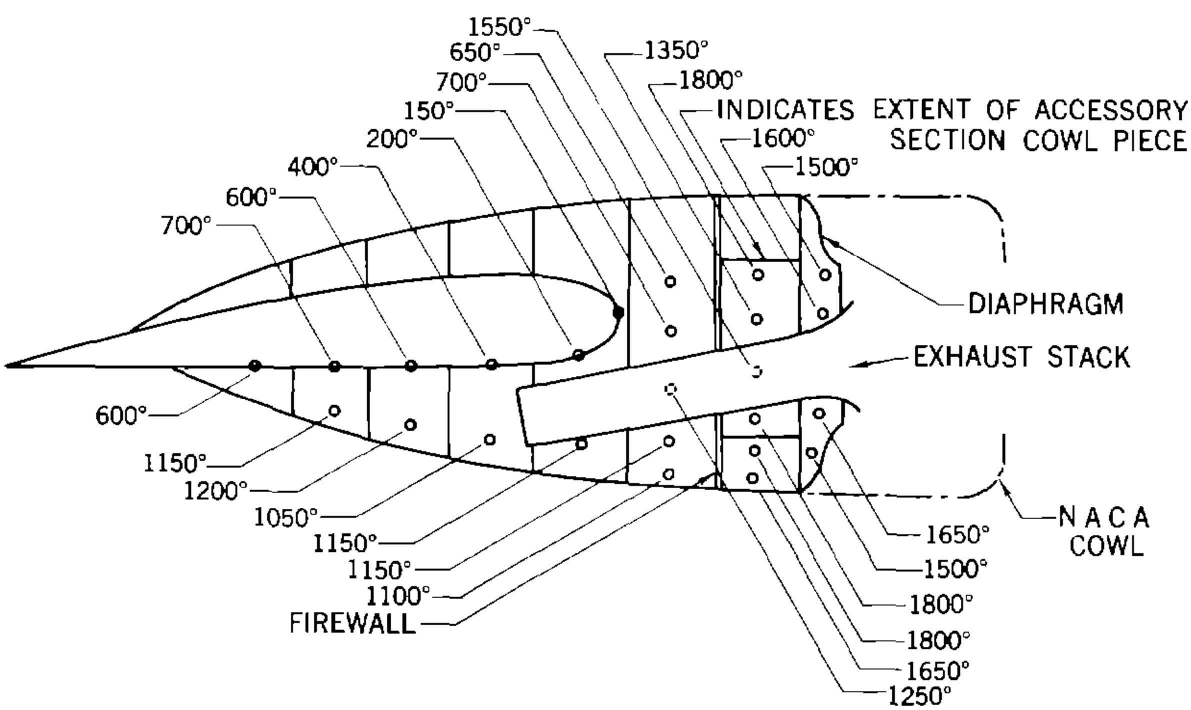


FIGURE 84 Highest temperatures (^{o}F) recorded at thermocouples located as shown in figure 83.

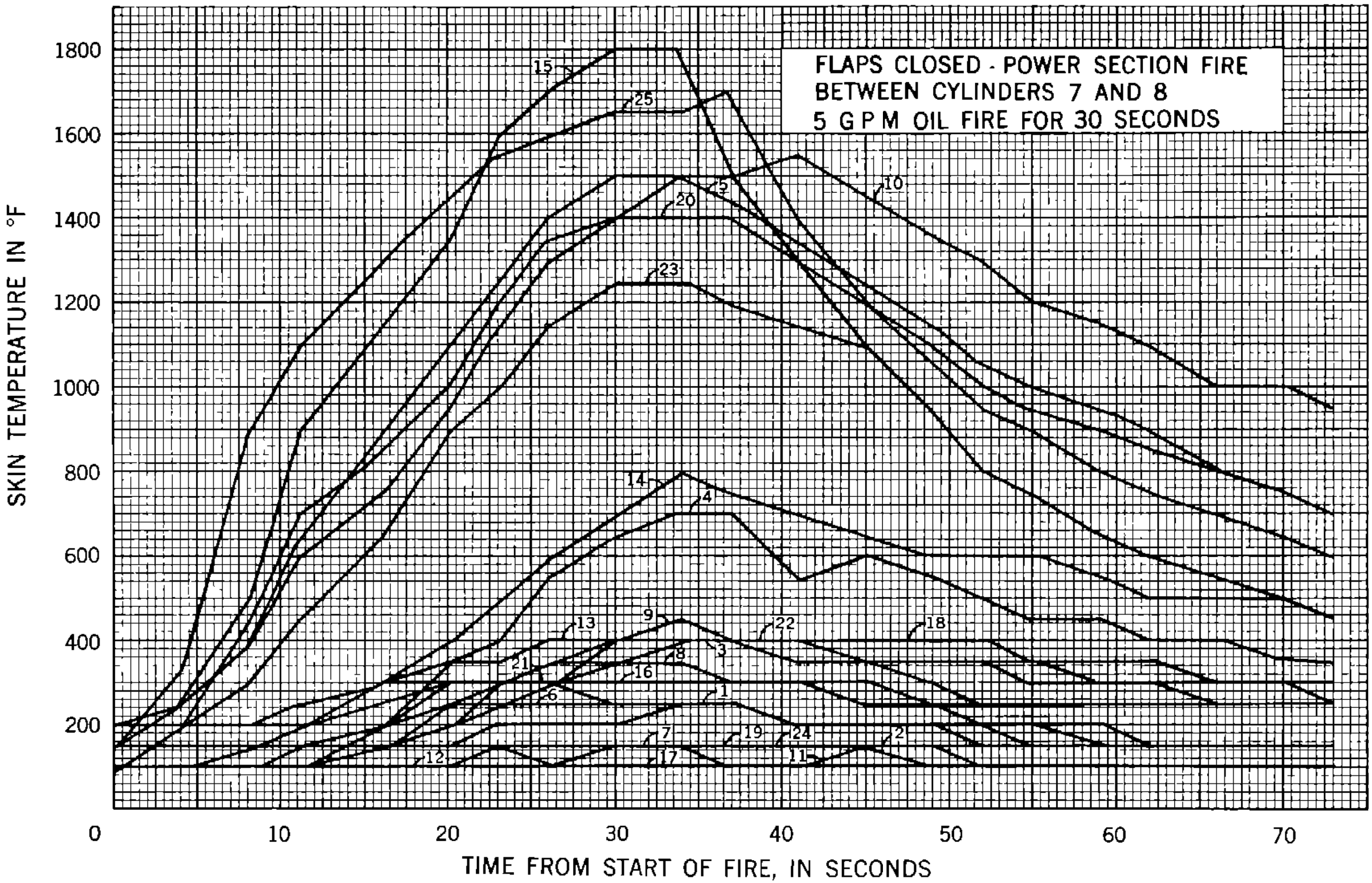


FIGURE 85 Skin temperatures vs. time (thermocouple location shown in figure 83).

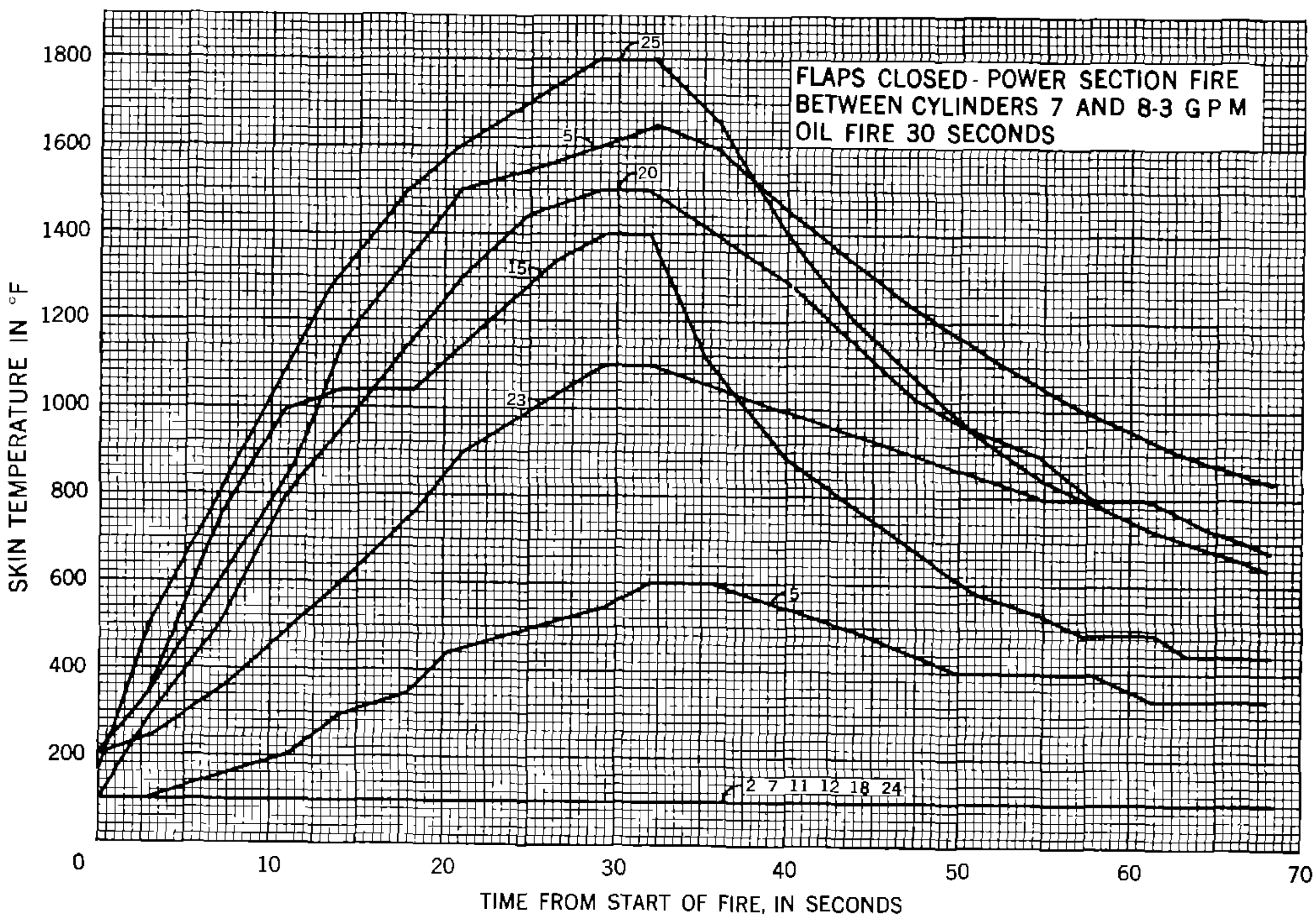


FIGURE 86. Skin temperatures vs. time (thermocouple locations shown in figure 83).

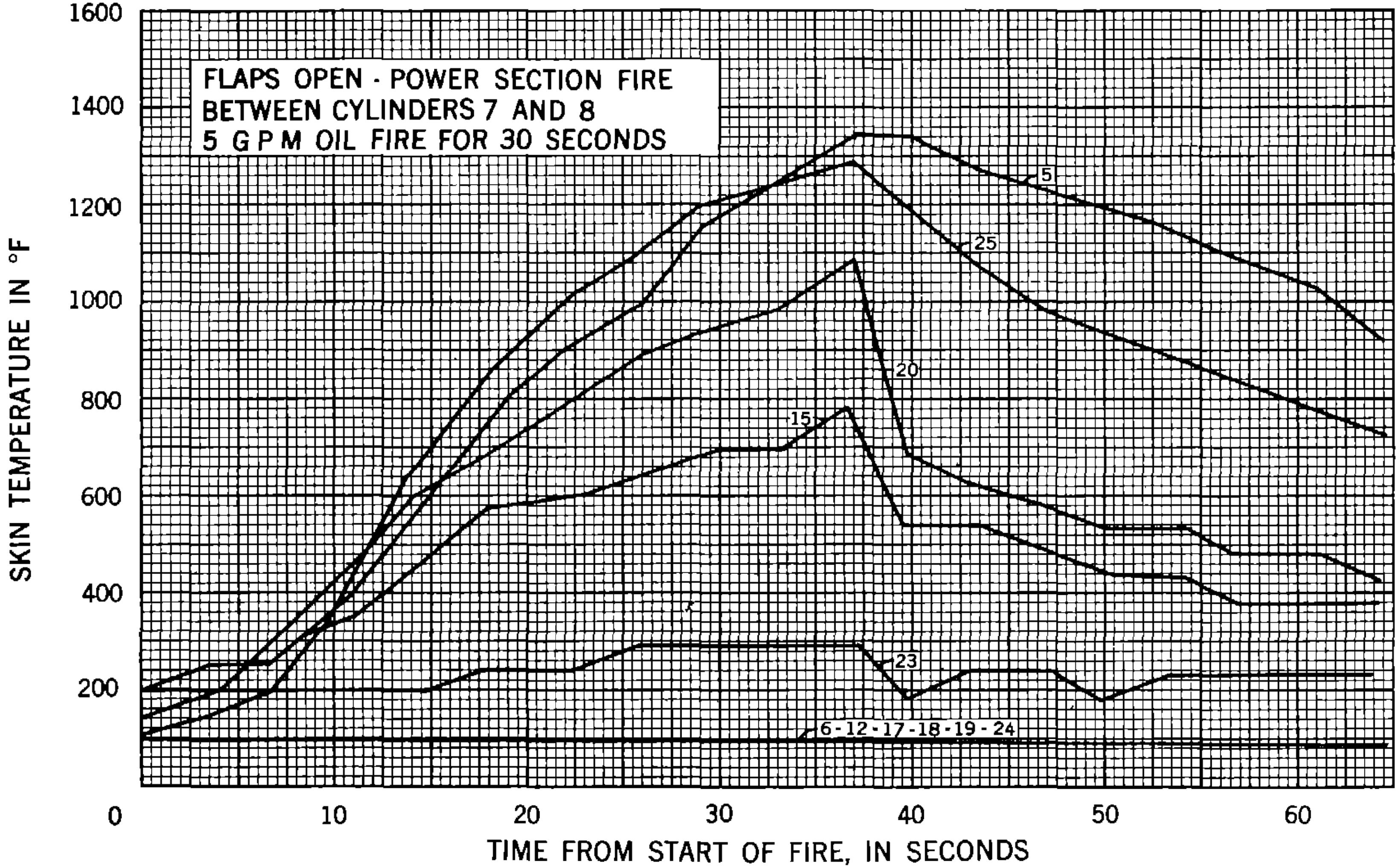


FIGURE 87. Skin temperatures vs. time (thermocouple locations shown in figure 83).

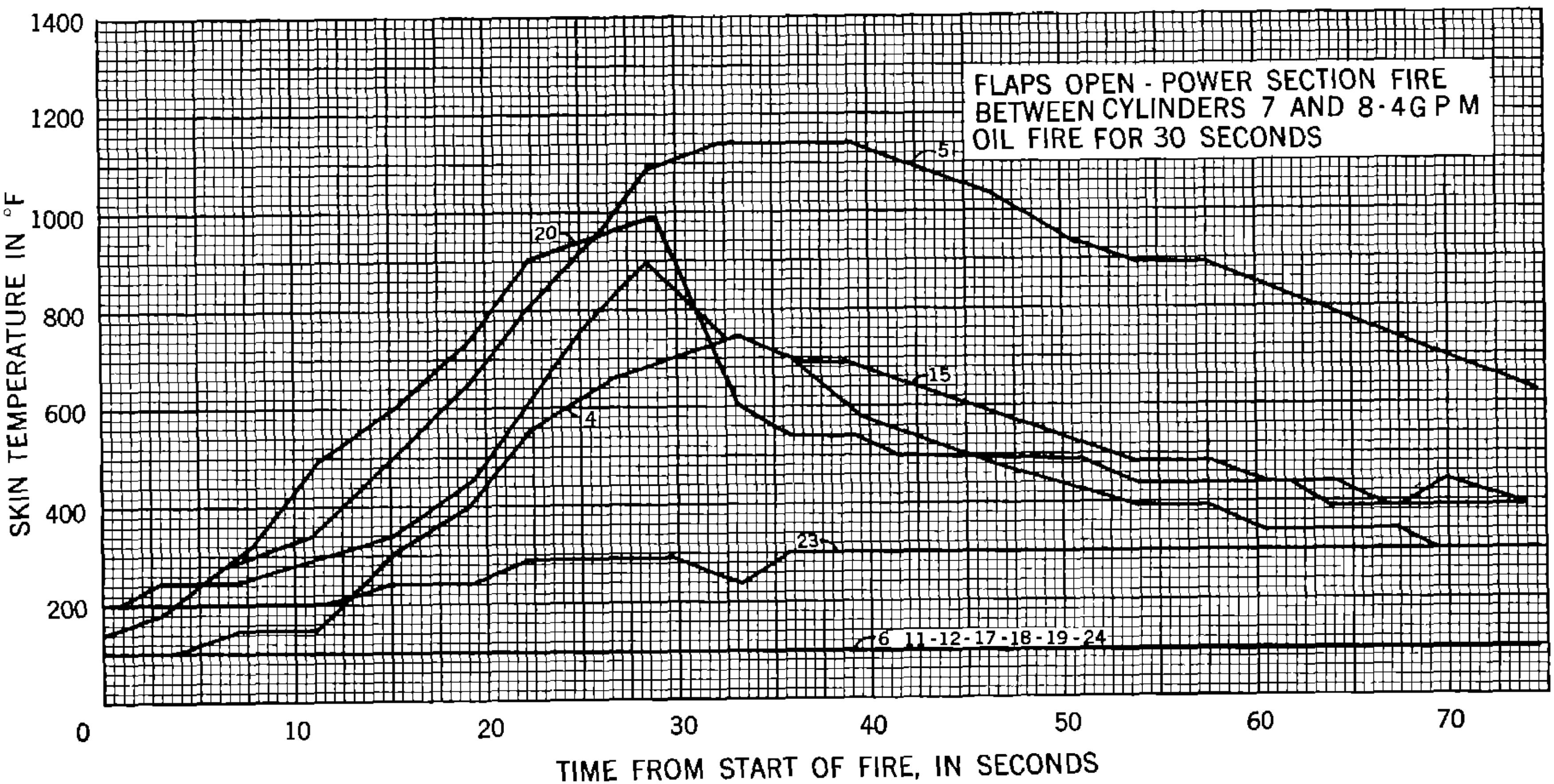


FIGURE 88. Skin temperatures vs. time (thermocouple locations shown in figure 83).

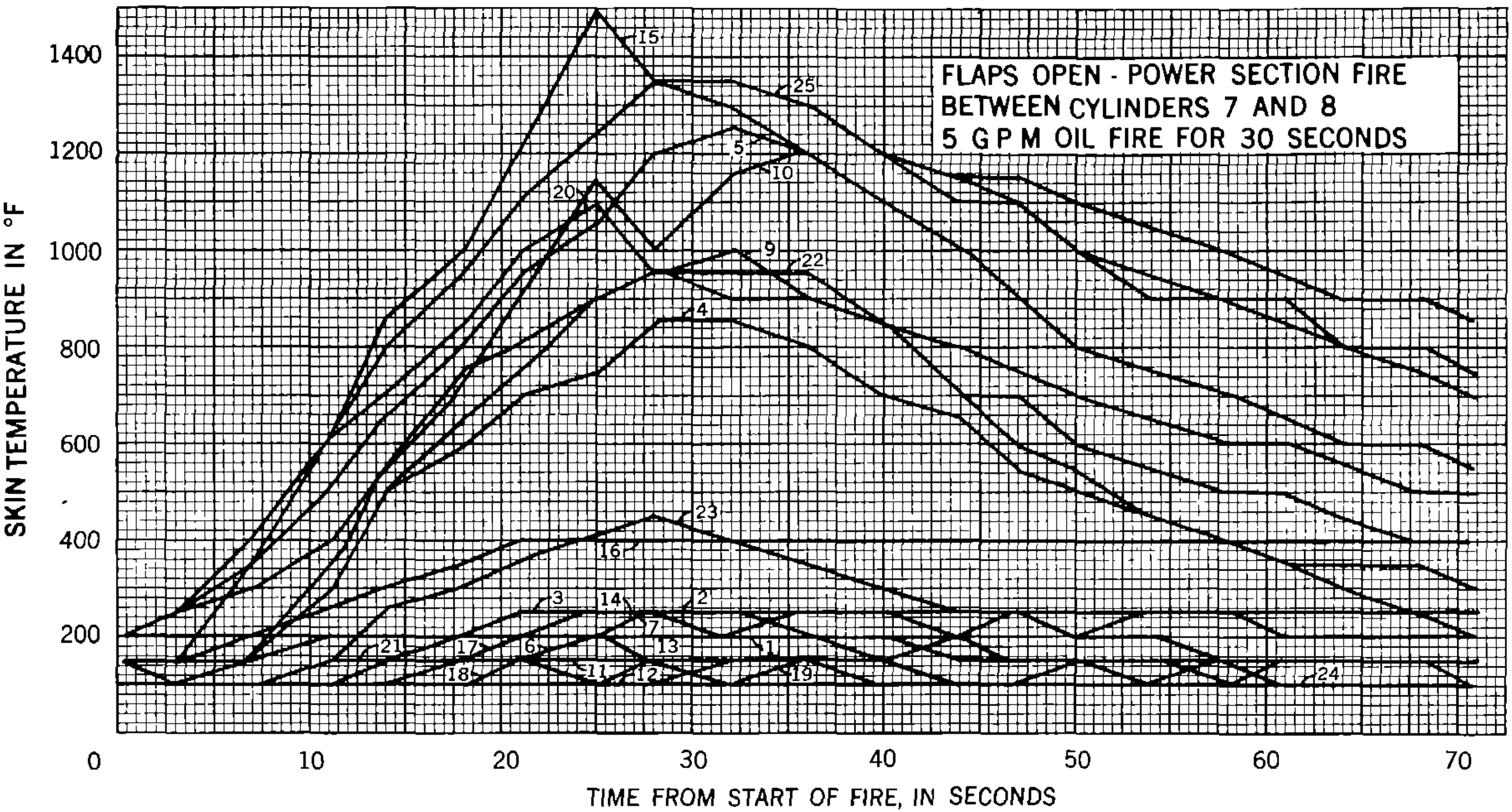


FIGURE 89. Skin temperatures vs. time (thermocouple locations shown in figure 83).

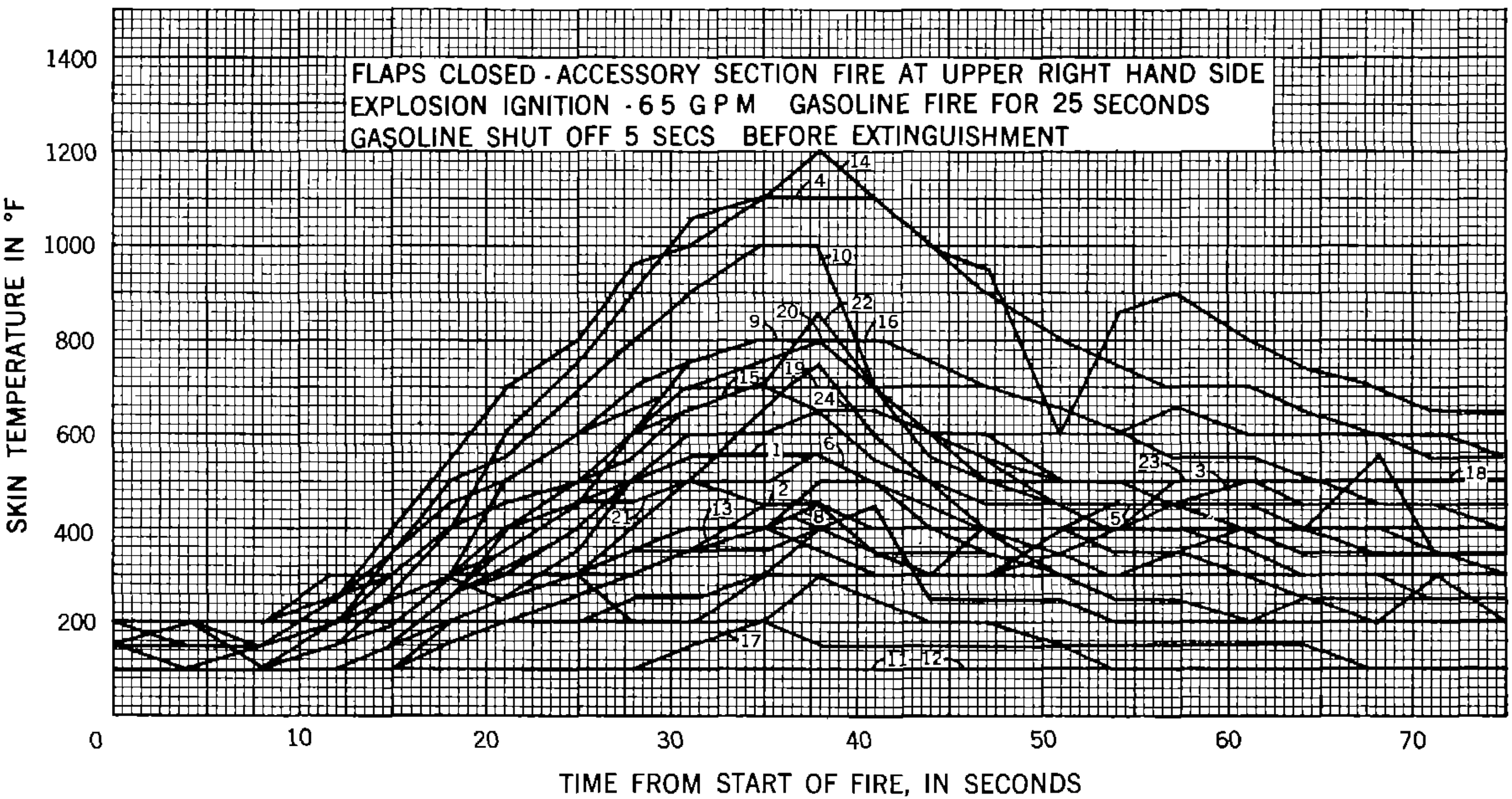


FIGURE 90. Skin temperatures vs. time (thermocouple locations shown in figure 83).

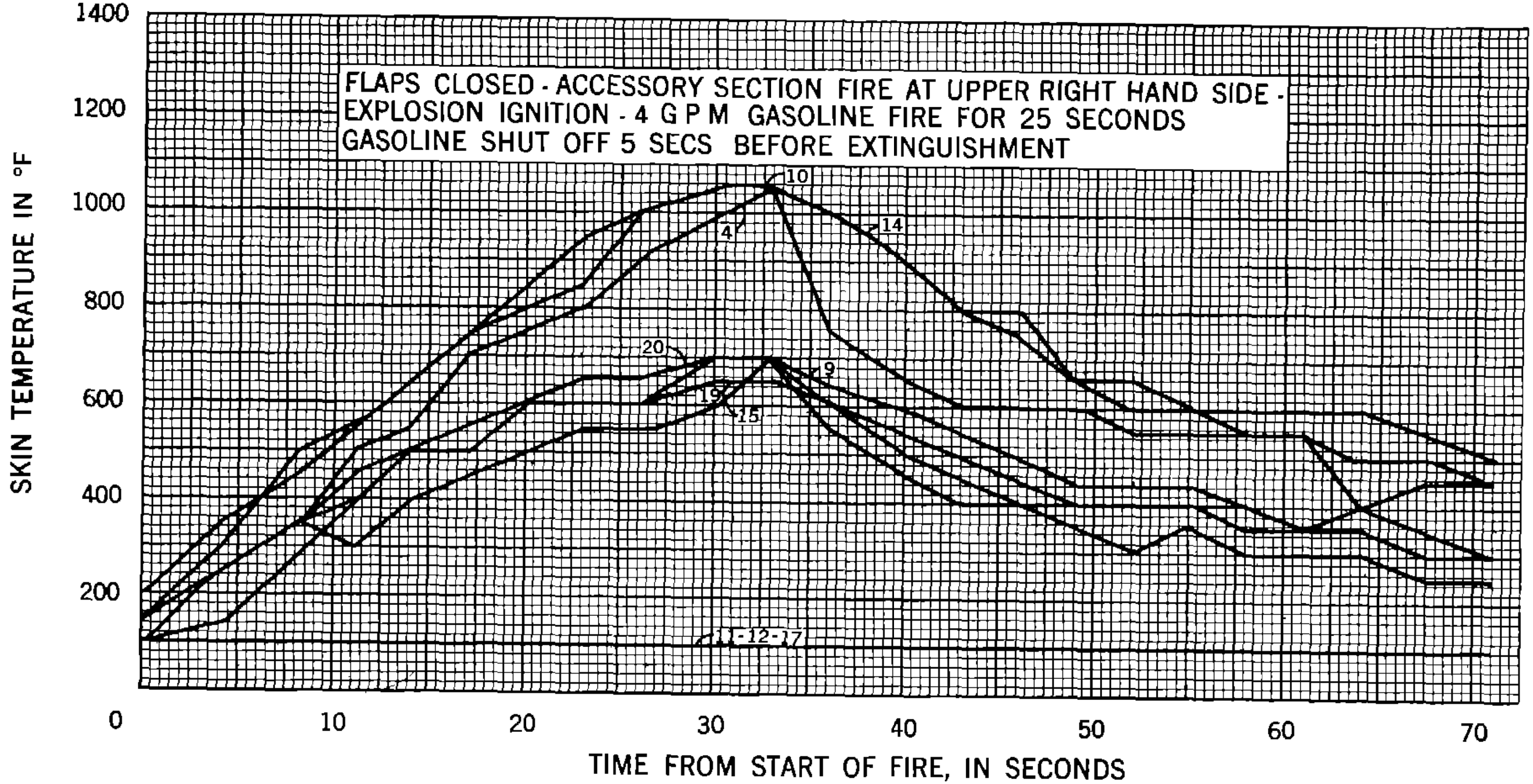


FIGURE 91 Skin temperatures vs time (thermocouple locations shown in figure 83)

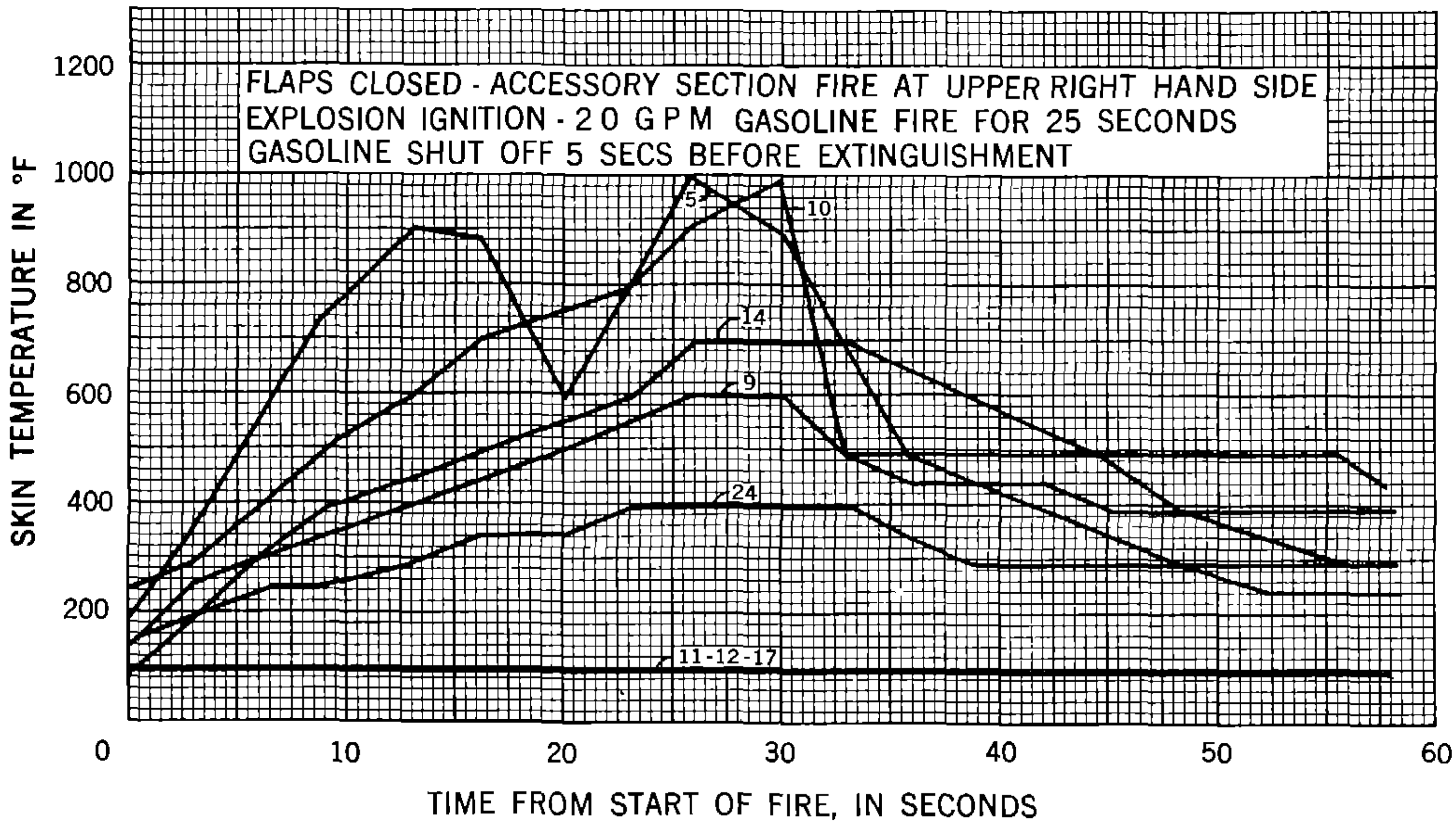


FIGURE 92. Skin temperatures vs. time (thermocouple locations shown in figure 83).

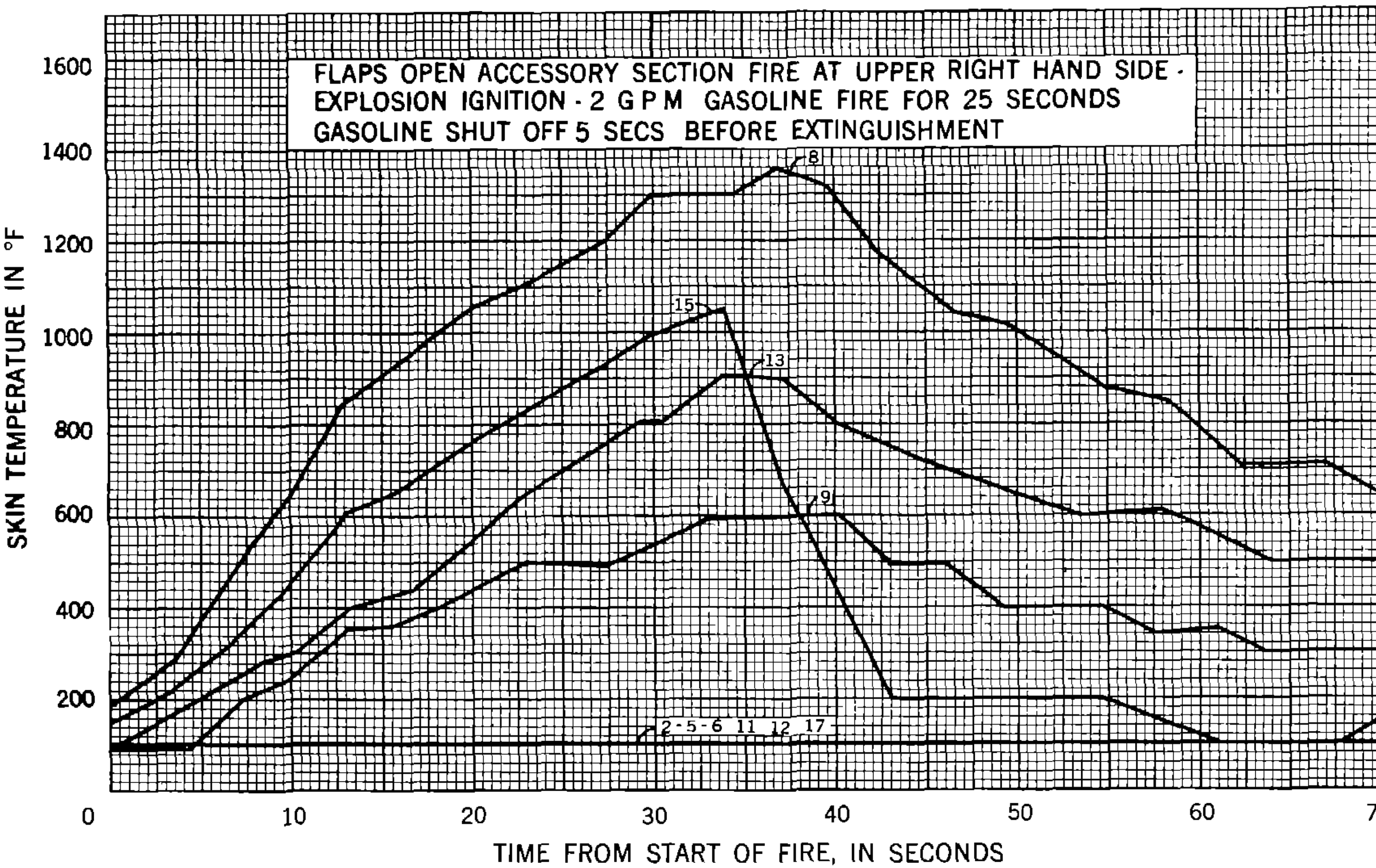


FIGURE 93. Skin temperatures vs. time (thermocouple locations shown in figure 83).

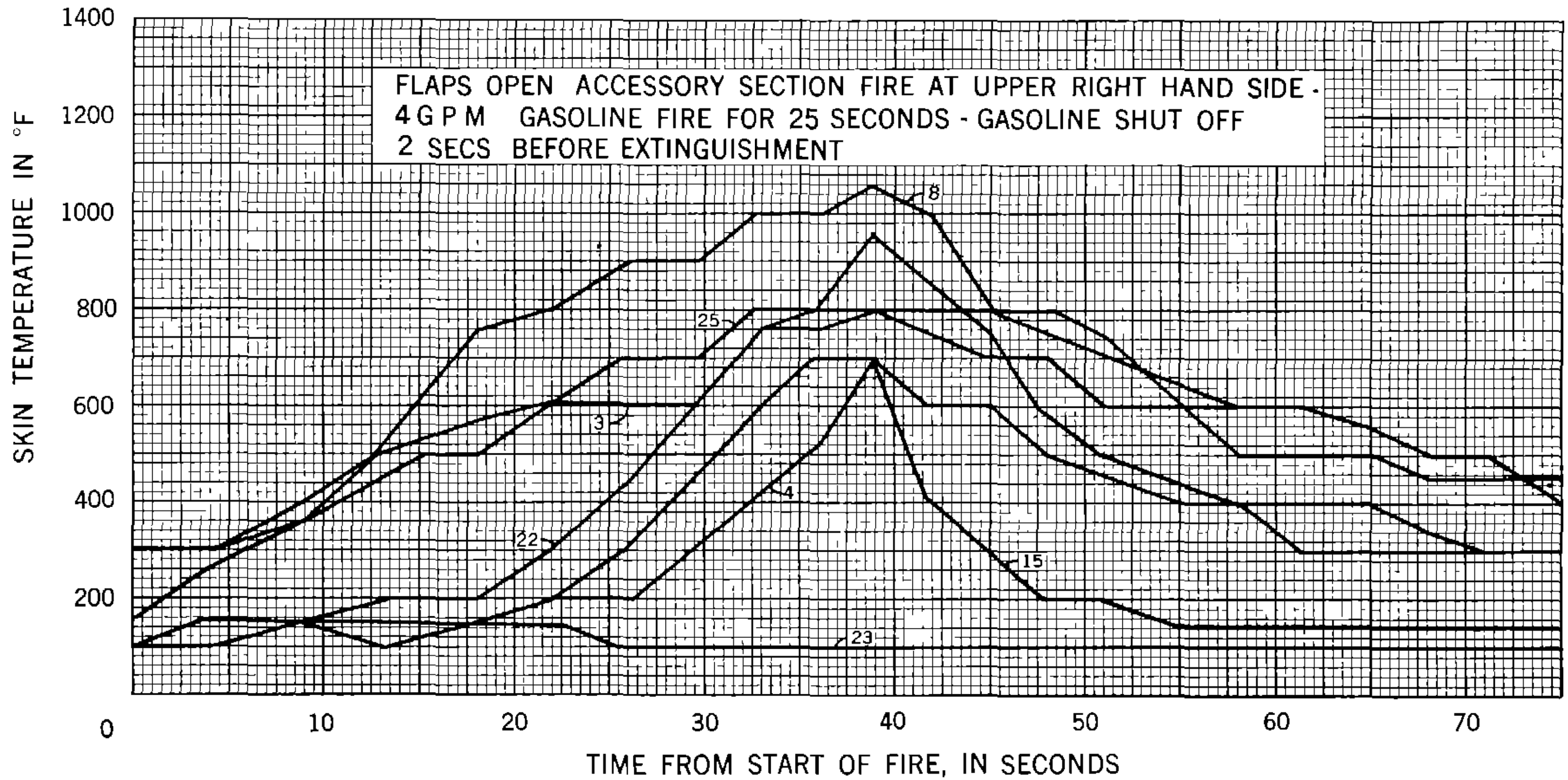


FIGURE 94. Skin temperatures vs. time (thermocouple locations shown in figure 83).

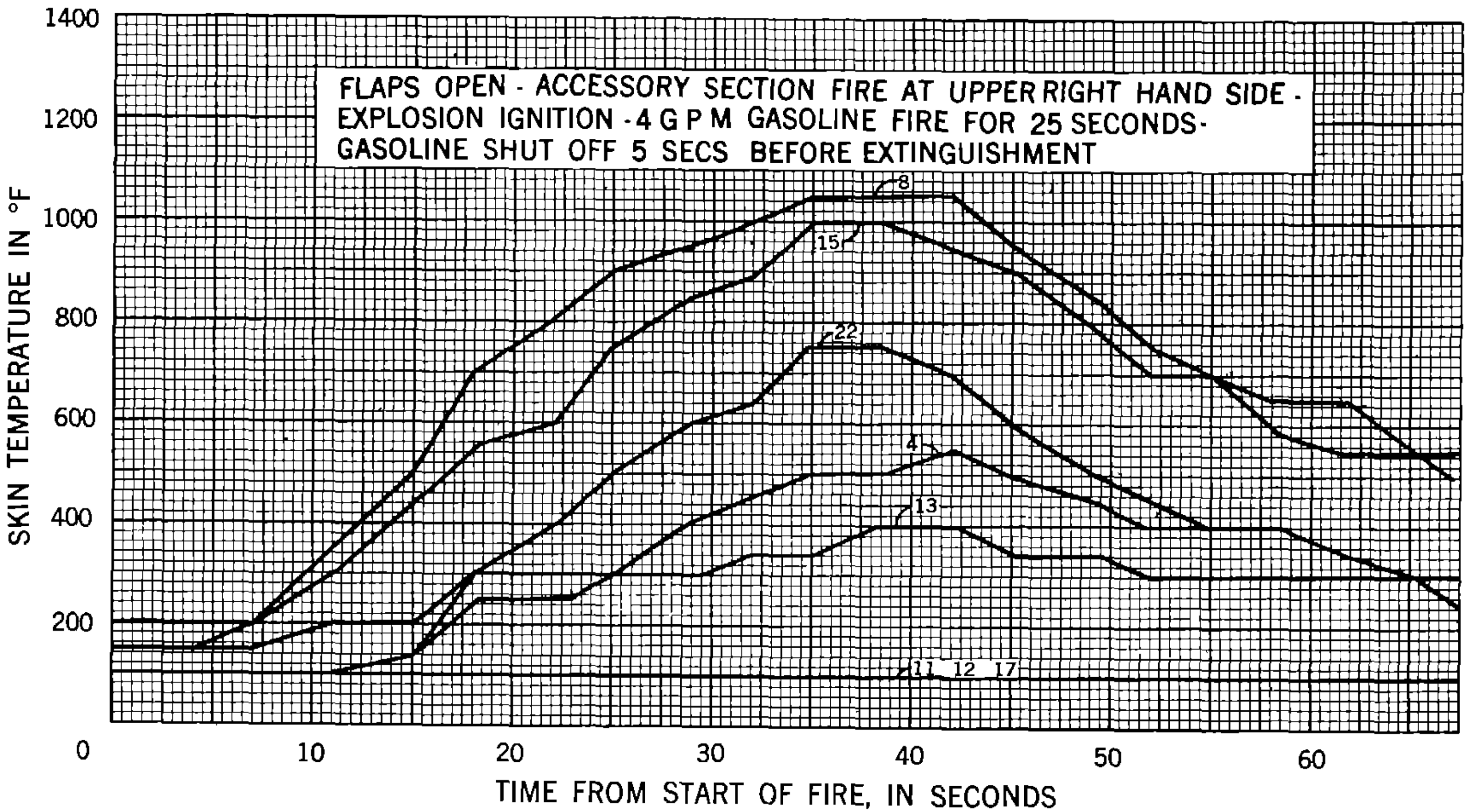


FIGURE 95. Skin temperatures vs. time (thermocouple locations shown in figure 83).

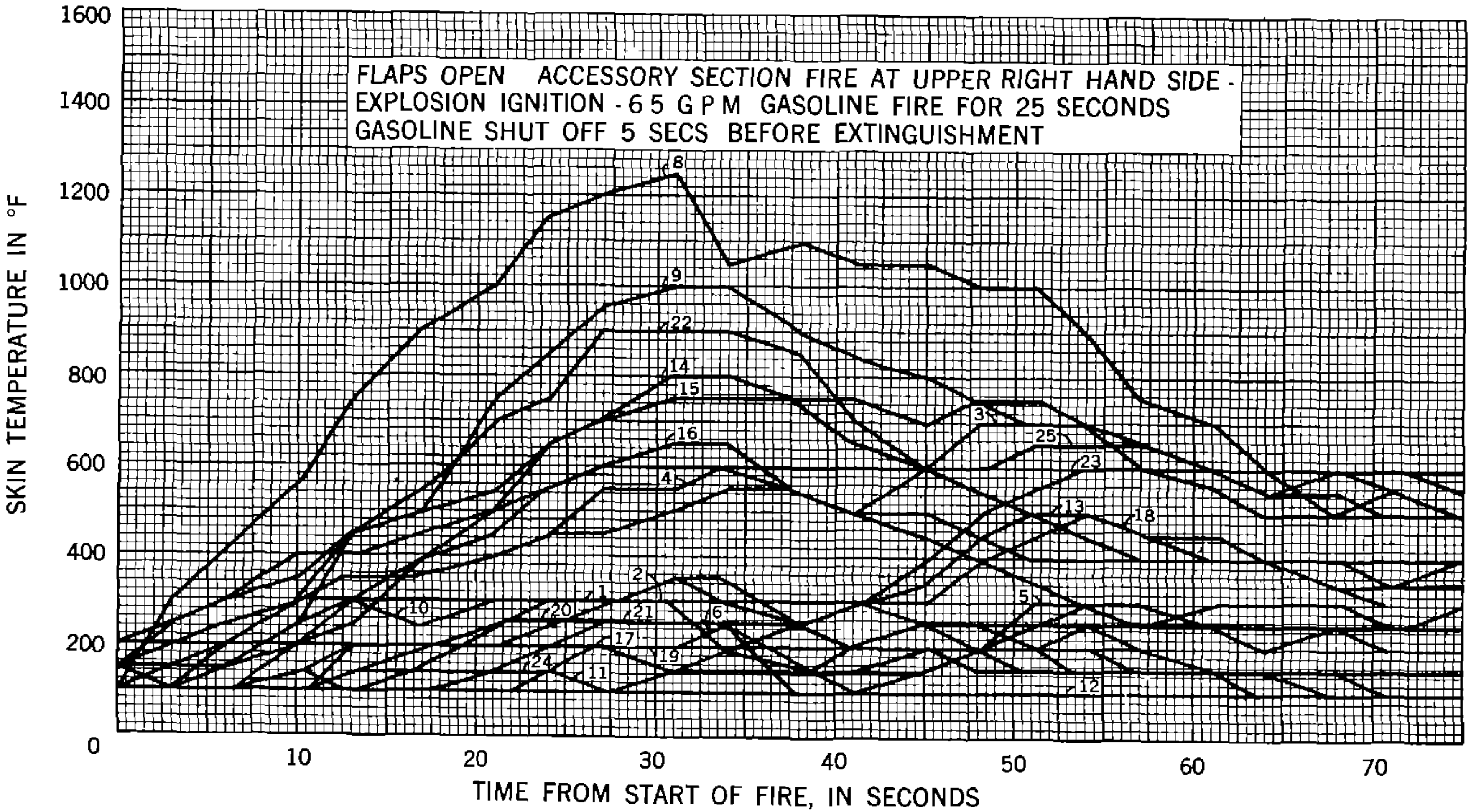
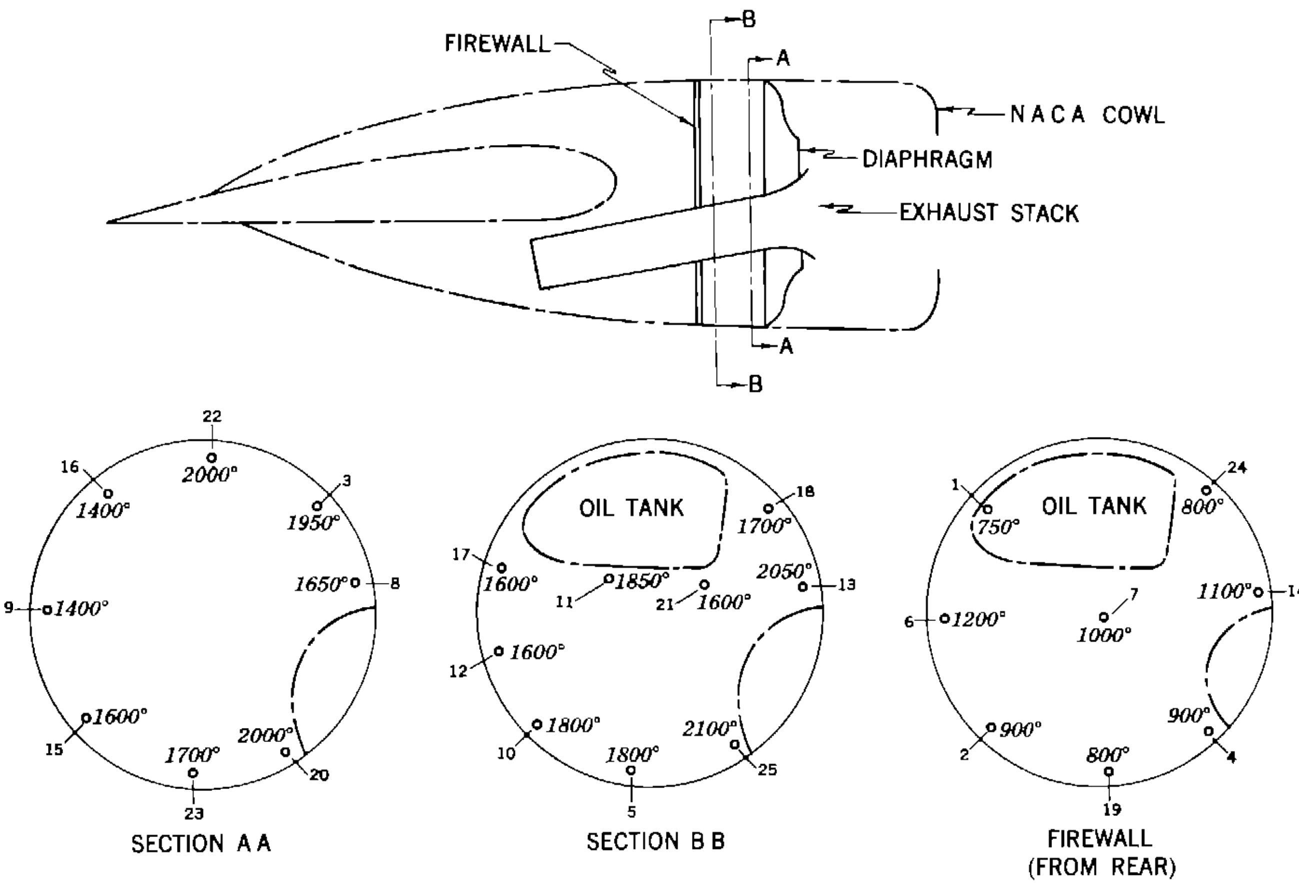


FIGURE 96 Skin temperatures vs time (thermocouple locations shown in figure 83)



SLANT NUMBERS INDICATE HIGHEST TEMPERATURES (°F)
RECORDED AT THE ACCESSORY SECTION
THERMOCOUPLE LOCATIONS

FIGURE 97 Thermocouple locations and highest temperatures recorded in the accessory section and on the firewall under various fire conditions

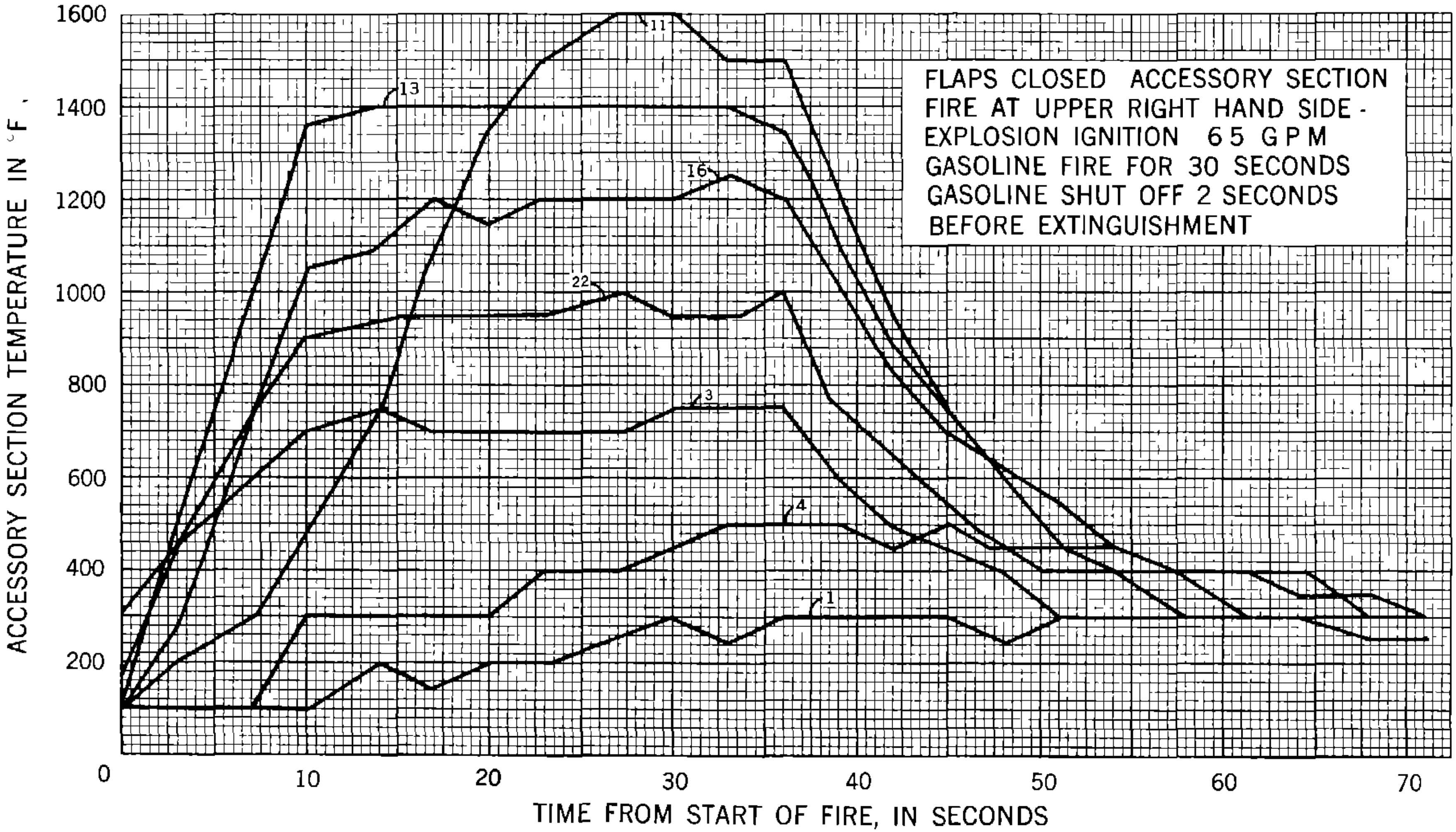


FIGURE 98. Accessory section temperatures vs. time (thermocouple locations shown in figure 97).

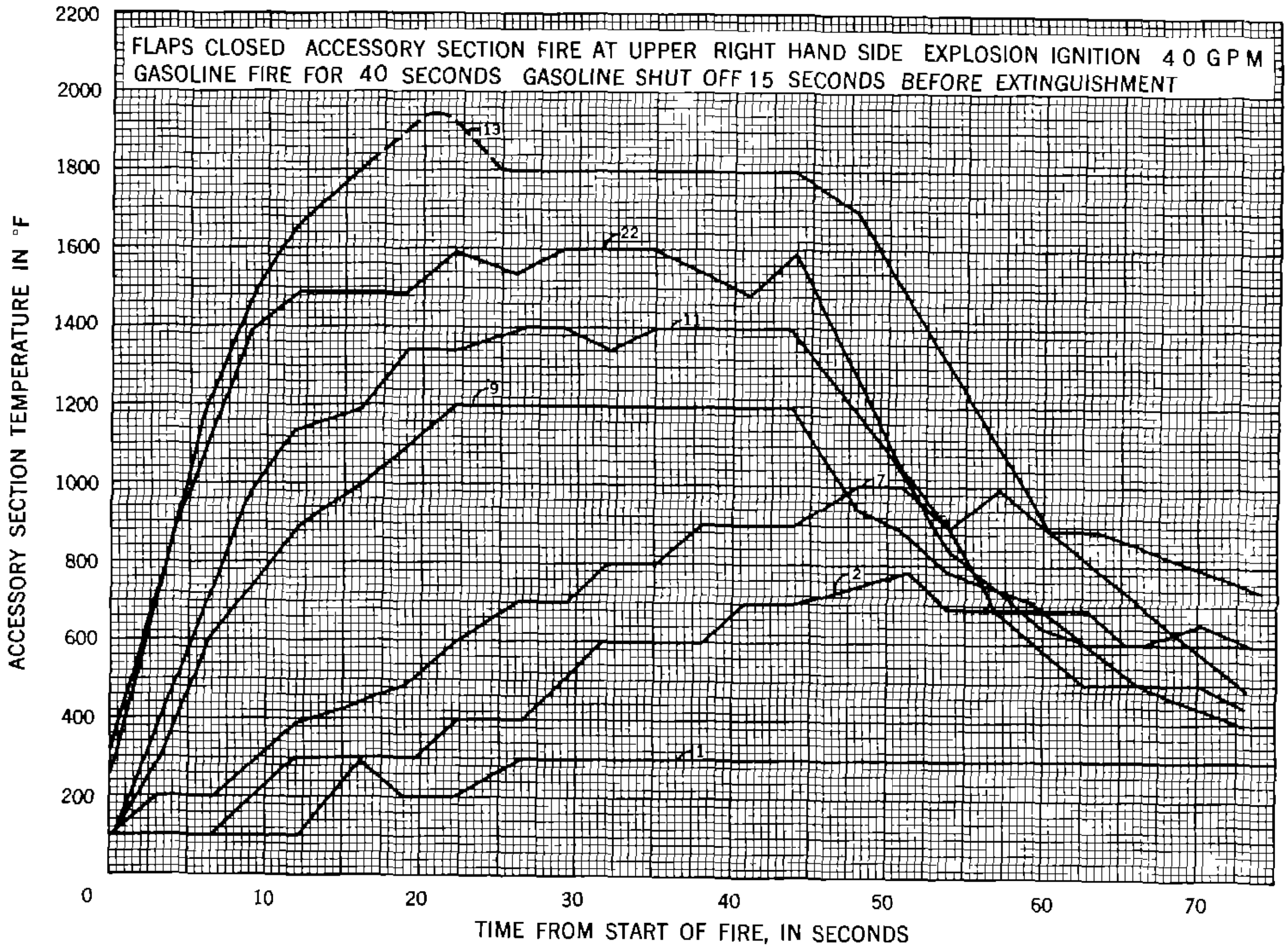


FIGURE 99. Accessory section temperatures vs. time (thermocouple locations shown in figure 97).

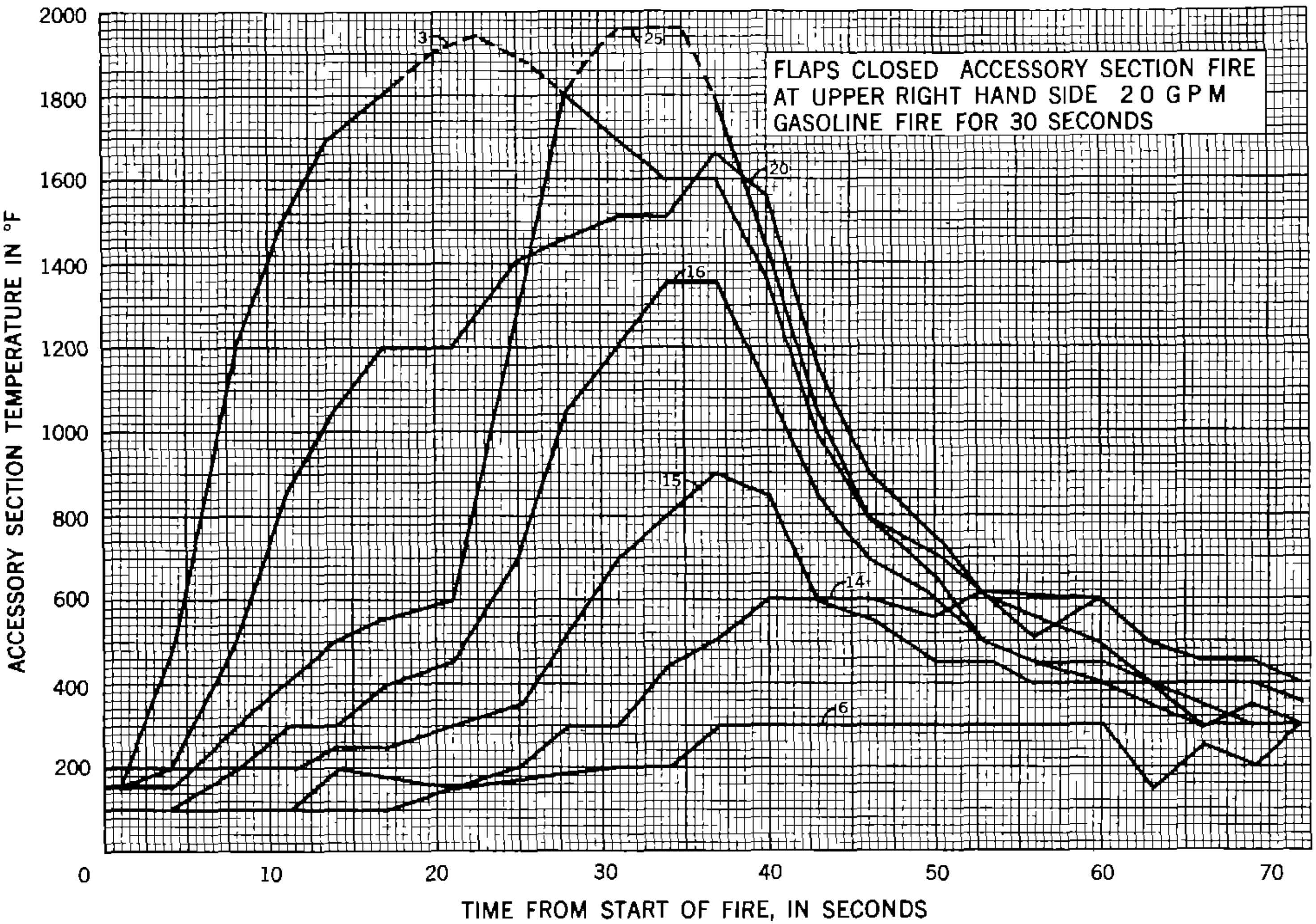


FIGURE 100. Accessory section temperatures vs time (thermocouple locations shown in figure 97).

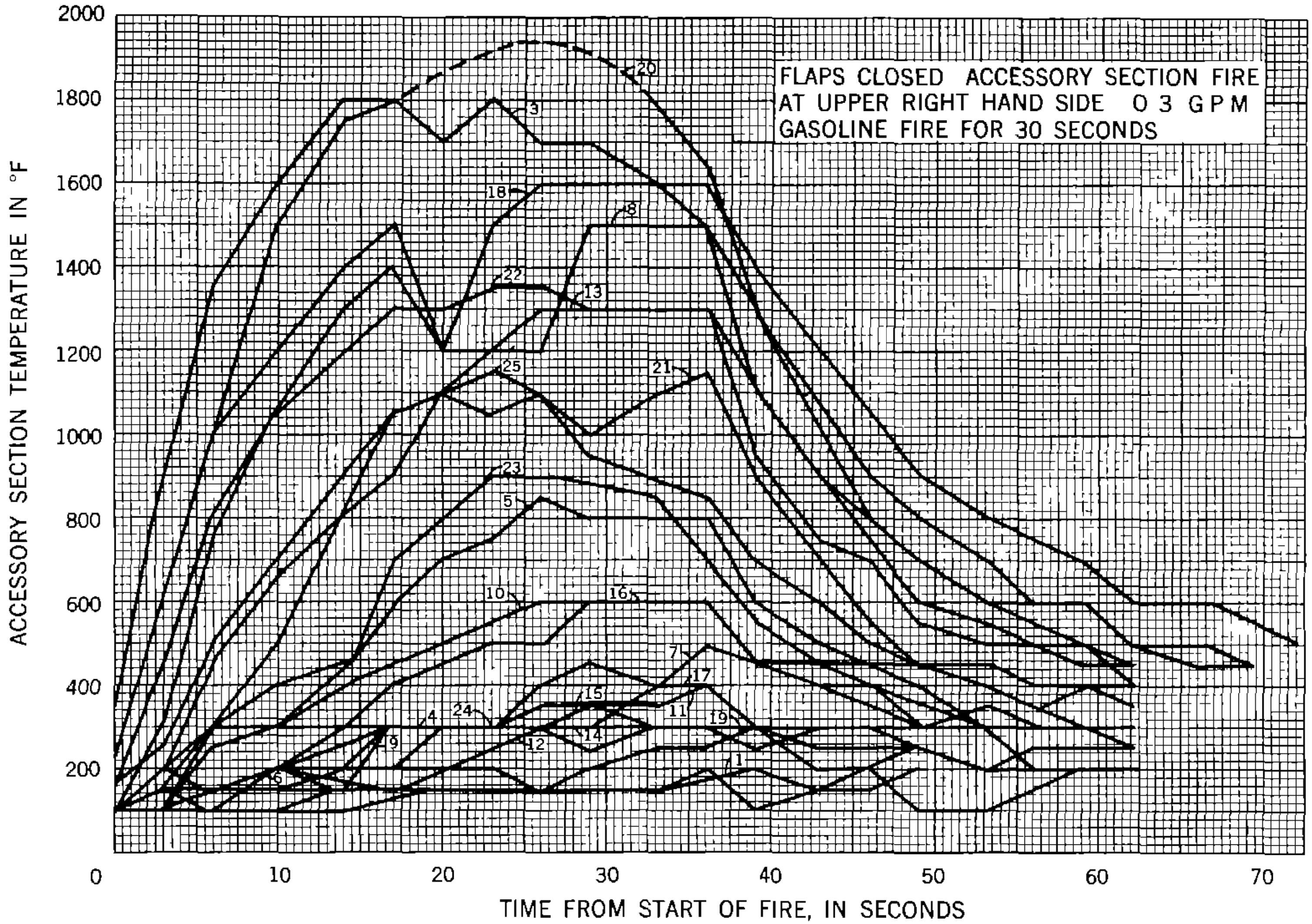


FIGURE 101. Accessory section temperatures vs time
(thermocouple locations shown in figure 97)

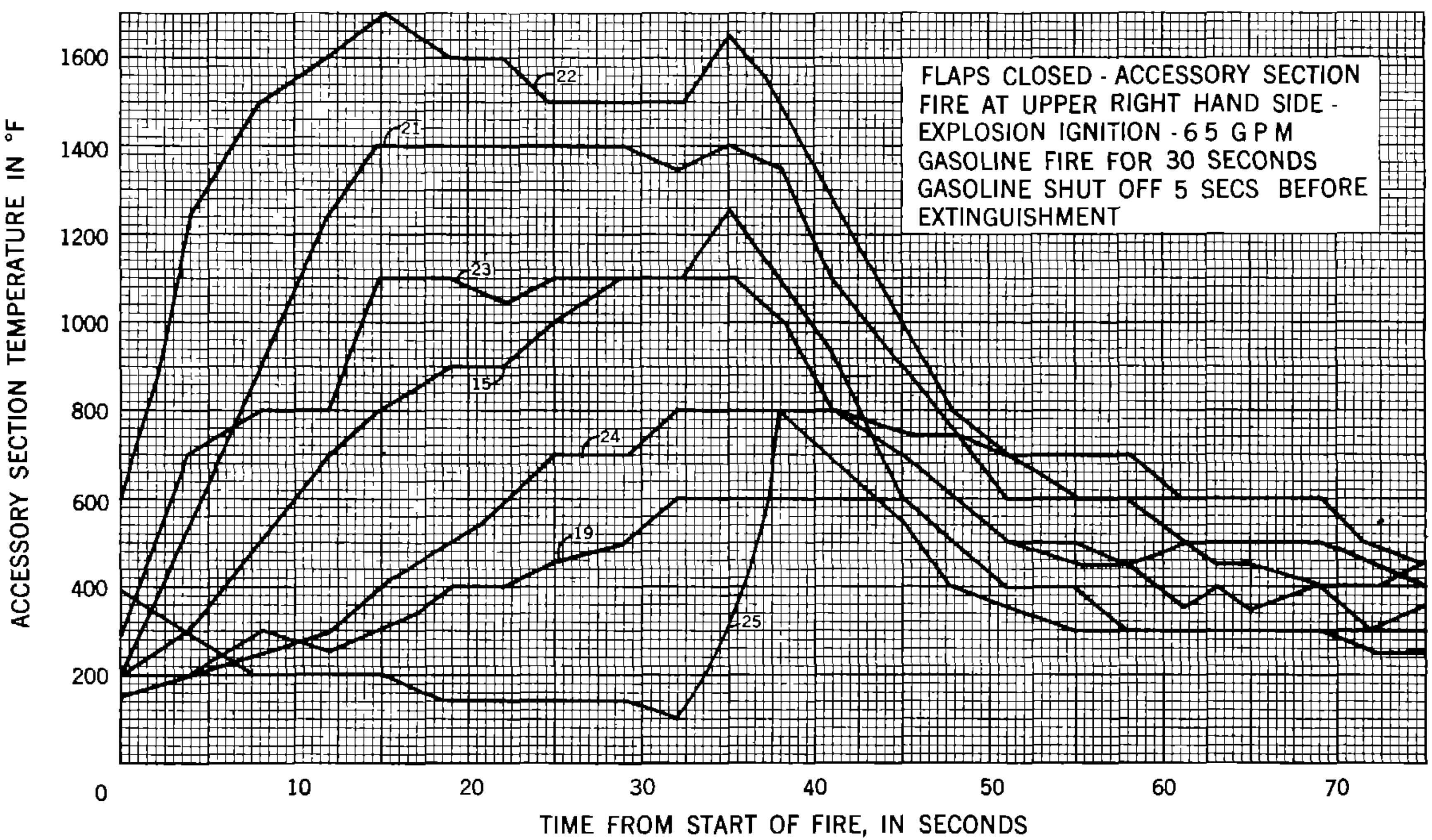


FIGURE 102. Accessory section temperatures vs. time (thermocouple locations shown in figure 97).

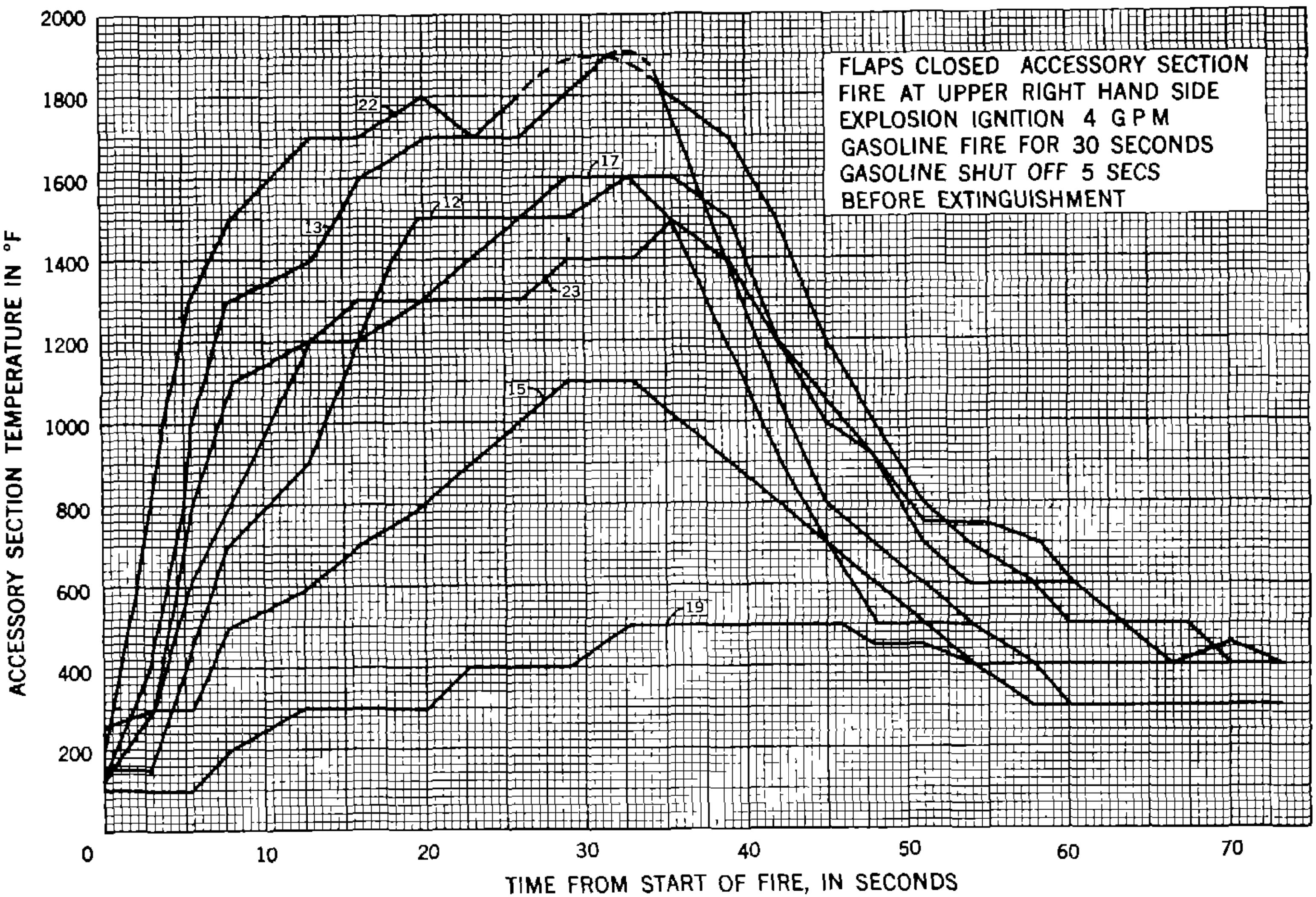


FIGURE 103. Accessory section temperatures vs. time
(thermocouple locations shown in figure 97)

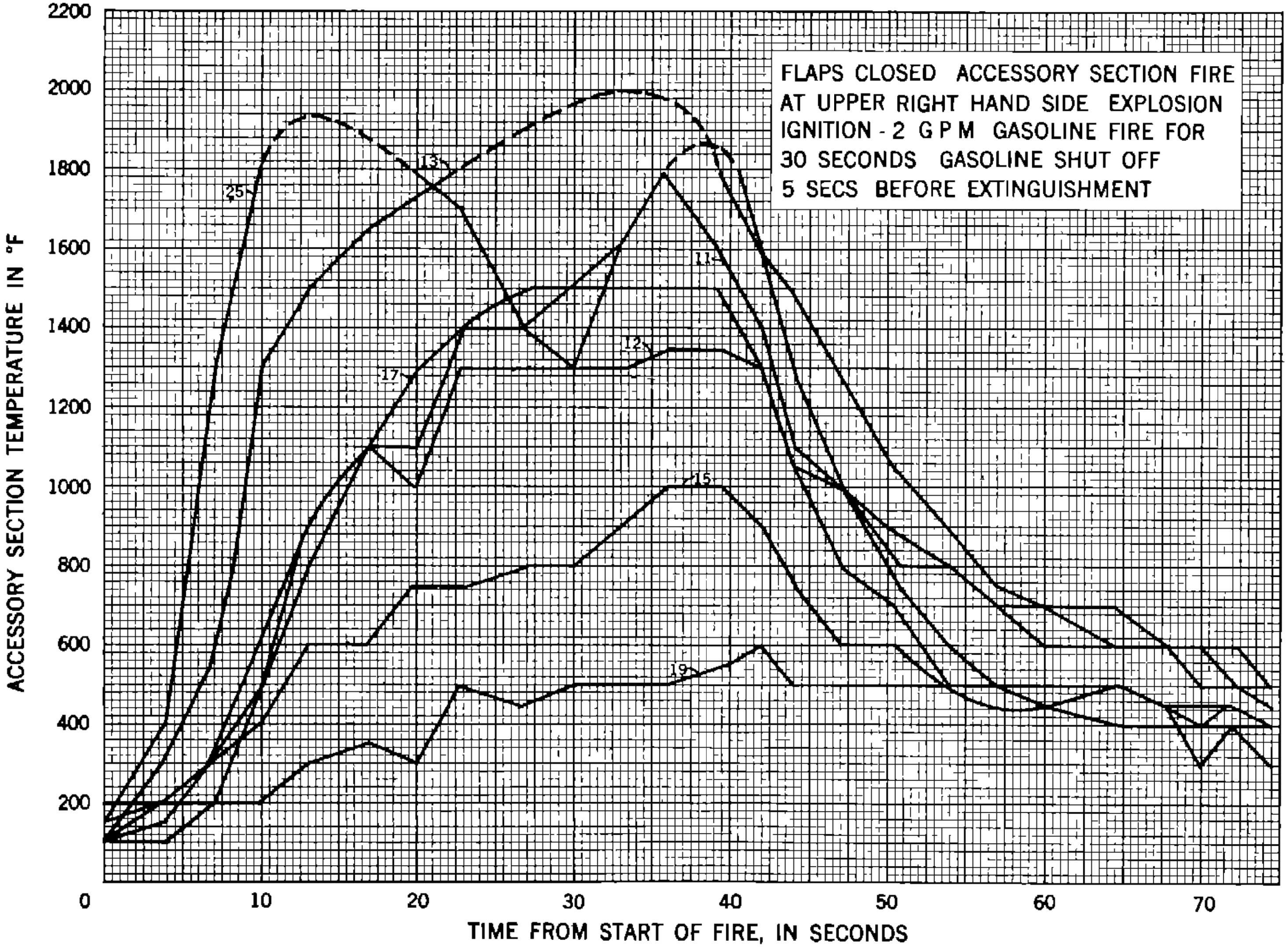


FIGURE 104 Accessory section temperatures vs time (thermocouple locations shown in figure 97)

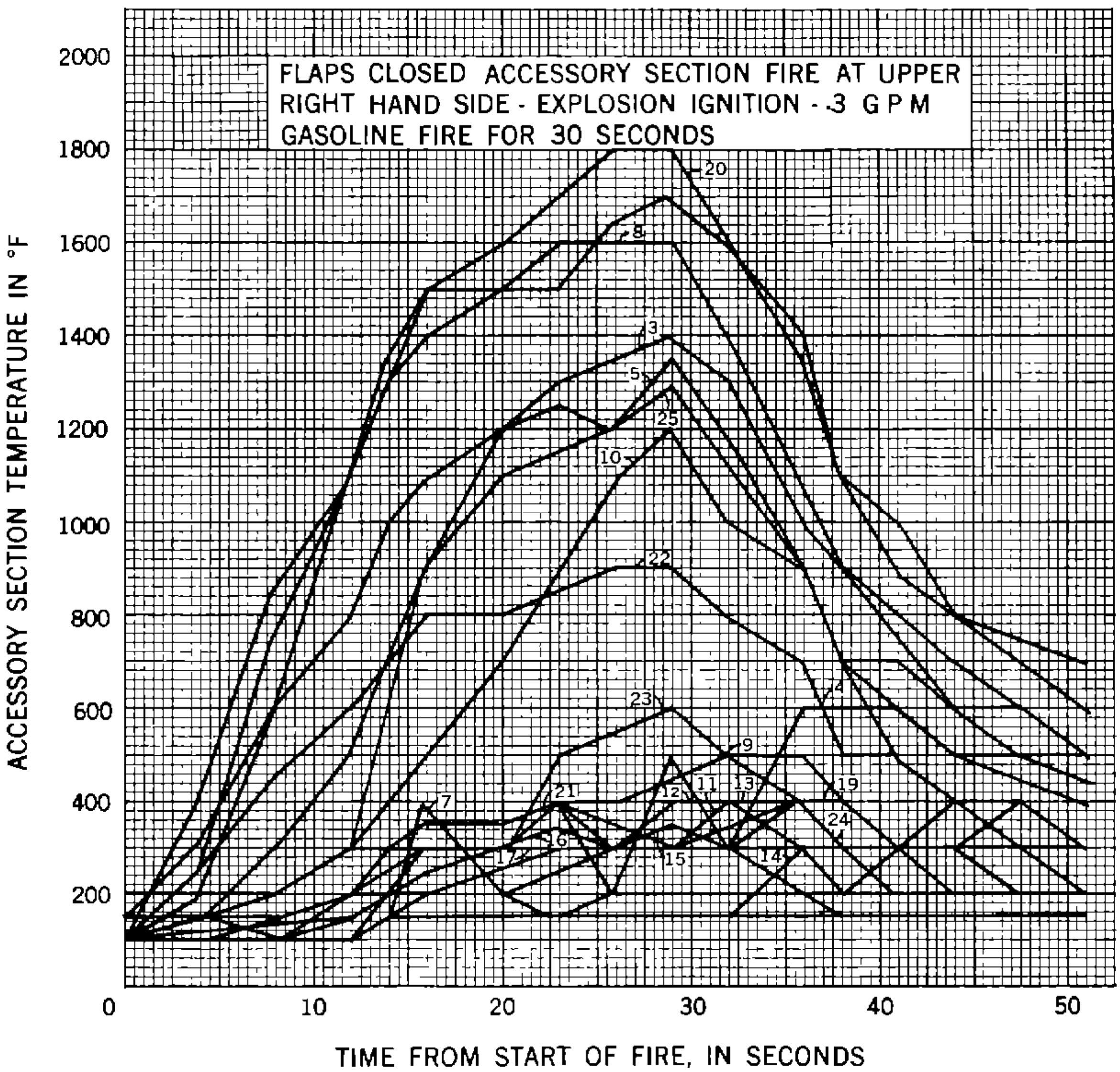


FIGURE 105. Accessory section temperatures vs. time (thermocouple locations shown in figure 97).

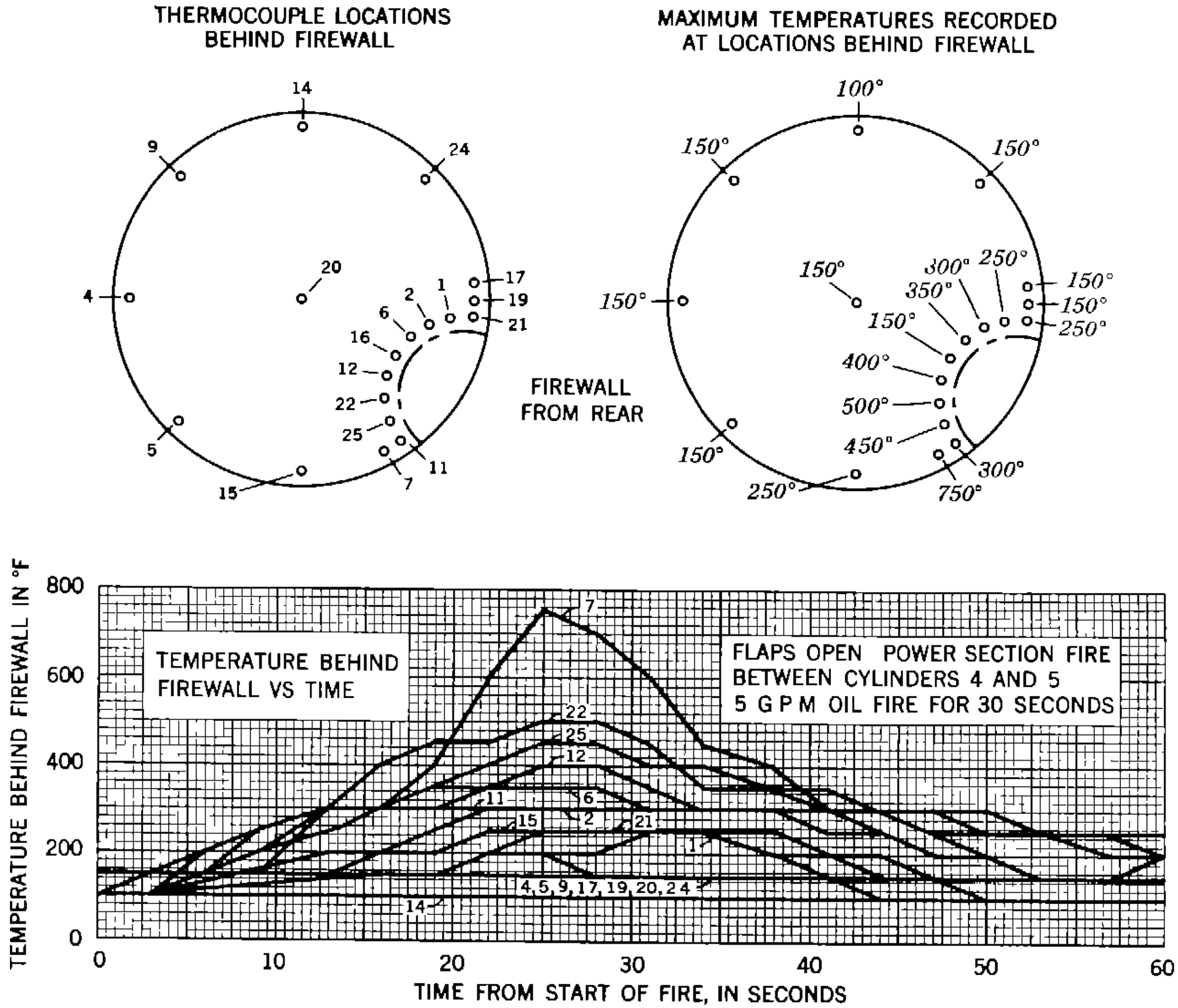


FIGURE 106 Thermocouple locations and highest temperatures recorded behind the firewall under various fire conditions.

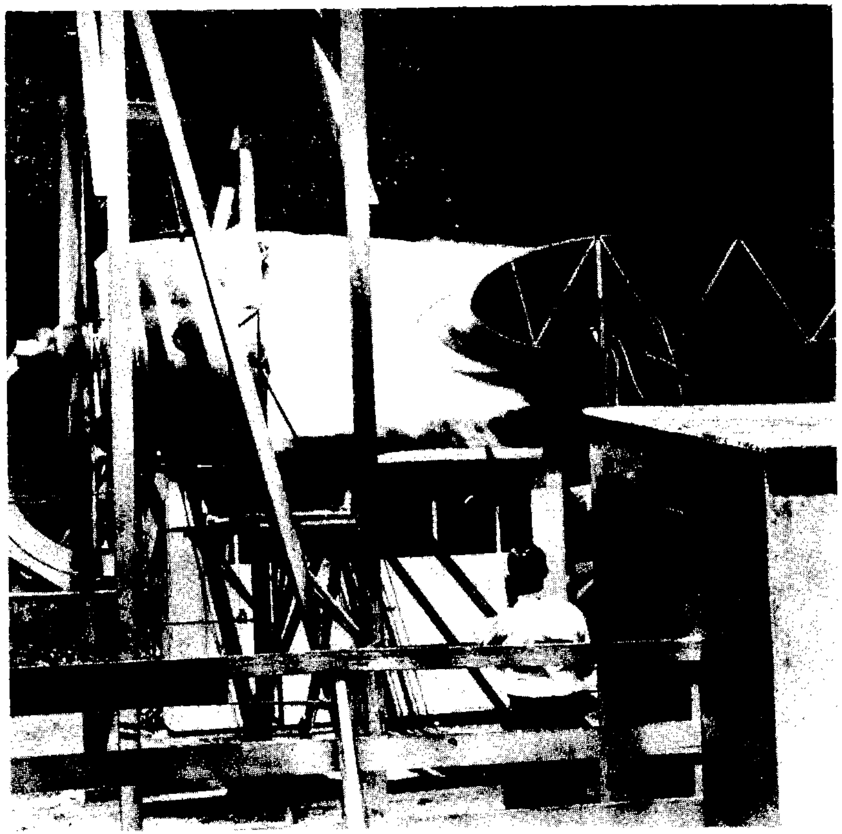


FIGURE 107. Fire pattern showing boundary layer effect.

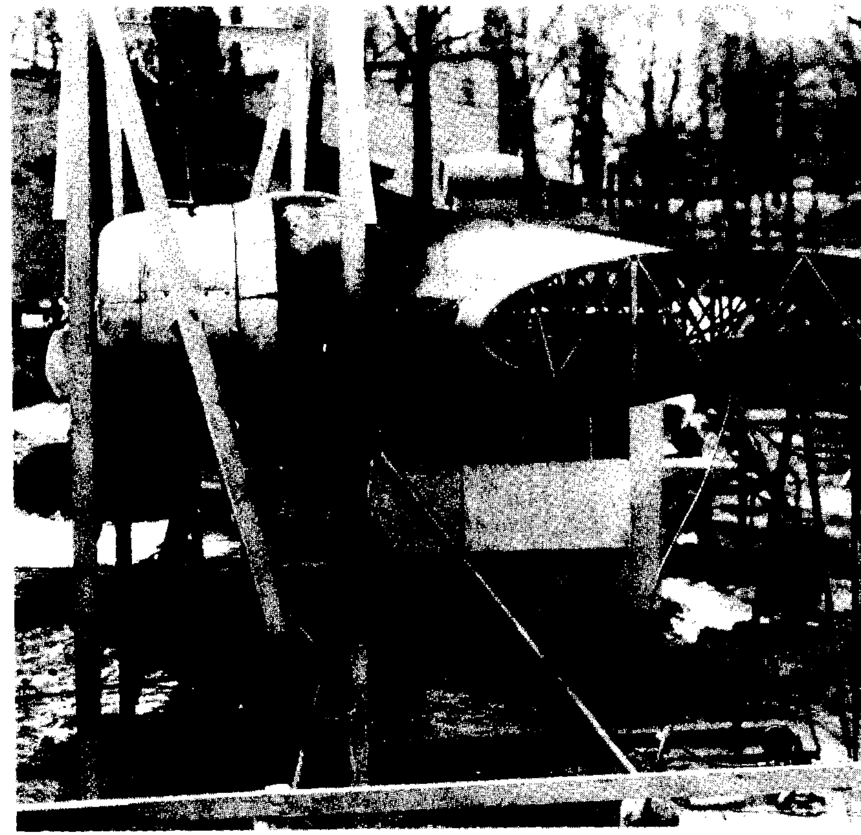


FIGURE 108. Soot pattern showing boundary layer effect.

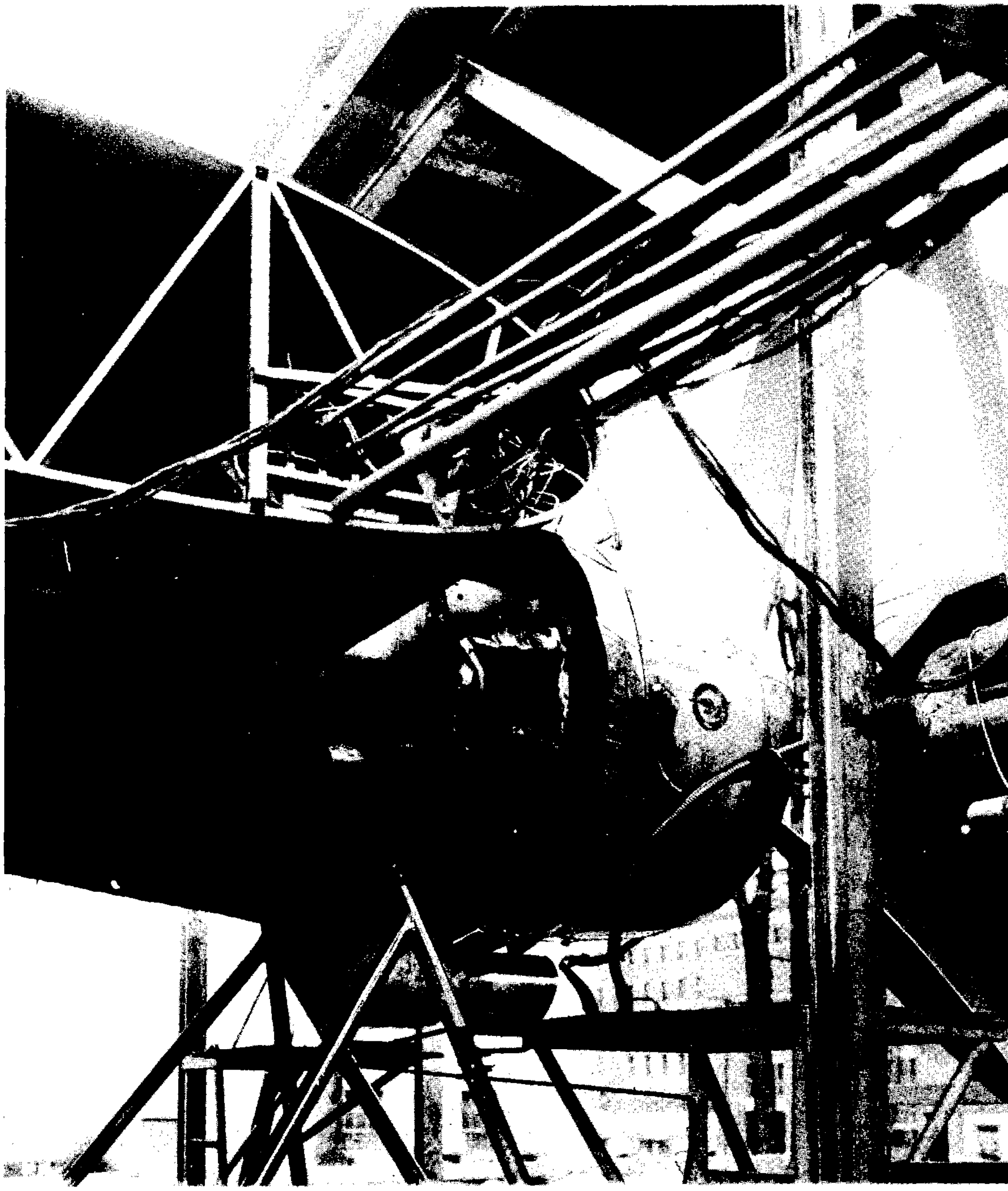


FIGURE 109. Effect of 3 gallons per minute power section oil fire of 30 seconds duration on aluminum alloy accessory section cowl.