AIRCRAFT FIRE EXTINGUISHMENT

PART I
A STUDY OF
FACTORS INFLUENCING
EXTINGUISHING SYSTEM DESIGN

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Technical Development Report No 184

CIVIL AERONAUTICS ADMINISTRATION
TECHNICAL DEVELOPMENT AND
EVALUATION CENTER
INDIANAPOLIS, INDIANA
October 1952

U. S. DEPARTMENT OF COMMERCE

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CIVIL AERONAUTICS ADMINISTRATION

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Manuscript Received April 1952

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SUMMARY

An initial attempt was made to compare a number of aircraft fire extinguishing agents under full-scale test conditions and using standard aircraft fire extinguishing equipment. It was found, however, that the influence of different physical properties of the agents prohibited an absolute comparison. Consequently, a study of factors which influence the aircraft fire extinguishing problem was made. This consisted of preliminary studies of requirements, of variables affecting requirements, and of extinguishing system design factors.

INTRODUCTION

One of the primary phases of aircraft fire protection is fire extinguishment This phase represents, in effect, the last line of defense in the struggle against disaster from flight fires. In those instances where fire preventive measures fail, the ability to control and extinguish aircraft fires spells the difference between a probable safe landing on one hand and death and destruction on the other.

Although considerable progress has been made in recent years toward the development of more effective and less toxic extinguishing agents for Class B and Class C fires, a very definite and serious gap exists in available information regarding the proper and effective application of these agents to aircraft power plant fires.

The designer of aircraft fire extinguishing systems has at his disposal only meager information Much of this is obsolete, having been obtained on relatively small reciprocating-engine power plants in pre-World War II days Consequently, in a majority of cases he must resort to expensive and time-consuming cut-and-try methods Those who must evaluate and approve aircraft extinguishing system installations are equally handicapped in their efforts by the lack of adequate tools and practical specifications to accomplish their task

This report, the first of a series,[1] describes fire extinguishing tests conducted on a Ryan Fireball (Navy FR-4) airplane power plant consisting of a special steel nacelle and a Westinghouse Model 24C-2 turbojet engine which was provided by the Bureau of Aeronautics, Department of the Navy. At the time of procurement of this power plant, the original intent was to conduct a complete and detailed investigation on this installation of all phases of fire protection. However, such rapid strides and changes were made in the field of turbojet power plant design that by the time the installation was ready for testing it had become obsolete, and there existed little similarity between the FR-4 power plant configuration and those of more recent design. As a result the original plan to make detailed fire protection studies on the installation was abandoned, and it was decided to conduct fire extinguishing studies since the steel nacelle provided unusual resistance to damage by fire and could be used repeatedly without requiring extensive repairs

STATEMENT OF PROBLEM

Aircraft fire extinguishment is a complex problem. It is made so by the numerous variables involved, each of which materially affects the solution. Proper extinguishing system design for aircraft power plants requires a knowledge of the requirements, of the influence of variables which affect the fulfillment of those requirements, and of the detailed design factors involved in meeting the requirements. These various phases have been listed below in outline form which permits the referencing of test data to the general problem of fire extinguishment

[1] Similar studies of fire extinguishing systems and their evaluation are under way and will be described in subsequent reports under the same general title, "Aircraft Fire Extinguishment "

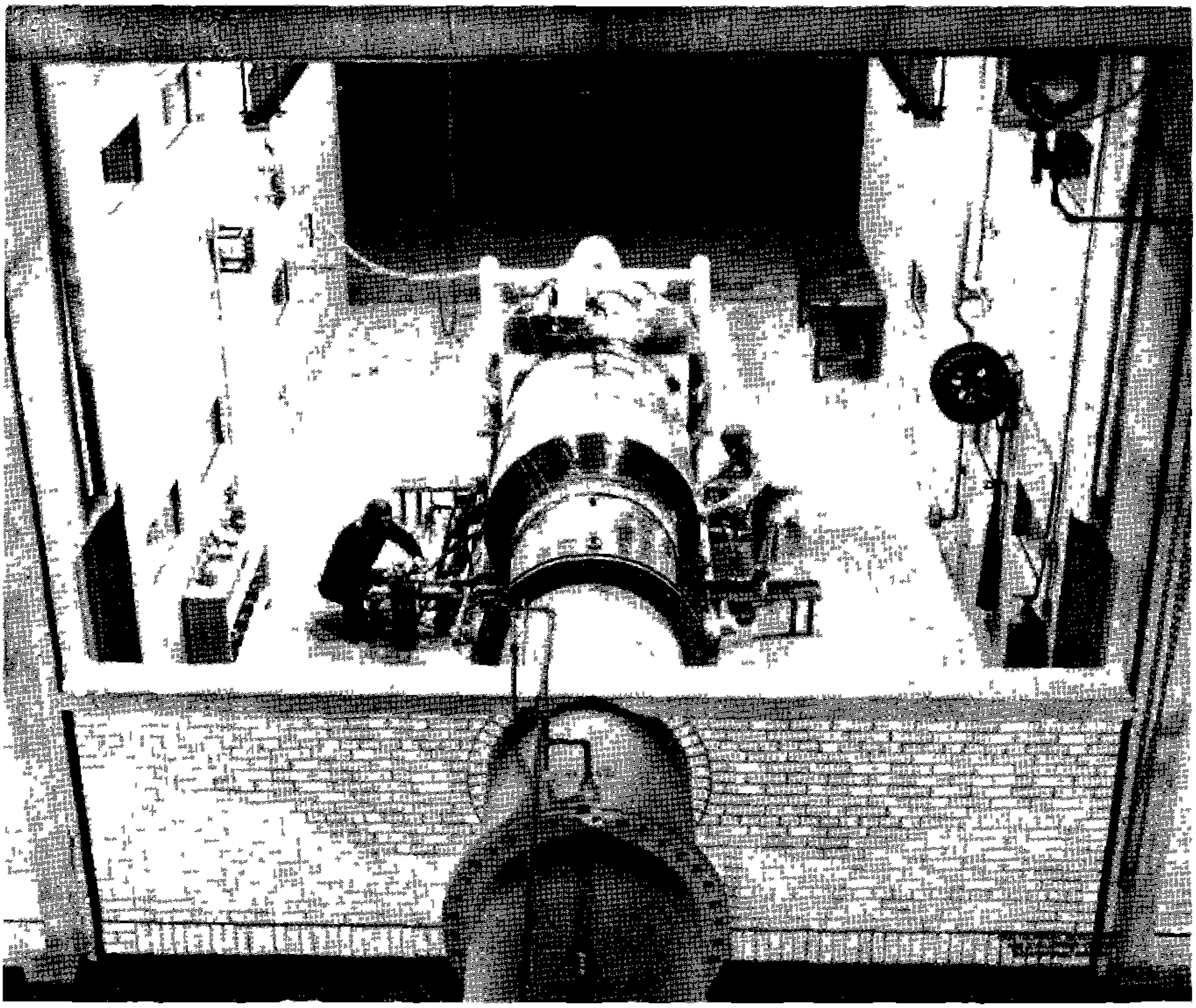


Fig. 1 Top Forward View of Test Cell, Blower Connection, and FR-4 Installation

I Extinguishing requirements
  A. An effective and suitable extinguishing agent.
  B. Adequate concentration of agent
  C. Adequate distribution of agent.
  D Adequate duration of concentration and distribution
  E. Prevention of reignition.

II Variables which affect fulfillment of requirements
  A. Nacelle or compartment configuration.
    1. Size.
    2 Aerodynamic characteristics.
    3 Construction (sealing, drainage, and fire resistance).
  B. Air flow.
  C. The combustible (materials burning).
  D. Duration of fire before extinguishment.
  E. Procedure prior to extinguishment.

III. Extinguishing system design factors.
  A. Extinguishing agent characteristics.
  B. Extinguishing agent container and discharge mechanism.
  C. System feed lines and nozzles.
    1. Effect of line and nozzle sizes
    2. Effect of line length.
    3. Distribution characteristics and the effect of extinguishing system design on efficiency

During recent years considerable emphasis has been placed on the development of more efficient extinguishing agents and has resulted in an indication that a number of halogen compounds, particularly the fluorinated hydrocarbons, would be effective and

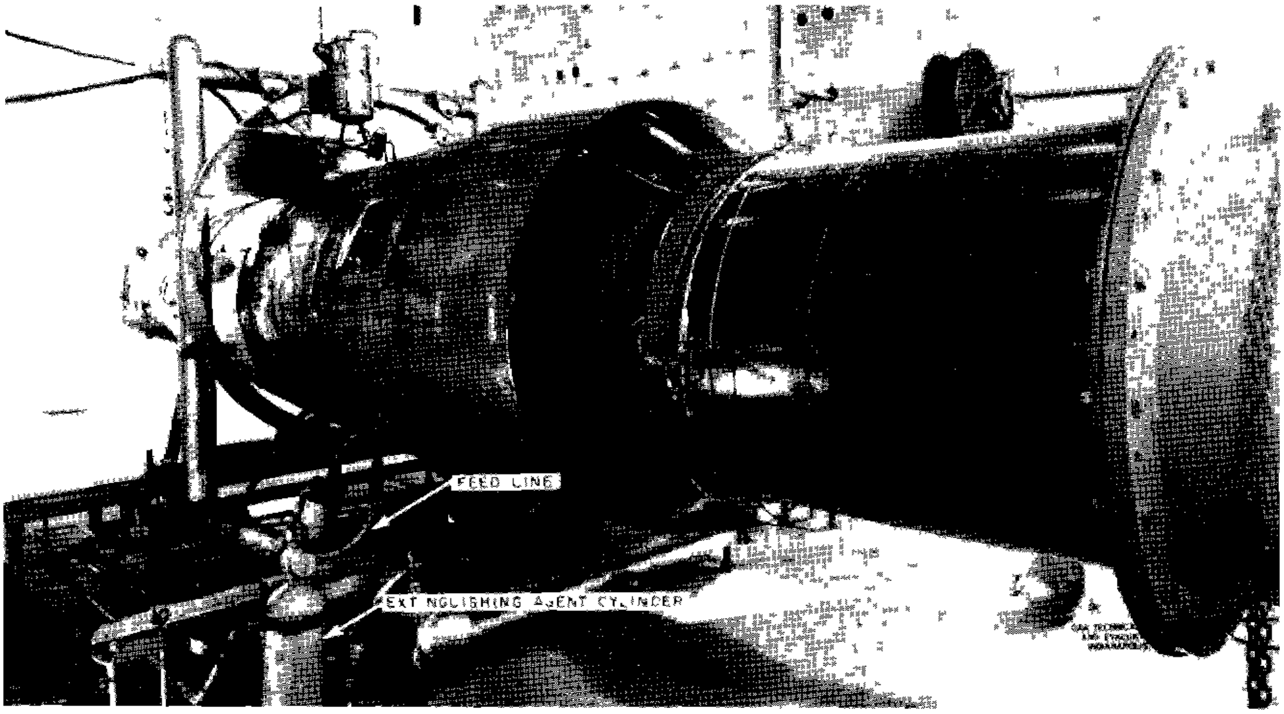


Fig. 2 FR-4 Test Installation Showing Fire Extinguishing Cylinder and Feed Line

possibly suitable agents for use in aircraft. However, the best manner of application and the effectiveness of these and of more commonly known agents under various conditions of environment are yet to be determined, and it is with these aspects of the problem that this report is concerned.

DESCRIPTION OF TEST EQUIPMENT

The fire extinguishing tests were conducted on a Ryan Fireball (Navy FR-4) power plant installation consisting of a Westinghouse 24C-2 jet engine and a specially constructed stainless steel nacelle. Aircraft fire extinguishing agent containers and valves of standard manufacture were used in the tests Extinguishing systems used were fabricated from copper tubing and standard Parker tube fittings

The test facility consisted of a test chamber, a control room, and an air blast supply to the test chamber provided by two large De Laval centrifugal type blowers. A view of the test chamber, test nacelle, and the blower outlet connection to the nacelle is shown in Fig 1 Additional views of the test chamber arrangement are shown in Figs. 2 and 3.

Unlike later designs, the FR-4 jet power plant installation included no fire wall between the compressor and burner sections of the engine and no separation of engine inlet and nacelle cooling air. This permitted reverse flow within the nacelle during ground operation of the airplane and provided generally inadequate protection from fires. The configuration of the test article is illustrated in Fig 4 Ram air was provided to the nacelle air inlet during the tests in order to simulate air flow conditions of flight. Nacelle cooling air is noted to be the ram-air spillage at the engine air inlet

Fig 5 is a view of the front portion of the nacelle section looking forward toward the nacelle air inlet opening. The three mounting brackets for the Westinghouse 24C-2 (J-34) type engine within this section are visible in the figure. The fire extinguisher ring shown was that used for handling fires not otherwise extinguished by experimental systems being tested and was connected directly to the test-chamber Cardox carbon dioxide system. The engine that was installed in the nacelle is shown in Fig 6.

A view of one type of extinguishing agent cylinder and valve used in the tests and the mounting location and feed line used in some cases may be seen in Fig. 2

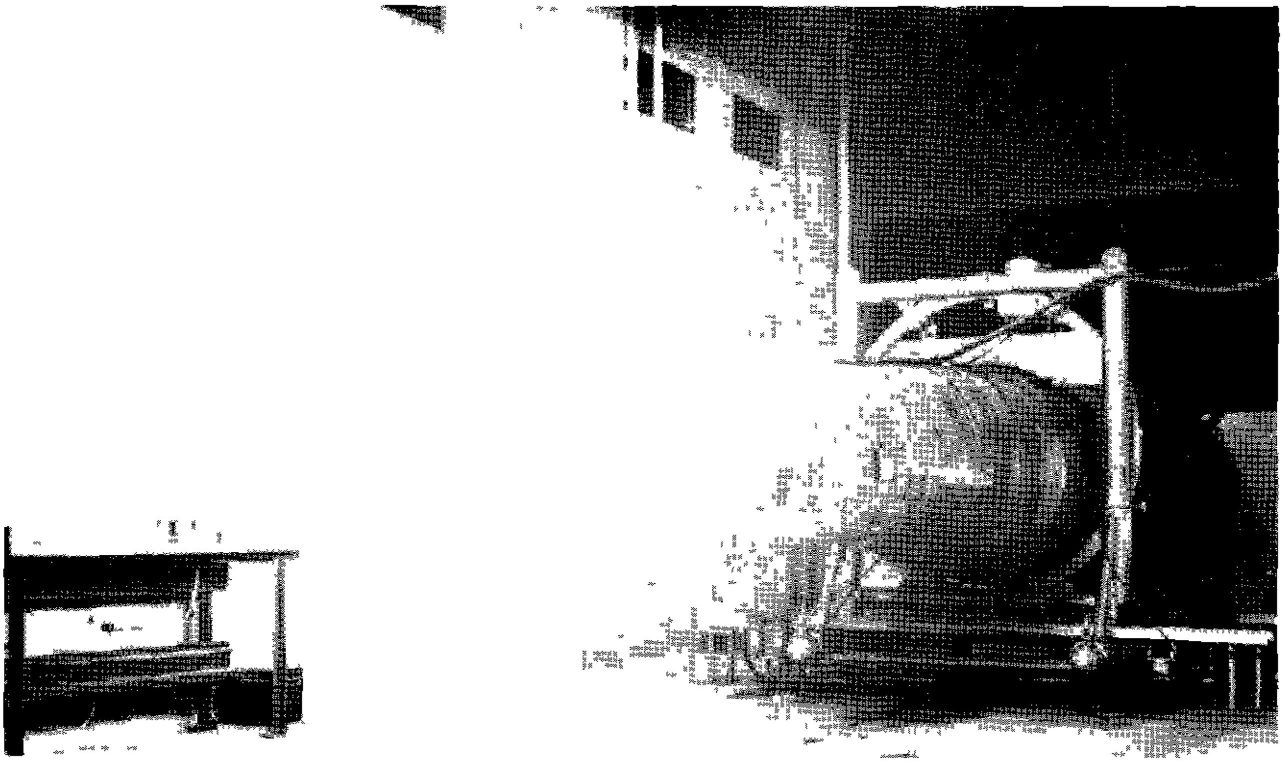


Fig. 3 Rear View of FR-4 Test Nacelle Showing Aft Section Fire Test

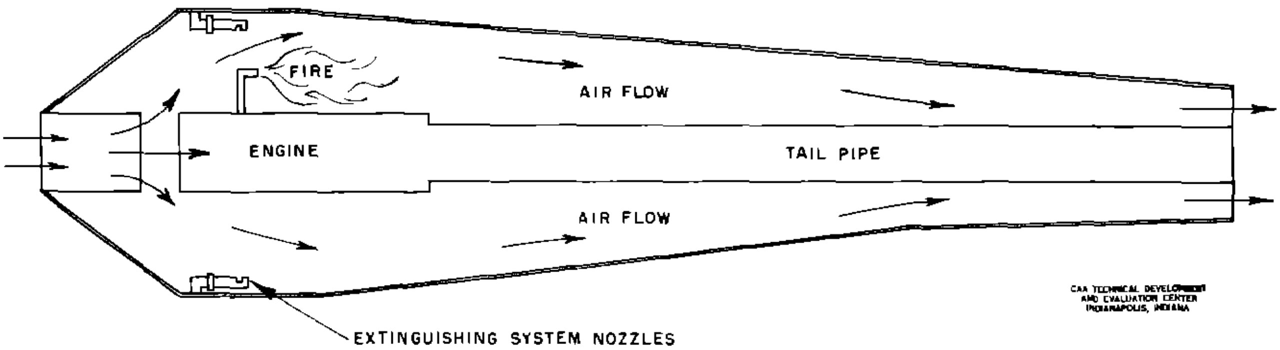


Fig 4 Sectional View of FR-4 (Ryan Fireball) Nacelle Indicating Direction of Air Flow Through the Nacelle and Relating Locations of Fire and Extinguishing System Nozzles Used for Most Tests

PROCEDURE

Although certain conditions varied for different tests, depending on the parameter being studied, a standard procedure was followed in order to eliminate undesirable variables. An automatic sequence panel was utilized to standardize the procedure for each test after desired engine-operating and ram-air conditions were attained. This panel caused the sequence of events shown in Table I. It will be noted that the extinguishing agent was discharged ten seconds after the start of the main fire and that the release of fuel continued for ten seconds after the discharge of the extinguishing agent

The fuel used for most tests was aviation gasoline (grade 100/130) although

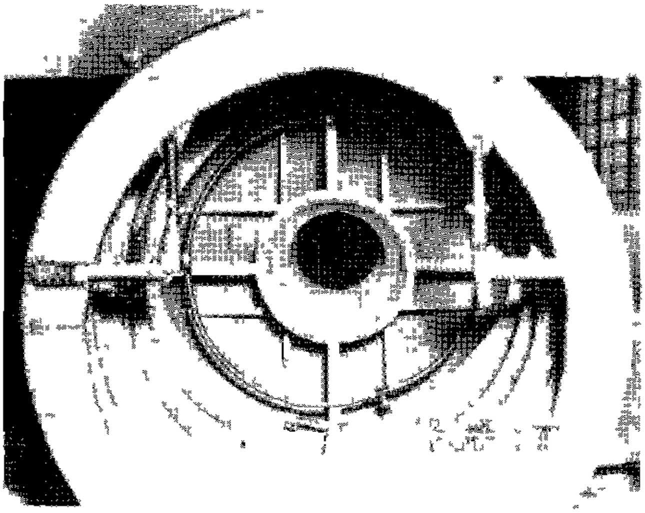


Fig. 5 Internal View of FR-4 Forward Nacelle Section

some tests were conducted using jet engine oil (Univis 54, AAF 3606) preheated to a temperature of 250 to 300° F. Both fuels were discharged through spray nozzles mounted in the nacelle, and ignition was provided by a spark ignitor and primer gasoline spray The aviation gasoline was released at a rate varying from 80 to 100 gallons per hour (gph), 1 3 to 1 7 gallons per minute (gpm), and the oil was released at a rate of 10 gph, 0 17 gpm. It was considered possible that such rates could occur from fuel and oil line failures in jet installations. These rates resulted in severe fires which would have rapidly damaged an aluminum nacelle. For any particular set of conditions, agent requirements were found by conducting a series of test runs and by determining (within one pound) the minimum amount of agent required for extinguishment.

PRESENTATION OF DATA

The tests conducted were of a preliminary nature and were designed to provide indications of the influence of some variables in the problem of aircraft fire extinguishment. The results obtained are hereby presented.

I. Extinguishing Requirements.

Tests were conducted and evaluations made under simulated aircraft flight conditions with reference to determination of effective fire extinguishing agents Detailed studies of the requirements for (B) adequate concentration of agent, (C) adequate distribution of agent, (D) adequate duration of concentration and distribution, and (E) prevention of reignition were not within the scope of this investigation

A. An Effective and Suitable Extinguishing Agent.

A number of well-known fire extinguishing agents and a few agents recently considered for use in aircraft were evaluated under simulated full-scale conditions. Evaluations were made by determining the quantity of each agent required to extinguish a fire which was caused to occur in the upper forward portion of the FR-4 nacelle adjacent to the engine compressor section Aviation gasoline was released through a spray nozzle at a rate of 90 gph and spark-ignited.

TABLE I

FIRE TEST SEQUENCE OF EVENTS

Event No	Event	Time of Occurrence as Timed from Event No 1 (seconds)
1	Panel switch ON	0
2	Ignitor and primer fuel ON	5
3	Main fuel to fire ON	10
4	Ignitor and primer fuel OFF	15
5	Extinguishing agent discharge switch ON	20
6	Main fuel to fire OFF	30

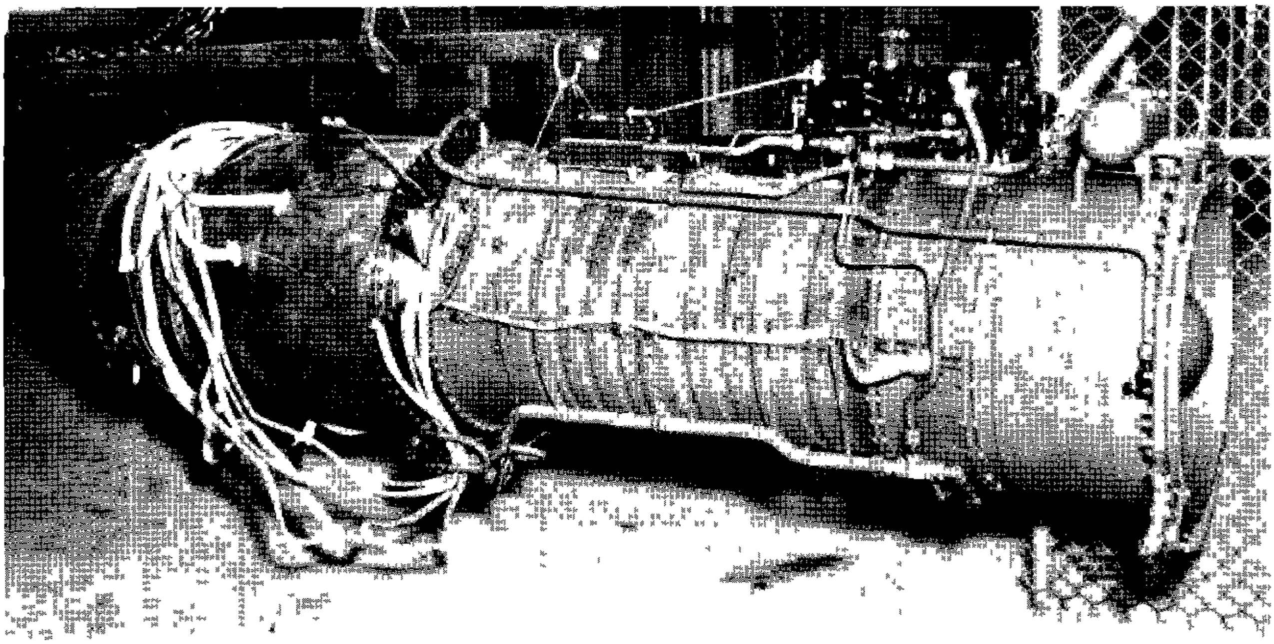


Fig. 6 Westinghouse X24C-2 Jet Engine Installed in FR-4 Nacelle for Fire Tests

During the tests, the engine was operated at 7,000 revolutions per minute (rpm), and air was provided in sufficient quantity to produce 1.0 pound per square inch (psi) of total pressure at the nacelle air entrance duct. Air flow measurements indicated that the air velocity at the fire location was approximately 45 feet per second (fps) and that the rate of air flow was 415 cubic fps. The conditions were such that fuel did not collect in the fire zone but was either burned or carried out by the air. This was desirable since it minimized the influences of nacelle configuration and extinguishing system design.

The extinguishing system used (designated System C) is shown in Fig. 7. The eight discharge nozzles were equally spaced around the periphery of the nacelle, as shown in Fig 4.

With the exception of carbon dioxide and dachlaurin (65 per cent bromochloromethane + 35 per cent carbon dioxide by weight), all agents were discharged from 205-cubic-inch containers equipped with one-inch solenoid-operated flood valves These valves were manufactured by American-LaFrance-Foamite Corp , for use with methyl bromide The cylinders were charged to 400 psi with nitrogen Carbon dioxide and dachlaurin were discharged from standard aircraft carbon dioxide 514-cubic-inch containers equipped with one-inch solenoid-operated flood valves manufactured by Walter Kidde & Company, Inc. The cylinder pressure for dachlaurin was 400 to 420 psi, and for carbon dioxide it was 700 to 800 psi. The agent cylinders were equipped with rigid siphon tubes and were discharged from an upright position

Results of the tests conducted are given in Table II. The values listed as the quantities required for extinguishment are the minimum amounts (within ± one pound) which would repeatedly extinguish the fire.

One of the relationships on which information is needed is that between agent evaluation tests made under controlled laboratory conditions and those made under full-scale conditions In Table III, the results obtained at the Purdue Research Foundation[2] are compared with test results on the FR-4 nacelle. The Purdue tests were essentially an evaluation of various agents in gaseous form by a method whereby the volume percentage quantity of the agents in combustible mixtures of n-heptane and air needed to prevent spark ignition were determined An indication of the relationship of results obtained by the two methods is provided by the table Relative values of the effectiveness of

[2]R. C Downing, B J. Eiseman, Jr , and J E. Malcolm, "Halogenated Extinguishing Agents," National Fire Protection Association Quarterly, October 1951

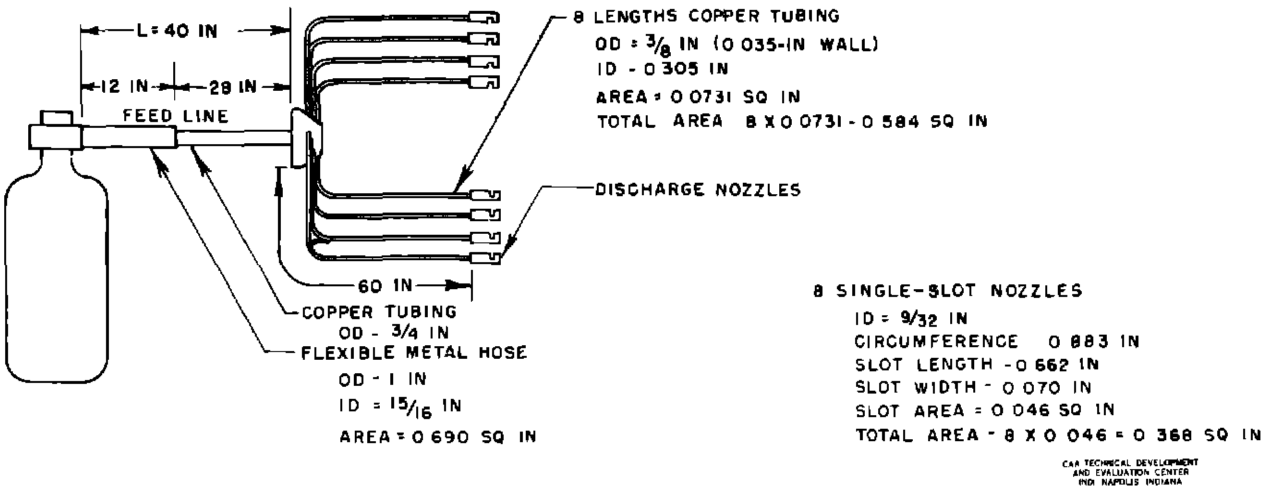


Fig. 7 Extinguishing System C

TABLE II

AGENT REQUIRED TO EXTINGUISH FR-4 NACELLE FIRE WITH FULL-SCALE EXTINGUISHING EQUIPMENT

Agent	Chemical Formula	Boiling Point (degrees F)	Quantity Required For Extinguishment (pounds)
Methyl bromide	CH_3Br	40	3
Bromochloromethane	CH_2BrCl	156	3
Dachlaurin	$CH_2BrCl + CO_2$*	-	3
Bromoform (tribromomethane)	$CHBr_3$	304	3
1,2-dibromotetrafluoroethane	$CBrF_2CBrF_2$	117.5	4
Carbon tetrachloride	CCl_4	170	7
Carbon dioxide	CO_2	-112	10

*Dachlaurin = 65 per cent bromochloromethane + 35 per cent carbon dioxide by weight.

the agent are listed and were determined by arbitrarily assigning a value of 100 to methyl bromide and by then calculating the relative effectiveness of each agent from the test results.

Another comparison of results obtained by different test methods is provided by Table IV The second column of this table lists the agent concentrations that were found necessary to extinguish fire in tests conducted by the German Luftwaffe[3] in a miniature wind tunnel. The third column lists the concentrations required to prevent ignition of a flammable mixture of n-heptane

[3]TR 276-45 of U S Naval Technical Mission in Europe, "Use of Monochlorobromomethane by the German Navy and Air Force as a Fire Extinguishing Agent," September 1945

TABLE III

COMPARISON OF FR-4 POWER PLANT FIRE EXTINGUISHING TEST RESULTS WITH THE PURDUE RESEARCH FOUNDATION TESTS

Agent	Weight Effectiveness (Methyl Bromide = 100)	
	FR-4 Power Plant Tests (per cent)	Purdue Tests (per cent)
Methyl Bromide	100	100
Bromochloromethane	100	94
1,2-dibromotetrafluoroethane	75	72
Carbon tetrachloride	43	52
Carbon dioxide	30	71

and air. The values listed are results of the Purdue tests.

The Luftwaffe tests were conducted in a 600-millimeter (mm) wind tunnel with an air velocity of 46 fps, or 31 miles per hour (mph) Agent discharge rate ranged from 2.2 to 4 4 pounds per second, and the combustible was gasoline

The FR-4 power plant test results given in Table II show that methyl bromide, bromochloromethane, bromoform, and dachlaurin were equally effective in extinguishing the gasoline fires and superior to the other agents tested Carbon dioxide and carbon tetrachloride were definitely less effective than the aforementioned agents. It is believed that the extinguishing system used may have been farther from the optimum for carbon dioxide than for the other agents tested, which fact may partially account for the relative ineffectiveness of this agent.

It may be noted in Table II that the halogenated agents having the lowest and the highest boiling points were among those found most effective This is an indication that the extinguishing system used in the tests provided mechanical atomization to a sufficient degree that test results on these agents were not critically affected by the boiling point

The results of the tests on halogenated agents, shown in Table III, indicate that a direct relationship exists between the two test methods used Such a relationship is an indication that both methods measure essentially the same property and that the Purdue method of evaluation produces results which correspond to those obtained under actual full-scale conditions existing in aircraft

The comparison that is provided by Table IV indicates the existence of a direct relationship between results obtained by the Purdue test method and the German Luftwaffe wind tunnel test method The consistently higher agent concentrations required in the case of the wind tunnel extinguishing tests may possibly be attributed to expected lower distribution and atomization efficiencies

The agreement noted between the relative effectiveness of different halogenated agents was obtained by three different methods and conditions This agreement substantiates the FR-4 power plant test results and also indicates that such results may not be peculiar to the particular conditions of testing

II Variables Which Affect Fulfillment of Requirements

As shown previously under "Statement of Problem," the variables which affect the fulfillment of fire extinguishing requirements include (A) the nacelle or compartment configuration, (B) the air flow through the compartment, (C) the combustible or materials that are burning, (D) the duration of the fire before extinguishment is attempted, and (E) the procedure prior to extinguishment Tests on the FR-4 nacelle included a limited study of the variables (A), (B), and (C) only

A Nacelle or Compartment Configuration

Tests conducted on the FR-4 power plant did not include detailed studies of the effect of nacelle design on extinguishing requirements However, the influence and importance of certain nacelle design factors

TABLE IV

COMPARISON OF WIND TUNNEL FIRE EXTINGUISHING TEST RESULTS WITH THE PURDUE RESEARCH FOUNDATION TESTS

Agent	Luftwaffe Tests	Purdue Tests
	Agent Concentration Required to Extinguish Gasoline Fire in Wind Tunnel (per cent by volume)	Agent Concentration Required to Prevent Ignition at Flammability Peak of n-Heptane and Air (per cent by volume)
Methyl bromide	15	9.7
Bromochloromethane	15	7 6
Dachlaurin ($CH_2BrCl + CO_2$)	12 - 15	-
Carbon tetrachloride	30	11.5
Dichlorodifluoromethane	35	14.9
Carbon dioxide	45	29.5

on requirements were indicated and are stated below.

1. Size.

Although this investigation did not include studies of the effect of compartment volume, the unusually long compartment provided by the FR-4 nacelle permitted a study of the influence of the longitudinal dimension of the compartment on extinguishing requirements. Utilizing an extinguishing system which discharged the agent into the air stream between the engine and the nacelle, as shown in Fig. 4, it was found that downstream locations of oil fires increased the extinguishing requirements The tests utilized extinguishing System C and were conducted with fires located at Location 1, approximately three feet downstream of the agent discharge location (see Fig 4), and Location 3, approximately ten feet downstream of the agent discharge location Results of the tests are shown in Table V

This data shows that agent requirements were not increased poundwise by the remote Location 3 for gasoline fires but were appreciably increased in the case of gasoline and oil fires The data also shows that methyl bromide was superior to bromochloromethane for extinguishing oil fires at Location 3 The tendency of oil to settle and drain away from the air stream and to collect at turbulent areas outside the air stream probably was the reason why agent requirements at fire Location 3 were greater for oil fires than for gasoline fires

TABLE V

EFFECT OF LENGTHWISE FIRE LOCATION ON EXTINGUISHING AGENT REQUIREMENTS

Fire Location	Gasoline Fires		Gasoline and Oil Fires	
	Methyl Bromide (pounds)	Bromochloromethane (pounds)	Methyl Bromide (pounds)	Bromochloromethane (pounds)
1*	3	3	3	3
3**	3	3	4	5

* Location 1 – 3 feet downstream of agent discharge nozzles
** Location 3 – 10 feet downstream of agent discharge nozzles

TABLE VI

EFFECT OF AIR FLOW ON AGENT REQUIREMENTS
FOR EXTINGUISHMENT OF FR-4 POWER PLANT FIRES

Total Pressure Nacelle Entrance (psi)	Calculated Velocity of Air at Fire Location (fps)	Calculated Volume Air Flow Through Nacelle (cubic fps)	Agent Required for Extinguishment	
			Methyl Bromide (pounds)	Bromochloromethane (pounds)
0.6	31	298	2	2
1 0	44	415	3	3

The increase in agent requirements at the more remote location in the case of oil fires was probably due to less efficient distribution downstream and loss of the agent during downstream travel These effects apparently were greater for bromochloromethane than for methyl bromide, as might be expected from the higher boiling point and lower volatility of the former.

2. Aerodynamic Characteristics

Fire extinguishing tests on the FR-4 nacelle indicated that the use of transverse structural ribs in the lower parts of the nacelle may greatly increase extinguishing requirements Such ribs provide areas of turbulence which are protected from the air stream and in which fuel and oil can collect and burn Agents discharged into the main air stream, even in excessive quantities, can frequently fail to reach such areas, and the remaining small fire becomes the ignition source for reflash as soon as the extinguishing agent is carried out of the compartment. The distribution of the agent to these areas is a difficult problem and seriously complicates extinguishing system design.

3 Construction (Sealing, Drainage, and Fire Resistance).

With regard to nacelle sealing, it was observed that the presence in the nacelle skin of open joints, cracks, or holes that allow fuel or oil to escape to the outside nacelle surface or to an area outside the compartment may cause reflash or explosion It was noted that burning fuel may leak out of such openings and not be extinguished even though all fire inside the compartment may have been put out If there exists a combustible mixture after the compartment clears of the extinguishing agent, the small external fires provide ignition through the openings This condition can nullify the results of an otherwise effective extinguishing system and may increase design requirements considerably

B. Air Flow.

A detailed study of the effect of air flow on fire extinguishing requirements was not within the scope of this investigation. However, the few tests conducted on this phase of the problem indicated that increased air flow appreciably increases requirements

Agent requirements for extinguishing gasoline fires in the FR-4 power plant were determined under conditions similar to those previously described in Item I. Two air flow conditions represented by total pressures of 0 6 and 1 0 psi at the nacelle entrance yielded the data shown in Table VI. The test results indicate that agent requirements were appreciably greater for the higher air flow condition The sensitivity of the test method was insufficient to permit other than a general indication of the effect of increased air flow.

C. The Combustible (Materials Burning)

The effect of the combustible on fire extinguishing requirements was investigated briefly by conducting tests in which aviation gasoline and a light jet engine lubricating oil (Univis 54, AAF 3606) were used as fuel for the fire to be extinguished Tests included a determination of the quantity of the agent required to extinguish both gasoline and oil fires at three nacelle locations that were Location 1, above the engine compressor section, Location 2, below the engine compressor section, and Location 3, above the tail pipe and approximately seven feet aft of the two other locations

The amount of agent required agreed within ± one pound for the two combustibles at Location 1 under conditions in which the combustibles were sprayed from nozzles, and there was little or no drainage or collection of excess combustible in the fire zone.

Agent requirements were greater for oil fires than for gasoline fires at Locations 2 and 3. From observations of numerous tests, this was partly attributed to the greater tendency of oil to settle out of the main air stream and remain in the nacelle compartment. This tendency promoted the occurrence of small localized fires in protected areas and resulted in reflash. Sprayed gasoline even when released in relatively large quantities would burn rapidly, and its high volatility resulted in rapid evaporation and dissipation by the air stream. The tendency for it to collect in the nacelle was appreciably less, thus greatly reducing the reflash problem. In general, extinguishing requirements were indicated to be more severe for oil fires than for gasoline fires because of the much greater tendency of oil to remain in the nacelle and cause reflash

III. Extinguishing System Design Factors.

Fire extinguishing tests conducted on the FR-4 nacelle included limited studies of (A) extinguishing agent characteristics, (B) agent container and discharge mechanisms, and (C) system feed lines and nozzles. The results of these studies follow.

A. Extinguishing Agent Characteristics.

The effectiveness of methyl bromide and bromochloromethane as fire extinguishing agents, when they were at sub-zero temperatures, was determined by full-scale tests. Fire extinguishing tests were conducted under conditions similar to those described in Item IA, except that cylinders charged with the agent were submerged in dry ice overnight before each test Under the testing conditions it was observed that (a) the cylinder pressure was somewhat reduced by the lower temperatures, and (b) the effectiveness of the two agents was not appreciably reduced by the lower temperatures when using the same discharge pressure

B Extinguishing Agent Container and Discharge Mechanism.

Siphon Tubes.

A brief series of tests was conducted under conditions similar to those of the agent evaluation tests in which the effectiveness of bromochloromethane was determined when discharged from cylinders 205 cubic inches in volume, with and without siphon tubes The cylinders not equipped with tubes were mounted in the inverted position.

As a result of using cylinders inverted and without siphon tubes, the quantity of agent required for extinguishment was reduced from three to two pounds in these particular tests The percentage of agent lost in this instance was probably greater than in cases where a conventional cylinder fill ratio is used However, the desirability of using inverted cylinders rather than siphon tubes for maximum effectiveness was indicated

Cylinder Size, Fill Ratio, and Charging Pressure.

The size, fill ratio, and charging pressure of the cylinder or container used with a fire extinguishing system determine the propulsive force applied to an agent other than carbon dioxide during discharge. Since an adequate rate of discharge depends upon this force, container pressurization of agents such as methyl bromide and bromochloromethane is of prime importance.

In numerous instances, results of fire extinguishing tests conducted on the FR-4 power plant emphasized the necessity for consideration of propulsive requirements as well as agent quantity requirements in extinguishing system design Whether from a reduced initial charging pressure, lowered cylinder temperatures, or greater system volume, it was found that a reduction in nozzle discharge pressure below the minimum value required to give adequate rate of discharge caused the system to become ineffective. Increased quantities of agent in these instances did not improve the extinguishing effectiveness.

With the use of liquid agents, present practice is to provide propulsive force by using a volume of nitrogen pressurized to 400 psi at 70° F and equal to the volume of agent used. Such practice may result in inadequate propulsion and inadequate rate of agent discharge in cases where the volume of the extinguishing system is large or where the cylinder temperature at the time of discharge is low. It does not consider the fact that propulsive requirements are a function of extinguishing system volume.

An alternative and more logical basis for design is the selection of container size by using the sum of agent volume requirements and nitrogen volume requirements. It is reasoned that rate of discharge from a system is directly related to initial and final liquid discharge nozzle pressures, whereas no direct relationship exists between agent and pressurization requirements Assuming a constant temperature expansion of gas, the pressurized gas volume needed may be calculated from the relationship

$$P_1V_1 = P_2V_2$$

where

P_1 = Minimum cylinder pressure to be available at the minimum operating temperature, psi

P_2 = Minimum nozzle static pressure required at the instant of final agent discharge, psi

V_1 = Required initial volume of gas in the cylinder, cubic inches

V_2 = Final volume at pressure P_2

Then by letting

V_a = Volume of agent required, cubic inches

V_c = Volume of cylinder, cubic inches

V_s = Volume of system exclusive of cylinder, cubic inches

the following relationships may be written

$V_c = V_1 + V_a$, cubic inches

$V_2 = V_c + V_s = V_1 + V_a + V_s$, cubic inches

Then by substitution

$$V_1 = \frac{P_2V_2}{P_1} = \frac{P_2(V_1 + V_a + V_s)}{P_1}$$

$$V_1P_1 = P_2V_1 + P_2(V_a + V_s)$$

$$V_1(P_1 - P_2) = P_2(V_a + V_s)$$

and therefore

$$V_1 = \frac{P_2(V_a + V_s)}{P_1 - P_2}$$

Also

$$V_c = V_1 + V_a = \frac{P_2V_s + P_1V_a}{P_1 - P_2}$$

Cylinder charging pressure at room temperature may be determined from the value of P_1 and from the pressure-temperature relationship of the nitrogen or other pressurizing gas used

Such a method assumes a knowledge of the nozzle pressure requirements which depend on the extinguishing agent and the system used and on the rate of discharge required. However, by estimating a satisfactory value of P_1 which will produce a sufficient rate of discharge (for the tests conducted, a value of 250 psi was ample), the calculated values of cylinder size and gas volume required will take into account the volume of the system and the temperature effect on pressure. This is therefore considered a more logical method than the arbitrary use of a 50 per cent fill ratio, $\frac{V_a}{V_c}$. This method is by no means a final answer to the problem and provides at best an approximation It does recognize the need for propulsive requirements as well as for agent quantity requirements in the design of an extinguishing system.

C System Feed Lines and Nozzles.

An extinguishing system must provide delivery of an effective agent in sufficient quantity. It should also provide an optimum rate of discharge and an optimum distribution of the agent. The use of proper feed line and nozzle sizes is essential to successful extinguishing system design in these respects. Little information is available to aid in the proper design of extinguishing systems.

Fire extinguishing tests conducted on the FR-4 power plant included preliminary studies of the influence both of line and nozzle sizes and of line length on system effectiveness The distribution characteristics of different types of systems were also determined

1. Effect of Line and Nozzle Sizes.

Fire extinguishing tests using extinguishing systems of the same general configuration but having different line and discharge nozzle sizes were conducted on the FR-4 power plant The influence of line and nozzle sizes on system effectiveness was measured by determining the quantity of agent required for extinguishment in each case The test procedure was the same as previously described, using aviation gasoline as fuel. Tests were conducted on the systems shown schematically in Figs. 7 and 8 and designated Systems B-1, B-2, B-3, and C Standard 205-cubic-inch carbon dioxide cylinders that were equipped with one-inch

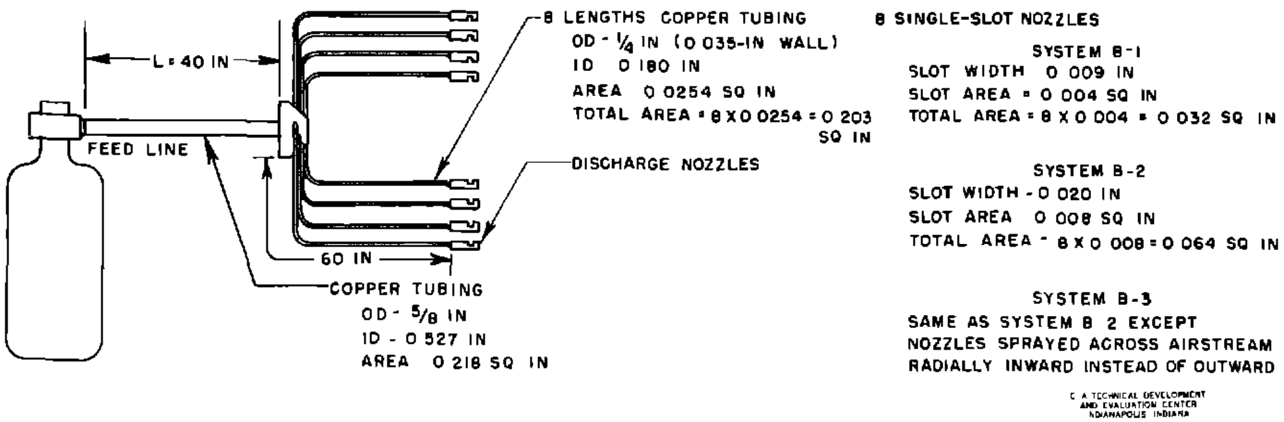


Fig. 8 Extinguishing Systems B-1, B-2, B-3

methyl bromide type flood valves were used where the quantity of the agent was five pounds or less. Otherwise, 646-cubic-inch cylinders were used In every case the agent was pressurized to 400 psi with nitrogen Results were obtained on methyl bromide and bromochloromethane, as given in Table VII They indicate that the line and nozzle sizes used in the construction of methyl bromide and bromochloromethane systems are of critical importance Line and nozzle sizes differing from the optimum may seriously affect the rate of flow and consequently would affect agent requirements If the rate of flow is excessively restricted, the system becomes ineffective even when using large quantities of an agent. It will be noted from the data of Table VII that the efficiency of System B-1 was improved by increasing the nozzle area (shown under System B-2), by changing the location of nozzles (shown under System B-3), and by increasing line areas (shown under System C).

The test results also indicate that

TABLE VII

EFFECT OF LINE AND NOZZLE SIZES ON EXTINGUISHING SYSTEM EFFICIENCY

System	Discharge Rate (pounds per second)	Nozzle Line Size (inches, ID)	Nozzle Locations***	Slot Width of Nozzles (inches)	Agent Requirements for Extinguishment (pounds)	
					CH_2BrCl	CH_3Br
B-1	2.5 (CH_2BrCl)	0.180	A	0.009	> 12*	—
B-1	0 8 (CH_3Br)**	0.180	A	0 009	—	> 12*
B-2	—	0 180	A	0 020	12	—
B-3	—	0.180	B	0 020	5	> 11*
C	9 0	0.305	B	0.070	2	—
C	9.0	0.305	B	0.070	—	2

* Extinguishment apparently not possible

** Methyl bromide vaporized within the system and resulted in a much lower rate of discharge than was the case with bromochloromethane.

*** Nozzle Location A — Nozzle directed radially away from the engine and across the air stream

*** Nozzle Location B — Nozzle directed radially toward the engine and across the air stream excessive system restriction has a more critical effect on methyl bromide than on bromochloromethane. During measurements of the discharge rate, methyl bromide was observed to discharge as a vapor or gas and to have a strong tendency to vaporize within an excessively restricted system This reduced the discharge rate considerably and accounts for its relatively poor effectiveness with System B-3.

2. Effect of Line Length.

The study of the effect of line length on extinguishing system efficiency was made by conducting tests similar to those described previously except that in this instance System C, Fig. 7, was the basic system used. The effect of line length was studied by varying the length of the feed line between the agent container and the distributor and by determining, for various line lengths, the minimum agent requirements for extinguishment of similar gasoline fires in the FR-4 nacelle. The effect of line length on pressurization requirements was also noted Results were obtained on three agents carbon dioxide, methyl bromide, and bromochloromethane. In the tests using carbon dioxide, copper tubing was used between the agent container and distributor This tubing had an outer diameter (OD) of one inch and a wall thickness of 0.062 inch. In tests using methyl bromide and bromochloromethane, the copper tubing of the feed line used was of 3/4-inch OD and of 0 058-inch wall thickness Because of an error in calculation this latter line area was believed, at the time of testing, to be larger than the total of line areas downstream of the distributor. However, it actually was less (the area of the feed line was 0 316 square inch, and the total area of eight distribution lines was 0.584 square inch), so that the testing conditions were not representative of service conditions in this respect and were conducive to expansion of the agent within the system.

The test results are shown graphically in Fig 9. In explanation of the data plotted for carbon dioxide, two cylinders were used in all tests except when the feed line length was 1 1/3 feet One-inch flood valves were used in all cases, and two cylinders were used for long line lengths because this was noted to increase system efficiency In the cases of methyl bromide and bromochloromethane, pressurization requirements with a 25-foot or longer line required the use of a cylinder larger than 205 cubic inches A 646-cubic-inch cylinder was used in these instances From the data plotted, it will be seen that

a The required quantity of bromochloromethane increased slightly with increasing line length. The increase was attributed primarily to the additional amount of the agent lost in wetting and traversing the longer lines.

b The required quantity of carbon dioxide increased appreciably with increasing line length and in direct proportion to the length of the line.

c. The required quantity of methyl bromide increased very rapidly with increasing line length, and test results were erratic. Fires could not be extinguished when using a 75-foot line, even with relatively large quantities of this agent. Unfortunately, the extent to which the use of an undersized feed line in the system contributed to the poor dependability and effectiveness of methyl bromide is unknown, but it may have been considerable. Additional testing will be necessary to determine this.

d. In all instances, pressurization requirements increased appreciably. In the cases of methyl bromide and bromochloromethane, fires could not be extinguished when using a line 25 feet or longer unless a volume of pressurizing gas larger than that provided by 205-cubic-inch cylinders was used. This was true even though the requirements for bromochloromethane were such that a fill ratio of less than 50 per cent was available with a 205-cubic-inch cylinder.

In summation, the results indicate that long feed-line lengths increase both agent quantity and pressurization requirements, thus reducing system efficiency considerably. In the case of methyl bromide, long feed lines may promote vaporization within the system and thereby seriously reduce the rate of discharge and render the system ineffective.

3. Distribution Characteristics and the Effect of Extinguishing System Design on Efficiency

The distribution characteristics and effectiveness of loop, ring, and distributor-nozzle type extinguishing systems were investigated These were determined by discharging water through each system and by collecting and measuring the quantity discharged from each discharge hole or nozzle The effectiveness of these systems was measured in terms of the amount of an agent required to extinguish gasoline fires in the upper and lower portions of the FR-4 nacelle.

In distribution measurements, large aerology balloons of sufficient size to prevent any tautness from discharge of the systems were used to collect the water from each outlet These balloons were secured

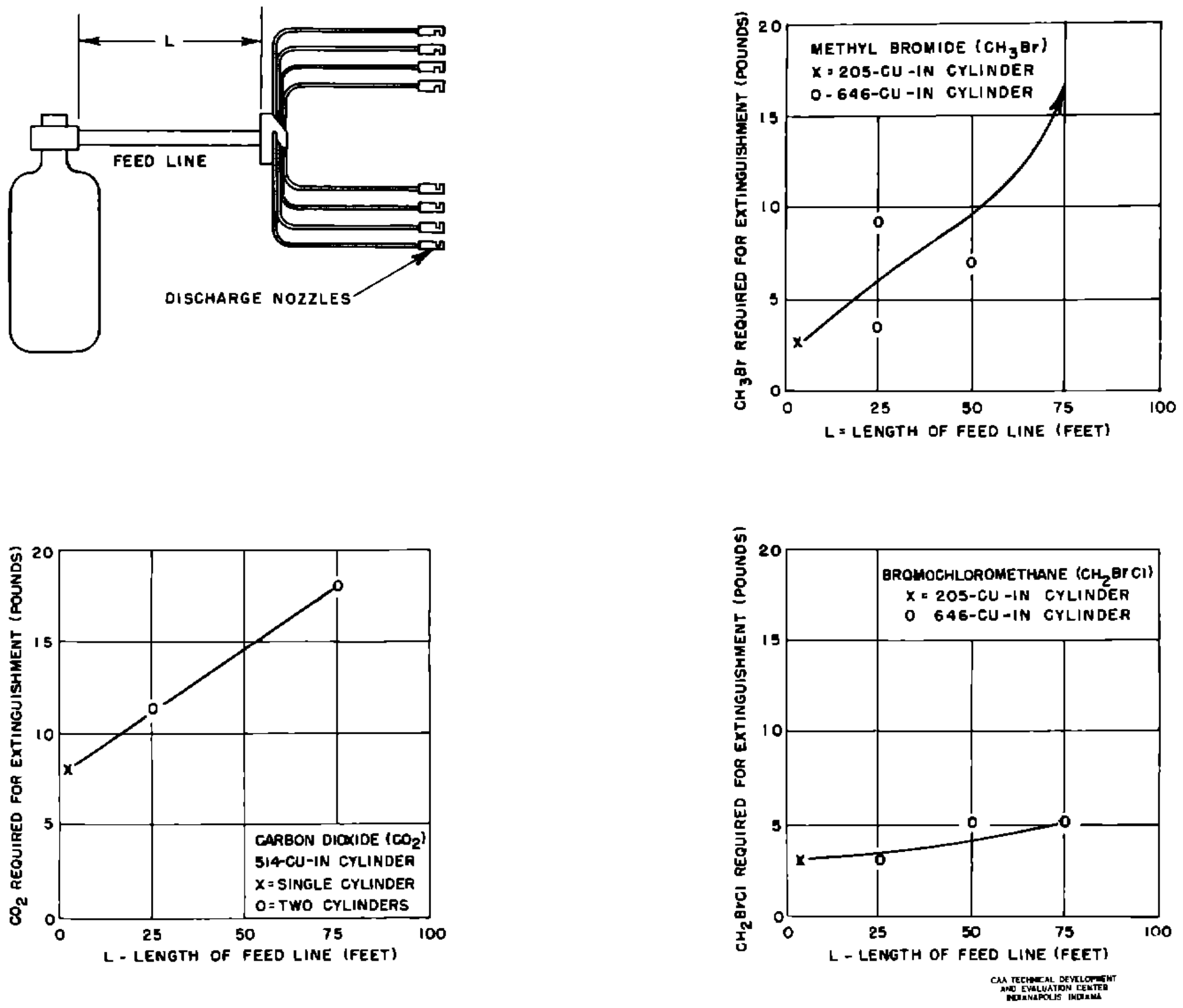
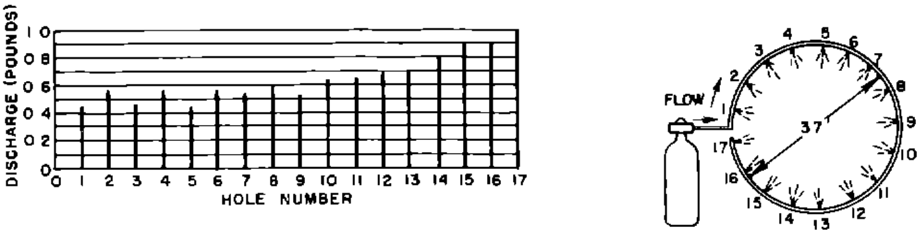


Fig. 9 Effect of Line Length on Extinguishing System Efficiency

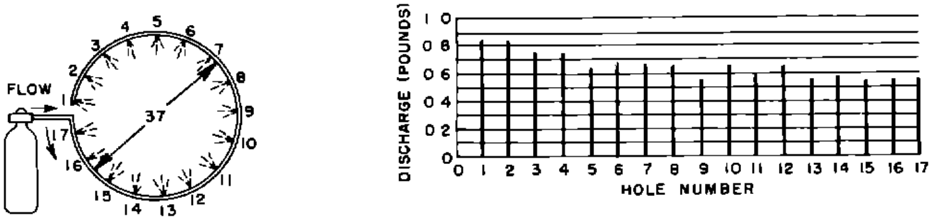
over the outlets and were carefully weighed before and after each test. Measurements were made on tubular loop-type systems (clockwise flow, System G, counterclockwise flow, System J), on ring System L, and on distributor-nozzle System C used in previous tests. Design data and schematic drawings of the systems tested are shown in Fig 10. As indicated in this figure, 11.7 pounds of water charged to 400 psi with nitrogen were discharged from 646-cubic-inch cylinders in each case except for System C where eight pounds of water were used The cylinders were equipped with one-inch methyl bromide type flood valves

Results of the tests are shown graphically in Fig 10 and are summarized in Table VIII From this table it will be seen that the loss of agent within each system was approximately the same and varied from 4.1 to 9.4 per cent of the charging quantity

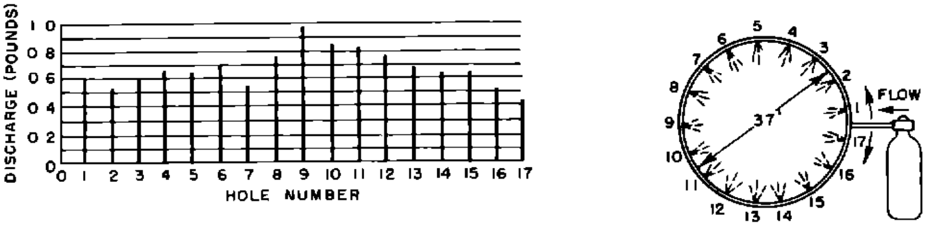
The values tabulated in the fourth and fifth columns show that a far greater variation in the quantities discharged from different outlets occurred with the tubular systems than with the distributor-nozzle system They also show that a considerably greater variation occurred with the ring-type two-way flow system than with the loop systems. These variations indicate that local effects, such as irregularities or burrs around the outlets, had a considerably greater effect on flow in the perforated tubing designs than in the distributor-nozzle system



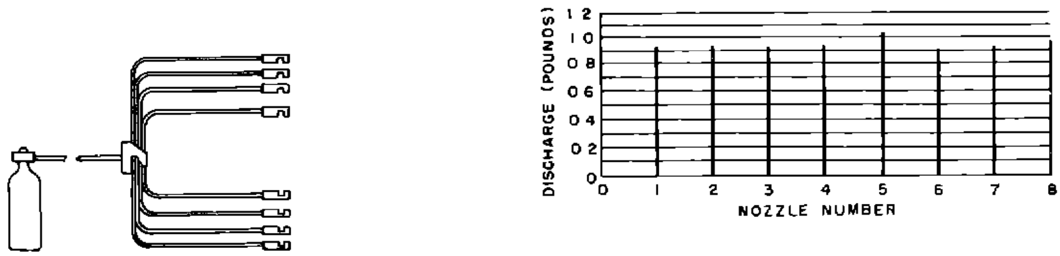
SYSTEM G — LOOP TYPE WITH CLOCKWISE FLOW



SYSTEM J — LOOP TYPE WITH COUNTERCLOCKWISE FLOW



SYSTEM L — RING TYPE WITH TWO-WAY FLOW



SYSTEM C — EXTINGUISHING AGENT DISTRIBUTION BY DISTRIBUTOR SYSTEM

SYSTEM	CYLINDER VOLUME	AGENT	CHARGE	FEED LINE	TUBING	DISCHARGE OPENINGS
G	646 CU IN	11 7 LB WATER	400 PSI NITROGEN	1 IN OD 40 IN LONG	COPPER 3/4 IN (0 065-IN WALL)	17 1/8-IN DIAMETER EQUALLY SPACED HOLES POINTING RADIALLY INWARD
J	646 CU IN	11 7 LB WATER	400 PSI NITROGEN	1 IN OD 40 IN LONG	COPPER 3/4 IN (0 065-IN WALL)	17 1/8 IN DIAMETER EQUALLY SPACED HOLES POINTING RADIALLY INWARD
L	646 CU IN	11 7 LB WATER	400 PSI NITROGEN	1 IN OD 40 IN LONG	COPPER 1/2 IN (0 035-IN WALL)	17 1/8-IN DIAMETER EQUALLY SPACED HOLES POINTING RADIALLY INWARD
C	646 CU IN	8 LB WATER	400 PSI NITROGEN	1 FT 1 IN OD AND 2 1/3 FT 3/4 IN OD	COPPER 3/8 IN X 60 IN (0 035-IN WALL)	8 NOZZLES 0 046 SQ IN SLOT EQUALLY SPACED AROUND CIRCUMFERENCE OF NACELLE DIRECTED RADIALLY INWARD (NUMBERED CLOCKWISE FROM 12 O CLOCK)

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Fig 10 Distribution Characteristics of Extinguishing Systems

TABLE VIII

COMPARISON OF DISTRIBUTION
OBTAINED FROM VARIOUS EXTINGUISHING SYSTEMS

System	Approximate Rate of Discharge (pounds per second)	Agent Loss (per cent)	Over-All Variation* in Discharge (per cent)	Maximum Variation From Q_{av} (per cent)	Total Discharged From Halves of the System	
					Weakest (per cent)	Strongest (per cent)
G	-	5 3	68	40 0	42.0	58.0
J	7 0	4 1	48	29.0	45 0	55.0
L	6 4	9.4	104	68.0	43 0	57 0
C	9 0	5.5	12	7.5	49 9	50 1

*Over-all variation = $\frac{Q_{max} - Q_{min}}{Q_{av}}$

Where

Q_{max} = Maximum quantity discharged by a single hole or nozzle.

Q_{min} = Minimum quantity discharged by a single hole or nozzle.

Q_{av} = Average quantity discharged from each hole or nozzle

General distribution characteristics of the systems tested are shown graphically in Fig 10 The perforated ring system and the loop systems produced unequal distribution of the agent and a greater discharge at the points of greater distance from the feed-line connection. The distributor-nozzle arrangement, System C, produced a relatively equal discharge of the agent at all nozzles. The information tabulated in the last two columns of Table VIII provides an indication of the extent of inequality of distribution by the different systems. These figures show that the perforated tubing systems produced approximately 40 to 60 per cent distribution between the weakest and the strongest halves and that the distributor-nozzle design gave equal distribution throughout

Upon completion of distribution measurements, the systems were installed in the FR-4 nacelle and evaluated by determining agent requirements for extinguishment of gasoline fires in the upper and lower regions of the nacelle The feed-line connection in each case was located approximately 30° below the horizontal center line of the nacelle See Fig 2 This location was expected to result in the discharge of greater quantities of the agent in the upper region than in the lower one by Systems J and L and in the discharge of smaller quantities by System G. Equal distribution at all points was to be expected from System C, eight nozzles of which were equally spaced around the nacelle periphery and directed radially toward the engine Results of the fire extinguishing tests are shown in Table IX. As would be expected from the distribution pattern, System G proved more effective in extinguishing lower region fires than upper region ones. Systems J and L were inadequate, but the test results did not completely show the effect of unequal distribution. System C was equally effective at both fire locations

The efficiency of System C was considerably better than that of the perforated ring and loop systems The reasons for this are not fully understood, however, this improved efficiency may be partially explained by the slightly higher discharge rate and the more uniform and effective spray pattern of System C. The blow-off or blast effect from System C would be expected to be greater than for the tubing systems and may have contributed materially to the effectiveness of System C.

CONCLUSIONS

Aircraft fire extinguishment is a highly complex problem and involves a very large

TABLE IX

COMPARISON OF EFFICIENCY
OF VARIOUS EXTINGUISHING SYSTEMS

System	Approximate Rate of Discharge of CH_2BrCl and CH_3Br (lbs. per sec.)	Amount of Agent Required for Extinguishment					
		Fire Location Upper Nacelle Region			Fire Location Lower Nacelle Region		
		CH_2BrCl (lbs.)	CH_3Br (lbs.)	CO_2 (lbs.)	CH_2BrCl (lbs)	CH_3Br (lbs)	CO_2 (lbs)
G (loop, clockwise flow)	7.3	15	15	20	5	5	16
J (loop, counter-clockwise flow)	7.3	9	5	-	7	-	-
L (ring, 2-way flow)	7.3	10	10	-	No Tests		
C (distributor-nozzle system)	9.0	2	2	10	2	2	10

number of critical variables Basic information regarding the influence of these variables must be obtained before solution of the problem can be achieved by sound engineering design. Present design methods are inadequate and too frequently are the result of cut-and-try procedures.

This investigation was, in many respects, of a preliminary nature and resulted in denoting the influence of various factors on the problem and in directing attention toward critical factors Further work will be necessary to provide detailed design data of direct use to the designer.

Test results and observations made during the investigation indicated that

1. The evaluation of extinguishing agents by the Purdue Research Foundation's laboratory method compares favorably with evaluation by full-scale tests such as were conducted on the FR-4 power plant However, the physical characteristics and the requirements for the optimum method of discharge must always be considered in the complete evaluation of an agent

2 Under conditions of full-scale testing and of optimum discharge and distribution, methyl bromide and bromochloromethane are of approximately equal extinguishing ability

3. The structural design of a nacelle or fire compartment can have a considerable effect on extinguishing requirements Structural ribs and irregularities in a compartment through which air flows may greatly increase requirements by creating traps or pockets protected from the air stream and thereby greatly increase the agent distribution problem

4. Successful extinguishment may depend, in many instances, upon the proper sealing of joints and holes in the nacelle skin or fire walls. Open joints or holes, through which gasoline or oil can pass, can cause reflash of fires and increase extinguishing requirements considerably

5. The higher volatility of methyl bromide over bromochloromethane is advantageous with respect to ease of distribution of the agent within a fire zone. However, this same property makes the methyl bromide more sensitive to system restrictions and line length and causes it to have a tendency to change to a vapor or gaseous state within the system Such a change seriously reduces the rate of discharge and must be avoided by proper system design.

6. The use of siphon tubes in cylindrical containers for agents is not so efficient as the use of inverted cylinders without siphon tubes

7. Consideration of pressurization requirements is just as important as consideration of agent requirements in the designs of extinguishing systems Cylinder or container size should be based on both.

8. Properly designed extinguishing systems must provide sufficient quantity of an agent, sufficient rate of discharge, and adequate distribution Inadequate performance with respect to any one of these primary requirements may cause a system to be ineffective

9. The use of long feed lines and of line sizes below the optimum materially reduces system efficiency. Long feed lines increase agent and pressurization requirements and promote vaporization within the system of agents having low boiling points. The use of line and nozzle sizes differing from the optimum seriously affects the rate of discharge.

10. The conventional perforated loop or ring type systems have poor distribution characteristics compared with the distributor-nozzle type and are much less effective when used in a region of relatively high air flow

RECOMMENDATIONS

The following recommendations are based on the results of the tests conducted and the study made of the fire extinguishing problem.

1 Further study of the fundamental factors involved in the extinguishment of aircraft fires, in extinguishing system design, and in system evaluation is strongly recommended. Information on optimum methods of application of methyl bromide, bromochloromethane, and other halogenated agents recently considered for use in aircraft is particularly needed.

2. Utilization of the halogenated extinguishing agents which have been found to be appreciably better than carbon dioxide is recommended in aircraft as soon as optimum methods of application have been determined and physical characteristics have proved suitable.

3. It is recommended that structural irregularities be eliminated from the inner surfaces of nacelles.

4 The elimination of holes or open joints in the nacelle and bulkheads is recommended as a means of reducing the reflash hazard

5. The use of the shortest possible feed lines in extinguishing systems is recommended as a means of improving extinguishing system efficiency and reducing the tendency of some agents to vaporize within the system

6. The use of inverted extinguishing agent containers, and thereby the elimination of the need for siphon tubes, is recommended as a means of improving system efficiency and of reducing material and weight requirements.

7. Consideration of pressurization requirements as well as of agent requirements is recommended as necessary to proper extinguishing system specifications and design.

8. For agents other than carbon dioxide, the use of perforated tubing extinguishing systems either of the loop or of the ring variety is not recommended where distribution is of critical importance Distributor-nozzle type systems are recommended for use in compartments of relatively high air flow

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