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

PART IV

THE BOEING B-29

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SUMMARY

A careful study of the fire accident record of the B-29, made before the test program was started, revealed that the chief source of trouble was the exhaust system The testing, therefore, began with a thorough investigation of the temperatures encountered near the exhaust system when the power plant was in normal operating condition and when certain failures existed The region surrounding the turbosuperchargers and the exhaust stacks received particular attention, especially with respect to the peculiarities of design which permitted fluid leaking from the accessory section to come in contact with the stacks or prevented proper air flow through the region The temperatures in this region appeared to be dependent to a large extent on the amount and character of the air flow More important, the ease of ignition of flammable fluids appeared to depend on the air flow It was demonstrated that sufficiently high air flow could even prevent the occurrence of ignition

Fluid leaking within the accessory section will frequently drain out without harm except in certain locations over the turbosuperchargers Unfortunately, there are tanks and pipes installed over these areas which, if ruptured, might release the flammable fluids which they contain and cause a fire

In the tests, overheated motors did not appear to be ignition sources but blocked vacuum systems could be a real hazard

In conjunction with the ignition source investigation, gasoline, SAE 10 oil, and a few low volatility fuels were sprayed on the same ignition sources to determine the comparative flammability of those fluids The SAE 10 oil was found to be slightly more hazardous than gasoline under the same conditions of testing on the hot exhaust stack The low volatility fuels, although not differing materially from one another in safety, were somewhat safer than gasoline on a percentage basis of the number of fires starting to the whole number of attempts Actually, they appeared to be less predictable in their reaction than gasoline, and it was felt that the degree of improvement displayed was insufficient to constitute a real gain in safety Kerosene under the conditions of the tests appeared to be more hazardous than either 100 octane gasoline or low volatility fuels

Fire detectors and fire detecting systems received only a moderate amount of attention in the testing program The investigation was confined to the study of maximum temperatures and maximum rates of temperature rise occurring at the cowl flap openings (where detectors are frequently located) during normal and severe engine operation, and to the study of the flame pattern in the accessory section with the object of determining whether or not detectors, located in general areas, would provide satisfactory coverage for this zone The maximum rate of rise in the cowl flap region was found to be 450° F per minute, while the maximum temperature was 350° F No general area inside Zone 2 was found where units could be located to detect all fires originating in this zone

Two types of detectors which were in the experimental stage of development were mounted in the test installation for study Both operated successfully, but both required further development

A study of detection and extinguishing problems created when fires start forward of the cylinders in Zone 1 was made on both the B-29 and on a simulated L-49 configuration In the course of the study, additional information on the vulnerable parts of the power plant and the value of a fire-resistant propeller feathering system were obtained

Stopping the flow of flammable fluids to Zone 1 frequently is sufficient to extinguish a fire which has not spread beyond this zone

In order to accomplish this, it is sometimes necessary and usually desirable to stop rotation of the engine by feathering the propeller However, in the event of a large and damaging fire, the propeller feathering process may require too long a time to complete, with the result that the fire may spread beyond the power section To preclude this possibility, Zone 1 should be protected with an adequate and properly designed extinguishing system. Vulnerable parts of the airplane include the aluminum alloy skin and structural members, the seal at the diaphragm, and hoses carrying flammable fluids

Generally speaking, gasoline and oil will not ignite on the exhaust collector ring, but if these fluids gain entrance to the exhaust stack wells on either side of the nacelle, fires usually will result

In the L-49 configuration, it was found that fires which originated far enough forward to enter the projecting exhaust stack shroud were difficult or impossible to detect with the detectors located at the cowl flaps

Recommendations based on the conclusions drawn as a result of these investigations are included in the report

INTRODUCTION

The Technical Development and Evaluation Center has been active in the field of fire prevention and protection in aircraft since 1939, when testing began with modest facilities on the grounds of the National Bureau of Standards in Washington, D C The first type of aircraft power plant installation investigated was the Douglas DC-3[1] This was followed by the Curtiss-Wright CW-20[2] and later by the Waco YKS-37[3]

This report covers the fire investigations which were completed under simulated flight conditions on the B-29 power plant The major problems of fire detection and fire extinguishment were not included in the investigations because these problems were being investigated concurrently by another fire test group under contract to the U S Air Force However, a limited amount of testing was done which involved detectors

Specifically, the CAA program was directed toward a quest for these major items

1 Ignition sources in the B-29
2 The inherent weaknesses in design of the B-29 from the standpoint of fire elimination and fire control
3 The answer to the question, "Is a Zone 1 fire extinguishing system necessary?"
4 A less-flammable hydraulic fluid than is currently used in aircraft
5 A less-hazardous fuel than regular gasoline

Prior to starting the test program, the fire problems which had beset the B-29 were discussed with personnel of the Boeing Aircraft Company, studies were made of the records of actual B-29 fires, and a thorough study was made of the installation itself With this background, a general plan of testing was formulated which laid stress on the features appearing most prominent as fire hazards The attempt was made to plan tests so they would not only indicate the ignition sources but suggest, where possible, the corrective measures to be taken

Accident records revealed that the exhaust system was by far the most serious cause of fire, not only in igniting a fluid which had been exposed to it due to an independent failure in the fuel or oil system, but in itself frequently causing the fluid system failure and then providing the ignition Thus, a loose hose fitting in the fuel system would, in the absence of the exhaust system, probably result in nothing more serious than loss of gasoline A loosened ball-and-socket joint in the exhaust stack, on the other hand, might subject a good fuel line to excessive heat which, over a period of time, might cause its failure and then provide ignition for the leaking gasoline

Electrical equipment failures had caused trouble due to arcing or excessive heating, but available records show failure as having

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

[2] George L Pigman, "Determination of Means to Safeguard Aircraft from Power Plant Fires in Flight - Part II," CAA Technical Development Report No 37, October 1943

[3] H L Hansberry, "Determination of Means to Safeguard Aircraft from Power Plant Fires in Flight - Part III," CAA Technical Development Report No 38, April 1944

occurred only through careless maintenance or by exposure to excessive exhaust heat

In view of these findings, attention was concentrated in the testing of the exhaust system as a fire hazard with some investigation of ignition by overheated electrical or mechanical accessories

During tests, the B-29 engine was operated generally at 2,400 rpm and 31 in manifold pressure Engine temperatures were maintained at a high level by keeping the indicated cylinder head temperature at 350° to 450° F, somewhat in excess of normal operating temperature The wind tunnel was operated to provide a maximum air blast of 112 mph

For the convenience of the reader who may not be familiar with the B-29 engine installation, Fig 19 has been included for reference.

DESCRIPTION OF TEST EQUIPMENT

The basic test facilities and equipment used in all tests reported herein are described and illustrated in a previously published report[4] Briefly, the chamber in which the full-scale tests were conducted is a room 40 by 30 feet, 20 feet high, having doors at both ends which open the full width and height of the room In the center of this chamber is mounted the wing section and nacelle which houses the power plant under test See Fig 1

The 19-foot long wing section is mounted at its extremities so that the center line of the nacelle lies along the longitudinal center line of the room with the propeller dome approximately two feet from the front doors An air blast tunnel is located in front of the test chamber with its center line continuing and coinciding with the longitudinal center line of the room Air furnished by the tunnel passes through and over the nacelle, the doors at both ends of the test chamber being open during tests No abnormal obstructions are present to interfere with the air stream except two one-half inch diameter steel cables used for emergency suspension of the engine at the engine mounts

The tunnel is approximately 45 feet long, with an eight foot diameter throat ending two feet forward of the front doors of the test chamber or approximately four feet ahead of the propeller dome. The prime mover for the tunnel is a 2,300 v electric motor rated at 1,500 hp, but capable of developing up to 2,250 hp for short periods It drives a standard Curtiss electric three-blade, 16 1/2-foot-diameter propeller Since the motor is a constant-speed type, power changes and air speed changes are effected by varying the propeller pitch

The wind tunnel air speed was measured by three separate instruments. These were (1) static pressure pickups, (2) a velometer, and (3) an anemometer. The air speed measurements taken with each type were approximately the same and the highest speed obtainable was found to be 112 mph in each case This top speed is somewhat less than normal flight speed of the B-29 and other large aircraft However, it is sufficient to keep the engine cool for all power settings except the higher horsepowers produced by the R-3350 engine

The power plant used for all tests covered in this report was the Wright R-3350-57, 18-cylinder twin row Cyclone as installed in the Boeing B-29 aircraft See Fig 2 A Hamilton Standard propeller (24 F 60-73) was used with the engine The engine accessories and nacelle were identical to those used in the B-29 inboard (No 3) installation except for the following differences.

1 The main flexible fuel lines inside the accessory section were lagged with asbestos for protection against repeated fires

2 The propeller feathering system was modified to provide an oil supply to the feathering pump from a special wall-mounted oil tank rather than from the regular feathering supply tank The regular supply tank was removed from the nacelle in order to give access to that region for mounting thermocouples and detectors. SAE 10 oil was used in the feathering system, but the dilution of the main engine oil was negligible because large quantities of engine oil were being drained from the engine for use as fuel for the fires

[4] H L Hansberry, "Test Facilities, Aircraft Fire Protection Program," CAA Technical Development Report No 54, February 1947

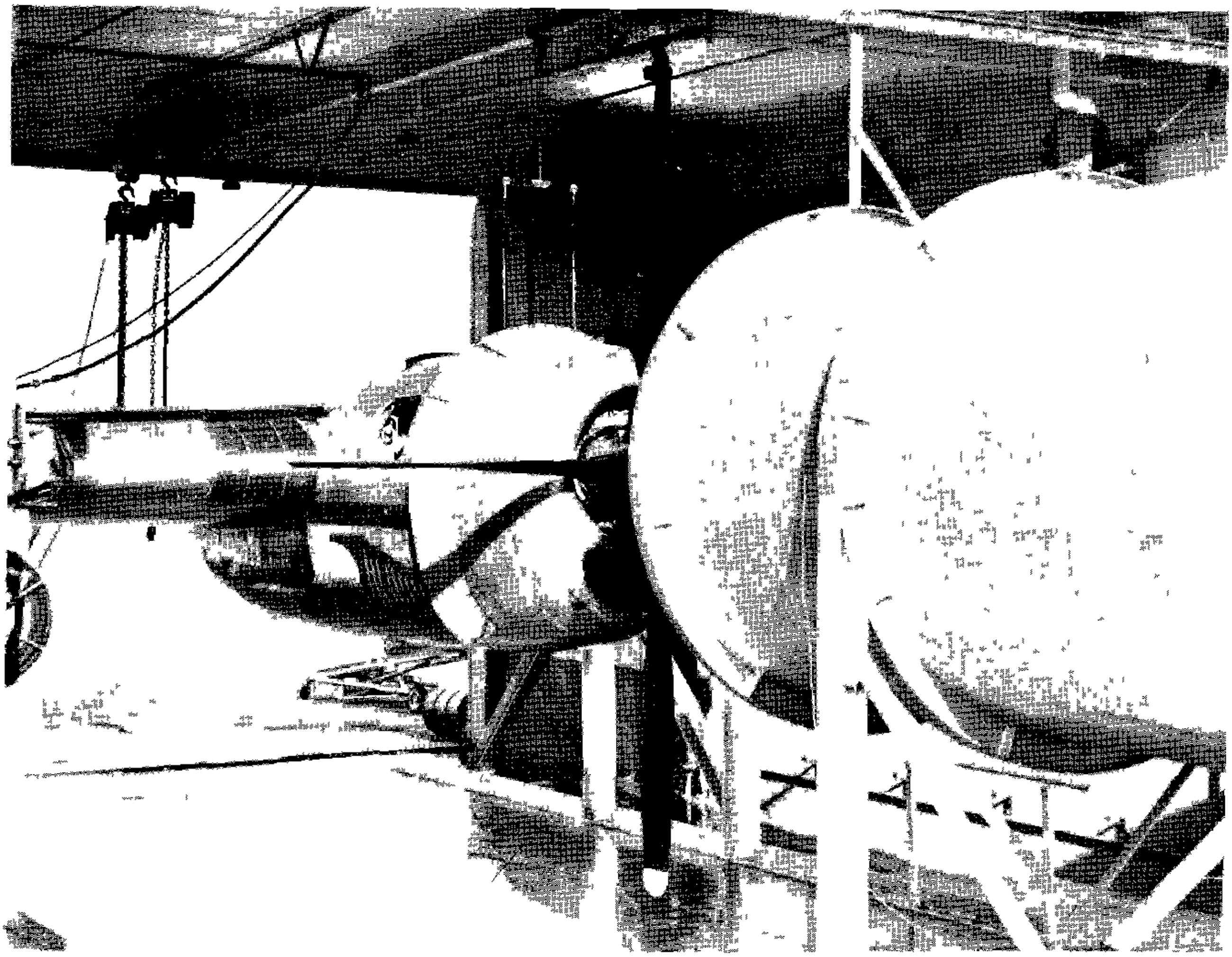


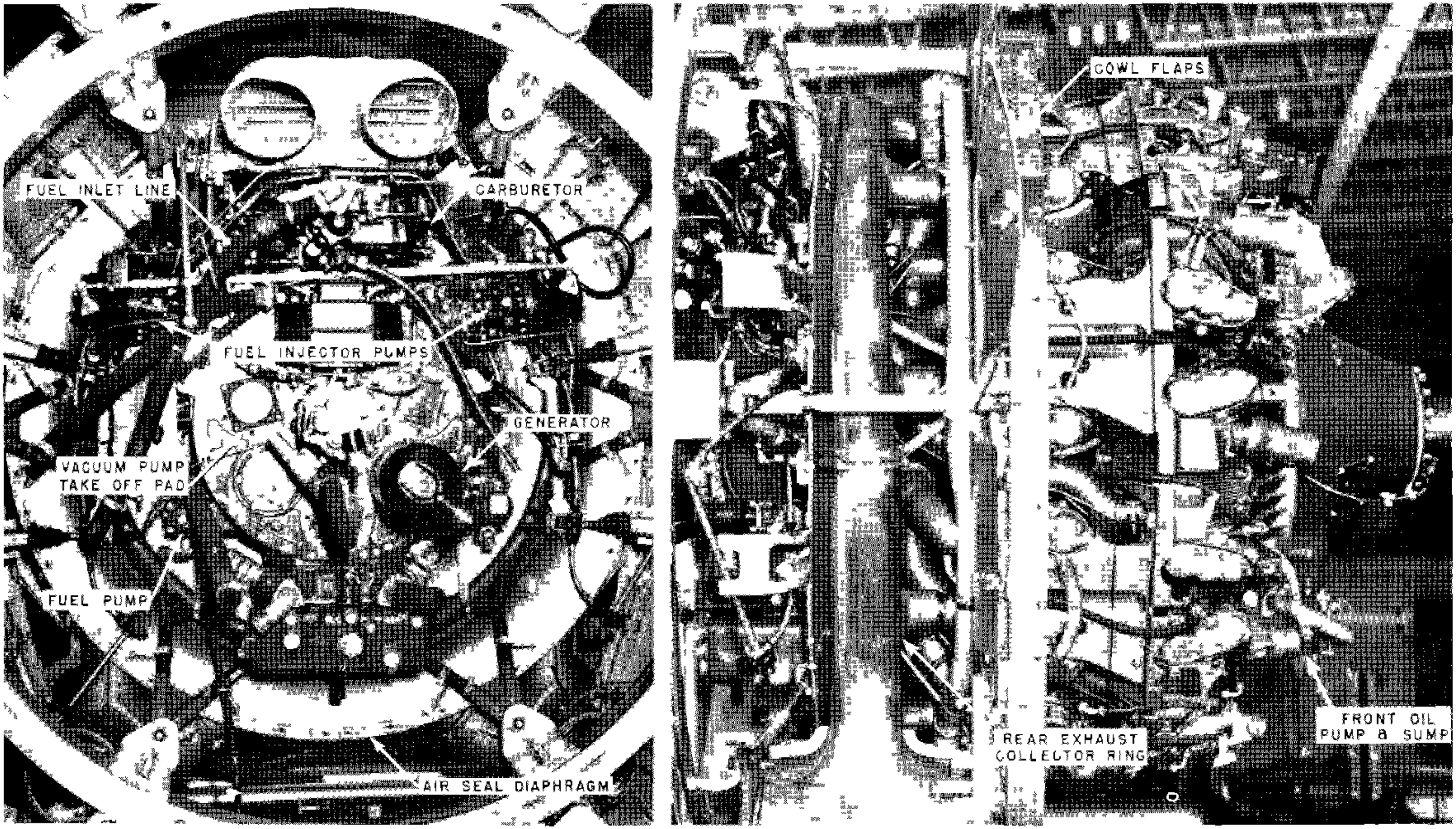
Fig 1 Wing Section and Nacelle of B-29 Mounted and Ready for Tests

3 A special fire extinguishing system was installed in the engine for incidental and emergency use This system included two perforated distribution rings in Zone 1 (power section), one perforated ring in Zone 2 (accessory section), one perforated ring in Zone 3 (wheel well), one perforated ring discharging into the main induction air duct, one nozzle into each exhaust stack well, and two forward into the space aft of the oil tank in Zone 2 In Zone 1, the two distribution rings were located just inside the cowling, one forward and one aft of the cylinder banks They were perforated to discharge radially inward The extinguisher system was connected to a supply tank holding four tons of carbon dioxide at 300 psi pressure As much extinguishing agent as was needed for a fire could be released by opening an electrically operated valve Other manually operated valves controlled the distribution of the carbon dioxide into the proper zone or zones

4 The wheel well (Zone 3) was of standard dimensions and contours but contained no wheels, landing gear, or other equipment Large openings existed between the wheel well and the inside of the wings

Pressure pickups for measuring baffle pressure drop across the engine had already been installed in the engine by the manufacturer Eighteen of these pickups, plus two other static pressure pickups located in Zone 2 (accessory section), were connected to individual manometers so that the pressure at each point could be read in inches of water

By noting the pressures at any particular power setting of the engine, it was possible to determine whether or not flight conditions were being simulated, and what effect was



REAR VIEW

SIDE VIEW

Fig 2 Views of Wright Cyclone Engine Prior to Installation in B-29 Nacelle being produced in the accessory section at the time

Tests were run at 1,435, 2,000, and 2,500 bhp The results are shown in Table I

With the wind tunnel operating at the maximum capacity of 112 mph, the baffle pressure drop (BPD) theoretically required for cooling at each speed and at the prevailing ambient temperature of 30° F could be attained, or nearly attained, by opening the cowl flaps to full open position However, the specified maximum cylinder head temperature could be maintained with less baffle pressure drop than theoretically required except at 2,500 bhp, at which setting the engine could not be kept below the specified maximum

It may be noted that at 2,000 bhp output the required cylinder head temperature could be held and a constant baffle pressure drop maintained with varying tunnel settings by adjusting the cowl flap openings This shows that it was possible to maintain approximately constant air flow conditions inside Zone 1 while changing the external air blast

Moreover, since Zone 1 fires tend to hang in low pressure areas created by the engine, it is believed that the results do not differ significantly from those to be expected at higher speeds Therefore, it is believed that the test conditions adequately reproduce flight conditions

In the study of fire problems on this power plant, the assumption was made that an infinite number of places existed where flammable fluids might start leaking and, that regardless of their origin, ignition of these fluids might occur To simulate leaks and fires originating at a large number of different points, with a minimum expenditure of time and labor and a minimum modification of equipment, nozzles were employed which could be mounted readily at any desired locations Flammable fluids were pumped to these nozzles from remotely located supply tanks or, in the case of lubricating oils, from the engine sump Artificial ignition, when required, was effected by generating an arc in a special spark plug ignitor which also could be attached at any desired point on the power plant

In addition to all this major test equipment, numerous items of minor equipment were employed to assist in obtaining data during particular phases of the investigation The use of these items will be described in detail as each phase of the investigation is presented

FIRE IGNITION SOURCES

This phase of the investigation was designed to locate the sources of ignition in the B-29 power plant under both normal operation of the engine and abnormal operation to simulate typical failures and disorders, to study such sources with a view to removing them or isolating them from flammable materials, and to relate the results of these studies to improved fire prevention in general aircraft design

PROCEDURE

The history of B-29 fire accidents had already shown that the exhaust system was the most logical place to begin a search for ignition sources Therefore, it was decided to make a temperature survey of the region adjacent to the exhaust stack and turbosupercharger

Preparation for the survey began by mounting 32 thermocouples inside Zone 2 (accessory section) as shown in Fig 3 Twenty-two of these were brazed to the inside surface of the two stainless steel shrouds which form the separating wall between the exhaust stack well and the accessory section The other ten were fixed in the air just above or beside the shrouds Thus, there were 16 thermocouples arranged almost symmetrically on each side of the zone, and each group of 16 was connected to a 16-point recording potentiometer calibrated from 0 to 2,000° F

Later, eight thermocouples were brazed to the surface of the right exhaust stack as shown in Fig. 4 These also were connected to a 16-point recorder. Three additional thermocouples, connected to single-point recording potentiometers, were used to measure air temperatures at three points in the exhaust stack well.

The survey was conducted by first operating the engine normally and then with simulated exhaust stack failures The failures were simulated by separating the flanged joints in the stack, thus allowing some of the hot exhaust gases to escape. During the course of these runs, records were made of the temperatures at each point where a thermocouple was located

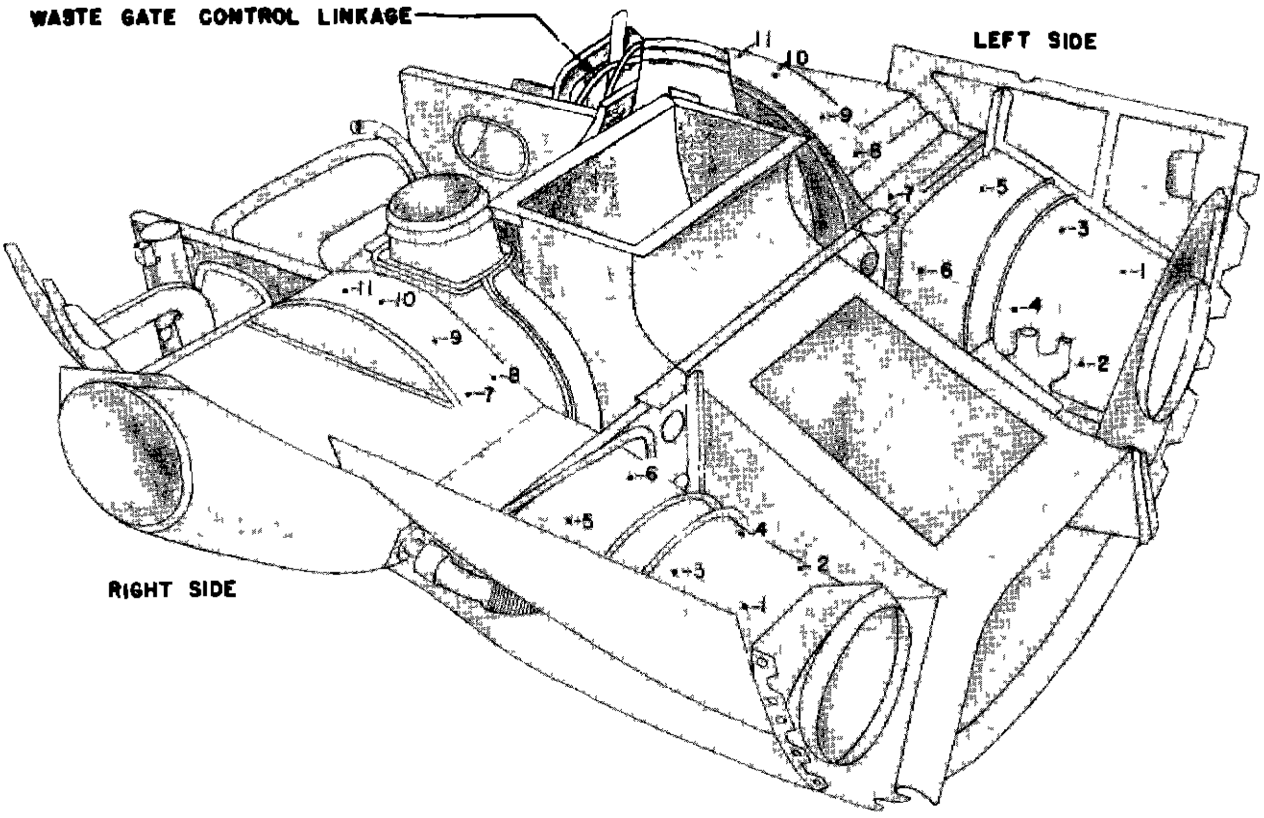
TABLE I

BAFFLE PRESSURE DROP AND ENGINE OPERATING TEMPERATURES

Summary of Test Data

Run No.	Engine Settings			Tunnel Air Speed mph	Cowl Flaps in. Open	BPD in. H20		Cooling Air Temp. Rise °F	Cyl. Hd. Temp. °F	
	rpm	M.A P. in. Hg.	bhp *			Obt'd	Theor Req'd * * *		Obt'd	Spec'f'd Max. *
1	2150	34.2	1435	112	2.0	1.6	3.4	185	440	450
2	2150	34.2	1435	112	5.5**	3.8	3.4	105	380	450
3	2400	42.0	2000	112	3.5	3.3	4.2	130	482	480
4	2400	42.0	2000	104	4.0	3.1	4.2	120	478	480
5	2400	42.0	2000	90	5.5**	3.1	4.2	125	482	480
6	2400	42.0	2000	112	5.5**	4.0	4.2	130	490	480
7	2750	52.0	2500	112	5.5**	4.4	4.6	135	520+	500

* From U.S A.F. Technical Order No. AN 01-20EJA-1
** Maximum Opening
*** From Wright Aeronautical Corporation Drawing No. IS-2000



• THERMOCOUPLES BRAZED TO SHROUD

ADDITIONAL THERMOCOUPLES FIXED IN AIR.

T.C NO.	RIGHT SIDE OF ENGINE	LEFT SIDE OF ENGINE
12	BELOW GENERATOR	BELOW FUEL PUMP
13	BELOW FEATHERING PUMP	BELOW FUEL INJECTOR PUMP
14	BELOW TURBOSUPERCHARGER OIL ANTI-LEAK VALVE	BELOW OIL DILUTION VALVE
15	NEAR WASTE-GATE CONTROL MOTOR	NEAR WASTE GATE CONTROL SHAFT
16	NEAR WASTE GATE CONTROL SHAFT	NEAR FUEL FILTER

NOTE: NUMBERS CORRESPOND TO THOSE ON CHARTS SHOWN IN FIGURE 7

Fig 3 Location of Thermocouples Inside Accessory Section

To study the effect of air flow on temperatures in the stack well, a special air intake duct was added to the louvered cover of the right exhaust shroud at its forward end just aft of the air seal diaphragm The duct was equipped with a valve by which the amount of air passing into the duct could be controlled For further control of the air through the well, a sliding cover plate was placed over the louvers so that the area of the louver openings could be remotely controlled by a pull cable acting against a spring return The duct and sliding cover plate are shown in Fig 5 The special air duct controlled the quantity or rate of air flow, while the cover, in effect, controlled the turbulence of the air flow inside the stack well (the greater the louver opening, the greater the turbulence) Thus, between them, they controlled the important characteristics of the air flow around

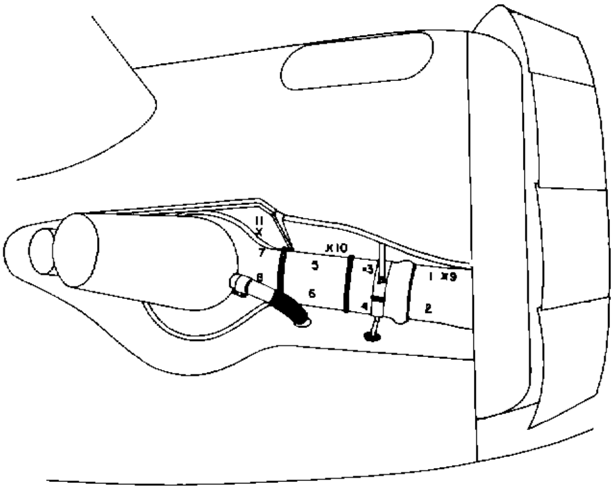


Fig 4 Location of Thermocouples on Right Hand Exhaust Stack Surface and in Stack Well

the stack and turbosupercharger which affected fire ignition With the louvers closed, all the air passed back over the turbosupercharger and out around the tail pipes

A pressure pickup was mounted on the turbosupercharger waste gate shrouding to measure the relative air flow through the well during changes in the valve and louver settings In Fig 6, it appears just aft of the tail pipe This pickup was a combination ram and suction arrangement consisting of two open-end tubes, one of which pointed upstream and the other downstream Both were enclosed in a venturi-type head Since a calibration was never made of this head during the course of the tests, the readings should be used only as relative indications of air flow.

In addition to the temperature and pressure data gathered on the exhaust system of the B-29, temperatures and pressures also were taken of the aircraft vacuum system under normal operation and under conditions of system blockage These measurements were taken to assist in setting up a bench test for investigating fire hazards in malfunctioning vacuum systems The results of this test work have been published[5]

Following the temperature survey, the search for ignition sources was continued by directing 100-octane gasoline onto the potentially hazardous areas in the accessory section. The gasoline was sprayed through a 3/32 in diameter nozzle at a rate of 0 5 gpm by a 400 gph AN 4101 TF aircraft fuel pump Later the nozzle was moved to the exhaust stack well for convenience in studying the effects of air flow on ignition A total of 168 tests were made in this general study of sources and causes of ignition

In a typical test, the nozzle was first secured in the desired location Then the engine and the wind tunnel were started and brought up to normal operating conditions or to the conditions to be imposed by the tests The fuel then was discharged through the nozzle and if ignition occurred, the fuel was immediately shut off If necessary, carbon dioxide was released into the accessory section until the fire was extinguished It usually was possible to run through a series of tests without shutting down the engine, by varying the fuel, the remotely controllable test parts, and occasionally the engine or tunnel settings.

The nozzle was located at a number of different points inside Zone 2 During each test, the occurrence or nonoccurrence of ignition under the test conditions was noted. If no ignition occurred, the path of fuel flow after ejection from the nozzle was roughly traced The path was revealed visually by leakage of fluid to the outside of the nacelle or into the exhaust stack well through gaps in the shroud as well as by the thermocouple records which indicated exposure to unburned fuel by a rapid drop in temperature.

A group of six unit type Edison detectors was assembled on a panel which could be placed in any region of the accessory section This was used in some of the tests to provide an indication of ignition when visual observation might not be reliable

DISCUSSION

The maximum temperature recorded on the inner surface of the exhaust stack shroud during normal operation was 460° F at thermocouple No. 7, left side, Fig 3

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[5] J J. Gassmann, "Investigation of Fires Originating in Aircraft Vacuum Systems," CAA Technical Development Report No 67, June 1947

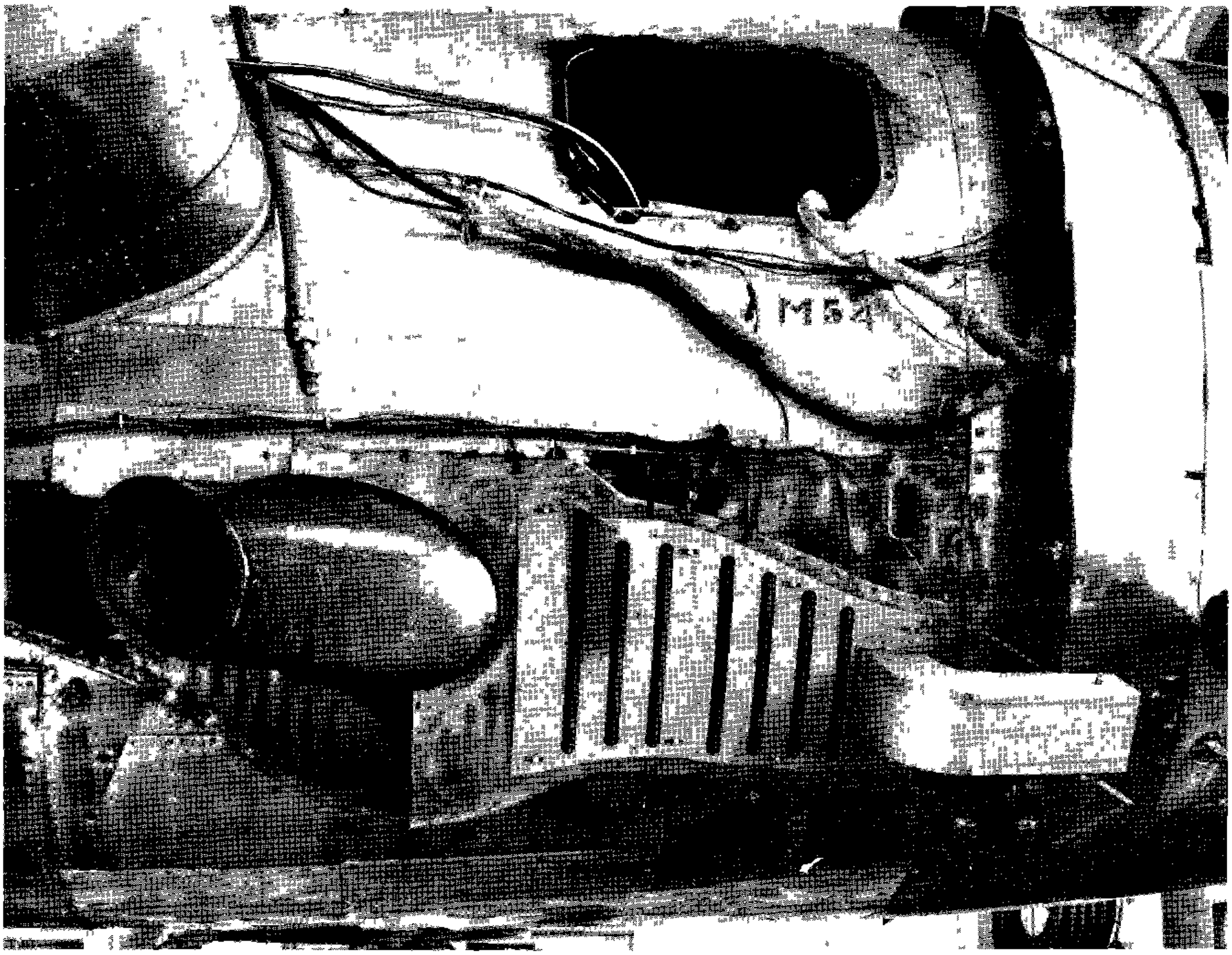


Fig 5 Air Scoop and Louver Cover on Exhaust Stack Well

This is near the place where one layer of steel shrouding is discontinued for about 2 in just above the junction between the exhaust stack and turbosupercharger, Fig 6 This spot consistently was about 100° F hotter than the rest of the shroud The temperature was not duplicated at No 7 thermocouple on the right side because this thermocouple could not be located at an exactly comparable spot on the shrouding

As previously mentioned, breaks in the exhaust stack were simulated by separating the flanged joints in the stack When the flanged joint midway between the air seal diaphragm and the turbosupercharger was separated 1 1/4 in , the temperature at thermocouple No 7, right side, reached 1, 140° F, but when separated one-eighth inch, the maximum temperature (after 12 minutes of operation) was only 350° F.

Next, the flanged joint farther forward just aft of the air seal diaphragm was opened three-eighths inch for a test at 2, 400 rpm The vibration at this speed caused the opening to enlarge and within three minutes the maximum temperatures were near 1, 200° F at thermocouples Nos 3 and 5 High temperatures were more widespread than in the previous test This was attributed to the fact that escaping exhaust gases were able to gain entrance to the space between the two layers of shroud During these runs, the wind tunnel air speed was kept low When it was increased to maximum, the temperatures dropped as much as 400° to 500° Representative curves illustrating the above conditions are shown in Fig 7

Temperatures on the surface of the exhaust stack in the region of the stack well were 1, 050° to 1, 150° F during normal oper-

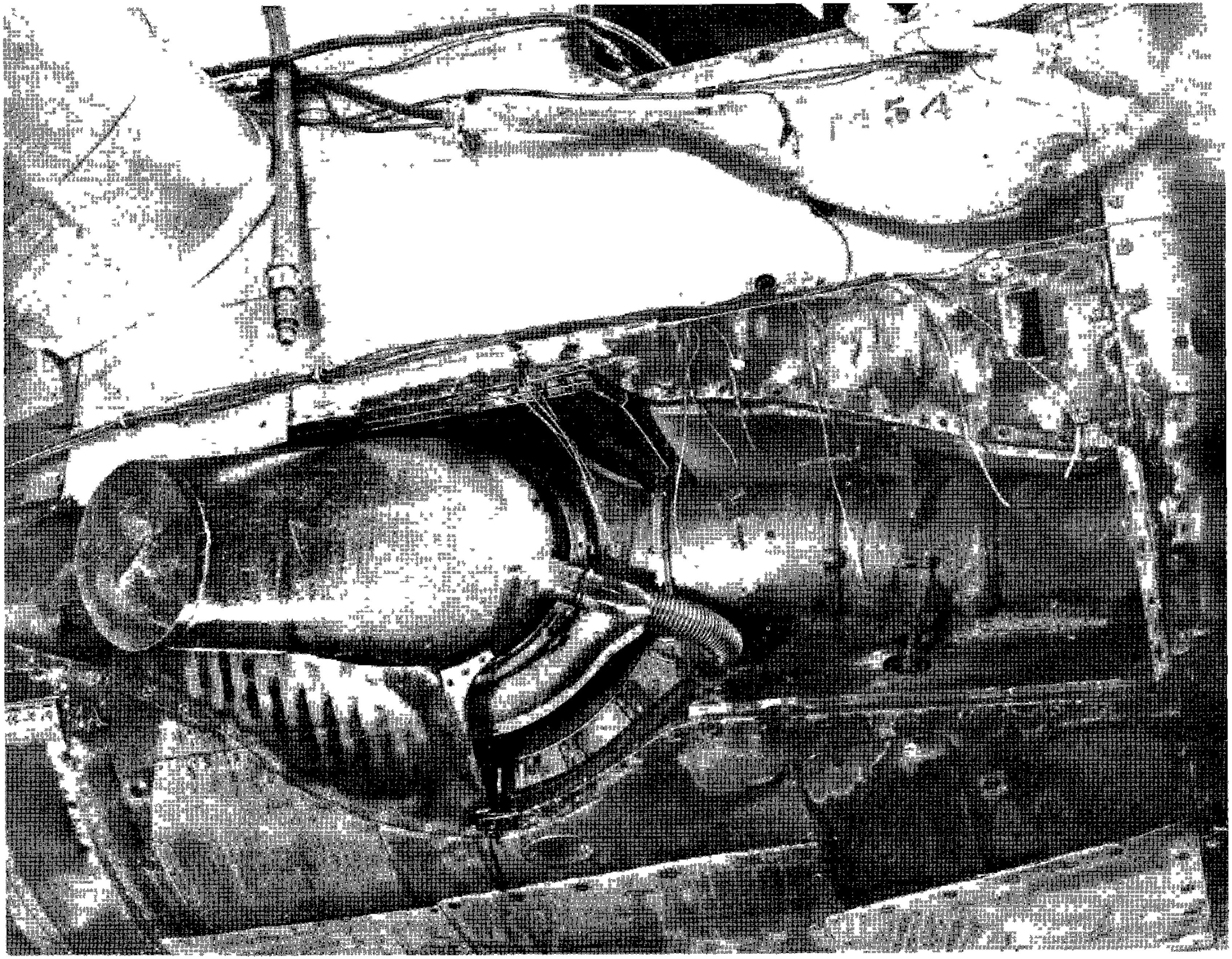
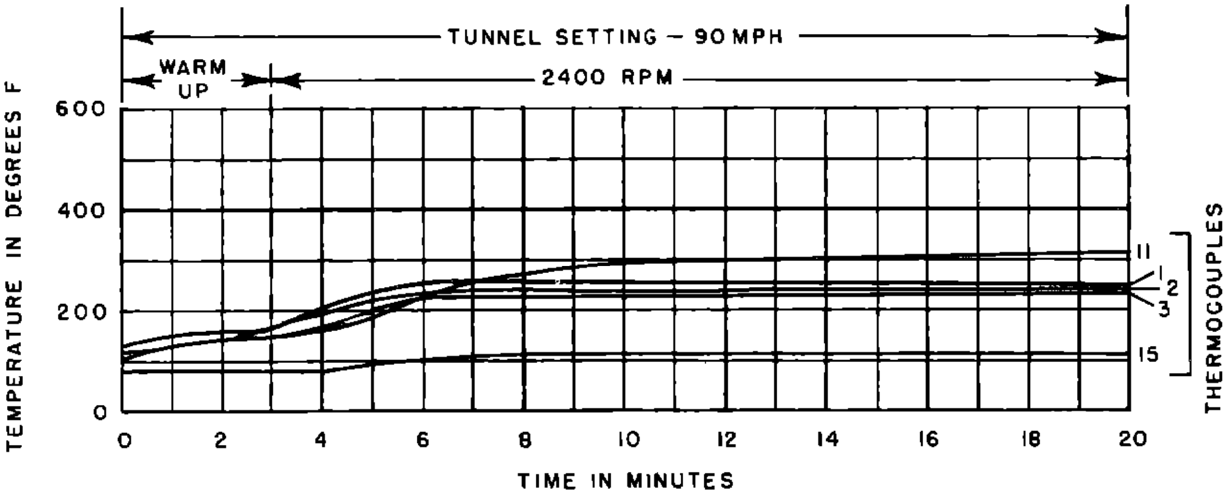
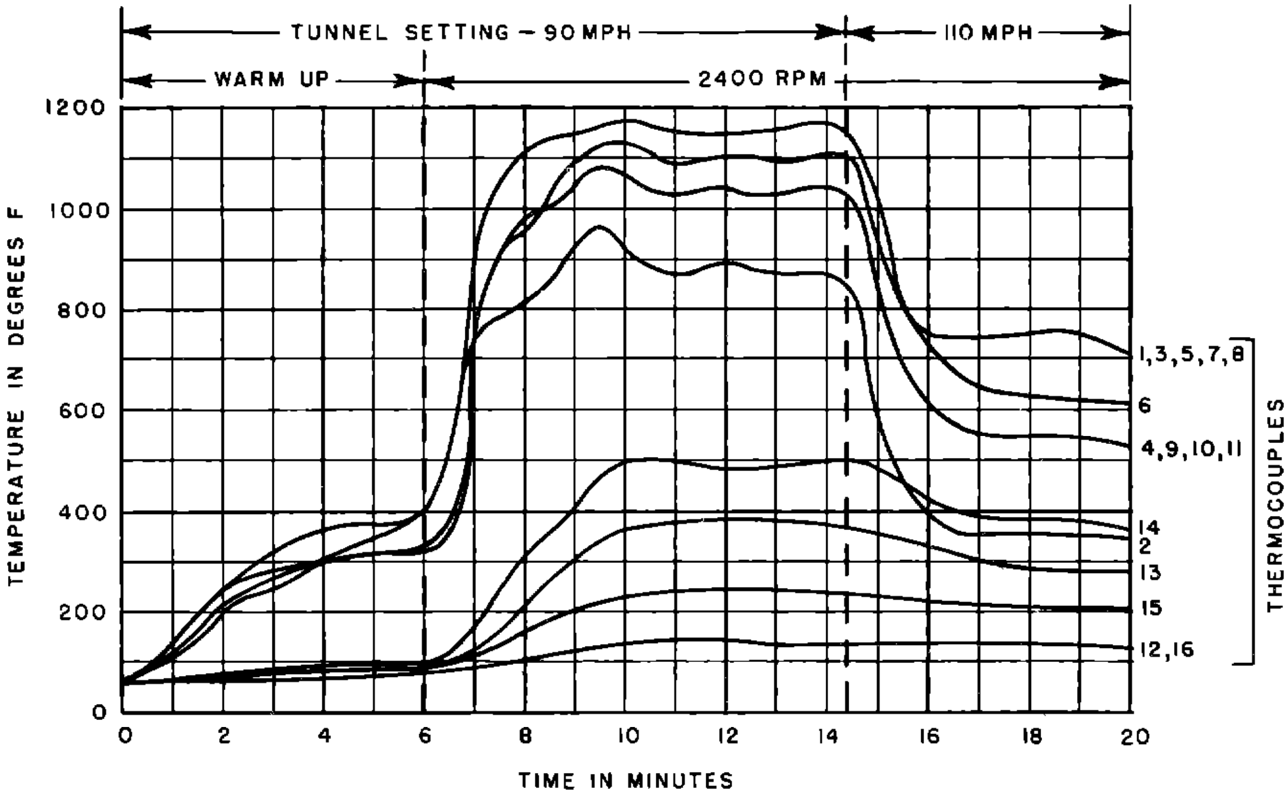


Fig 6 View Inside Exhaust Stack Well Showing Double Shroud Wall



(a) ENGINE NORMAL (TEMPERATURES OF ALL THERMOCOUPLES NOT SHOWN RUN BETWEEN THOSE OF NUMBERS 11 AND 15)



(b) SIMULATED EXHAUST STACK FAILURE (BREAK JUST AFT OF AIR SEAL DIAPHRAGM)

Fig 7 Internal Zone 2 Temperatures, on Shroud Surface and in Air During Normal and Abnormal Engine Operation (See Fig 3 for Thermocouple Locations)

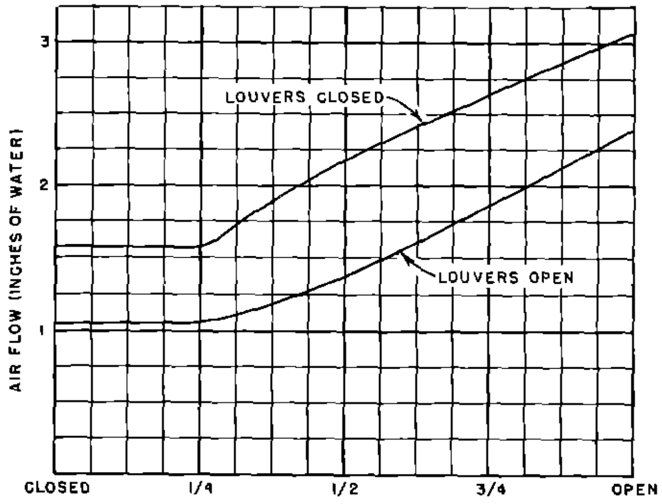


Fig 8 Variation of Air Flow Through Exhaust Stack Well with Change in Setting of Valve in Added Air Scoop (Air Flow Measured Adjacent to Waste Gate Tail Pipe)

ation However, these temperatures could be changed by changing the amount and character of the air flow through the well by means of the added air duct and the louver cover

Pressure readings in inches of water, taken near the waste gate, gave an indication of the relative amount of air passing through the well as the air valve and the louver openings were varied Fig 8 shows the pressures recorded The normal condition of the well is represented by having the louvers open and the air scoop closed Pressures for this condition averaged about 1 1 in of water The highest pressure was noted when the louvers were fully closed and the air scoop fully open The pressure under this condition was 3 1 in of water

Fig 9 shows graphically the relationship between the rate or quantity of air flow through the well, the turbulence of the air flow, and the temperature of the heated surface over which the air is flowing The curves are based on data obtained by thermocouple No 7 (Fig 4) in 32 tests wherein the character of the air flow in the exhaust stack well was varied by changing the opening of the valve of the special air intake duct and the opening of the louvers In the first case, rate of flow increased with increased opening of the valve, as shown in Fig 8 In the second case, turbulence increased with increased opening of the louvers

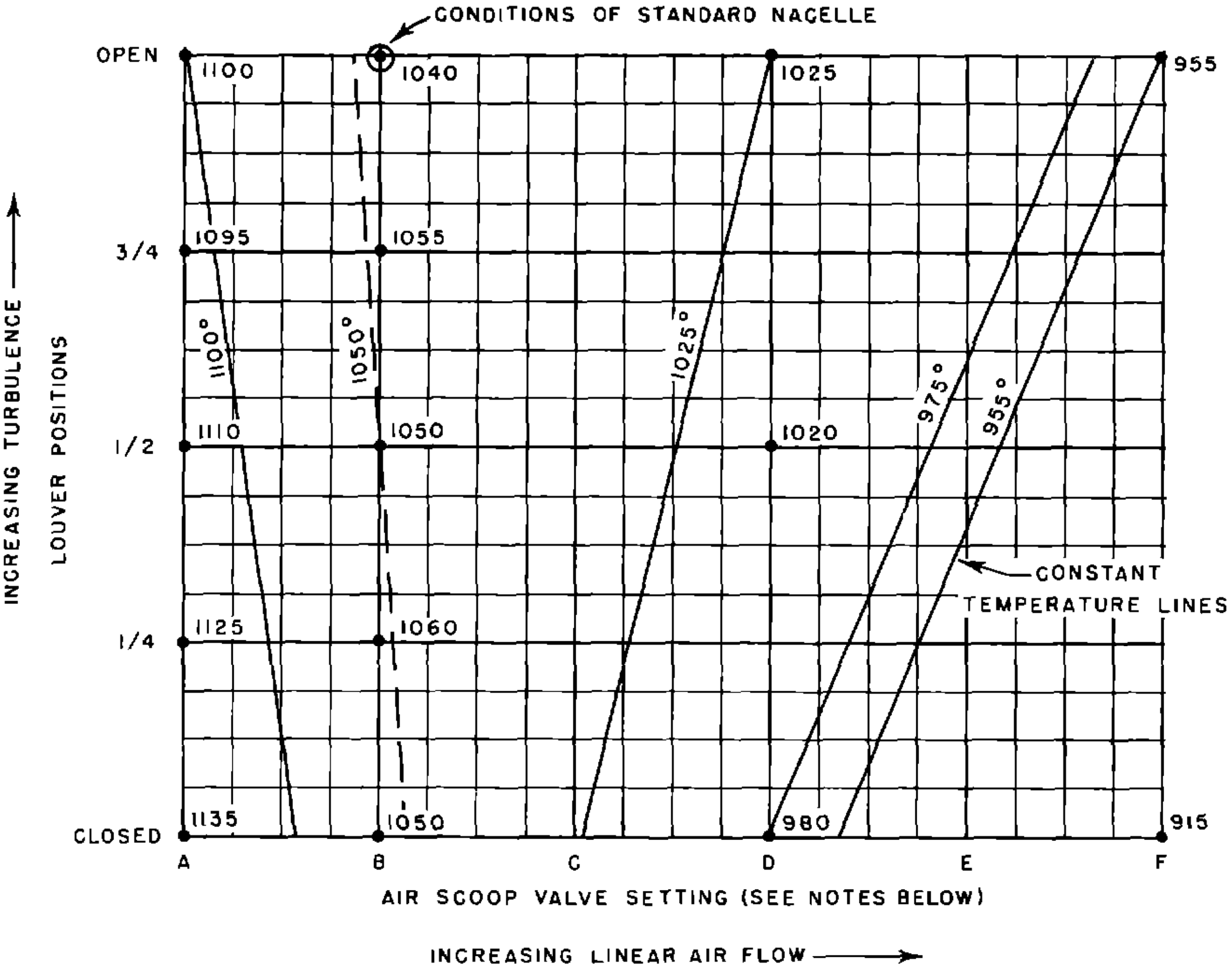
By assuming a proportional extension of the data into certain regions not covered by actual tests, a system of constant temperature lines has been drawn to show in Fig 9 that

1 as air flow increases, temperature decreases,
2 above a certain rate of flow, as turbulence increases, at a constant rate of flow, temperature increases,
3 below a certain rate of flow, as turbulence increases, at a constant rate of flow, temperature decreases,
4 at certain low rates of flow, increased turbulence has no consistent effect on temperature

Although the term "turbulence" is used here to describe the effect of increased louver opening, it is realized that at low linear rates of flow the increased opening has the effect of increasing the quantity of air reaching the hot surface Therefore, the condition described in item 3 would be expected to exist

The significant region of this plot is the region of higher flow rates where increasing turbulence in the vicinity of a hot surface is shown to have an adverse effect on safety by causing higher surface temperatures Furthermore, the higher the linear flow rate the greater this adverse effect becomes as revealed by the increasing slope of the constant temperature lines The apparent effect of this on fire ignition was revealed in the tests

Following are the results of the temperature and pressure studies made on the aircraft vacuum system under normal operation when the engine was running at 2,400 rpm and the wind tunnel was producing an air blast of 112 mph At the vacuum side of the pump, a differential of 8 in of mercury was indicated, while on the pressure side, a differential of 18 in was indicated The temperature of the vacuum side was 150° F, and of the pressure side, 250° F These temperatures are less than have been reported in flying aircraft When the vacuum side was blocked, the temperature on the vacuum side was 300° F, while at the pressure side it was 550° F The worst condition occurred when the pressure side was completely blocked This condition produced temperatures in excess of 800° F, at which point fire could result if the



NOTES 1 NUMBERS ON CHART ARE TEMPERATURES IN DEGREES F OF
EXHAUST STACK SURFACE (THERMOCOUPLE NO 7, FIG 4)
(EACH IS AVERAGE OF SEVERAL READINGS)
2 NOTATION OF AIR INTAKE OPENINGS
A-ADDED AIR SCOOP CLOSED,
OPENING FROM ZONE I
EXHAUST SHROUD STOPPED UP
B-ADDED AIR SCOOP CLOSED
C- " " " 1/4 OPEN
D- " " " 1/2 "
E- " " " 3/4 "
F- " " " FULLY OPEN
OPENING FROM ZONE I
EXHAUST SHROUD
OPENED (NORMAL)

Fig 9 Effect of Character of Air Flow Through Exhaust Stack Well on Temperature of Stack Surface

proper ratio of air to oil vapor were present Pressures exceeded 100 psi

As noted previously, it was possible to trace roughly the paths followed by a simulated fluid leak within the accessory section by two methods, viz , visual inspection during the flow and study of recorded temperatures of thermocouples located in the region of the leak Certain observations thus made are noteworthy

It appeared that there is insufficient flow of air within Zone 2 to carry a falling fluid very far from its natural course and that it will therefore flow to the bottom of the zone unless it reaches another exit to the outside Thus, all fluid which is not released very close to the outer cowling or in the neighborhood of certain portions of the exhaust stack shrouds finds its way to the bottom of the nacelle and apparently drains out through the gap just forward of the oil cooler air exit flap No fluid which followed this path was ignited in these tests.

In some tests, gasoline was ejected just above the forward end of the exhaust stack shroud, forward and outboard of the feathering pump, near the single louver in the cowling at this point The gasoline thus released was seen to flow out through cracks in the cowling, especially between the cowling and air seal diaphragm and between the cowling and stack shroud A little came out the louver It flowed down over the stack well cover and apparently into the well, but no ignition occurred in these tests even when the stack was separated at a nearby joint and temperatures were excessive

In two tests, fuel was released above the turbosupercharger shroud and compressor casing in the left side of Zone 2 In this case, fuel was seen flowing down over the turbosupercharger and the cooling bell, but again no ignition occurred

Fuel released above the joint in the stack shroud just forward of the turbosupercharger (Fig 6), flowed profusely through the joint down onto the stack and shroud, where ignition frequently occurred It is possible that the excessive temperature to which the shroud had been subjected due to exhaust gas leakage below it had warped the shroud and opened the joint wider than normal Although this is a contingency to be reckoned with in practice, for these tests the joint was restored to normalcy as nearly as possible, with additional bolts to draw the overlapped parts together Fire which was ignited in this manner nearly always spread into the interior of the accessory section This occurred instantaneously and with near-explosive violence In some instances, the accessory door was blown out

Unfortunately, the propeller feathering oil tank the turbosupercharger lubricating oil tank, and the gasoline and oil lines along the sides of the accessory section are so located that if a failure should occur in any of them, the flammable fluids which they contain might conceivably seep through the hazardous lap joint and become ignited A general relocation and rerouting of these items in the accessory section would be a desirable modification.

In later tests, the fuel nozzle was moved to various positions around the stack itself, and the investigation was confined to the influence of air flow through this region on fire ignition

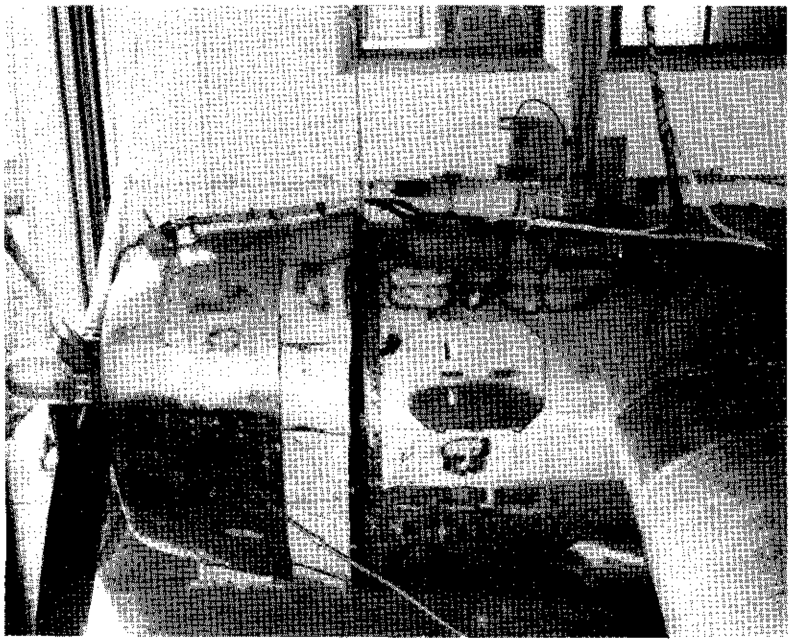
As previously pointed out, the recorded pressure of the air passing through the normal configuration of the exhaust stack well was 1 1 in of water. This was insufficient to prevent fires from readily being ignited in the stack well when gasoline was introduced into this region Even when the air flow was increased to produce a pressure of 1 6 in., fire would start The highest pressure observed was 3.1 in At that rate of flow, fuel was never ignited in the stack well in any of the tests.

A detailed study of these relations was not attempted on the full-scale power plant, but such a study is being made under controlled conditions on the bench

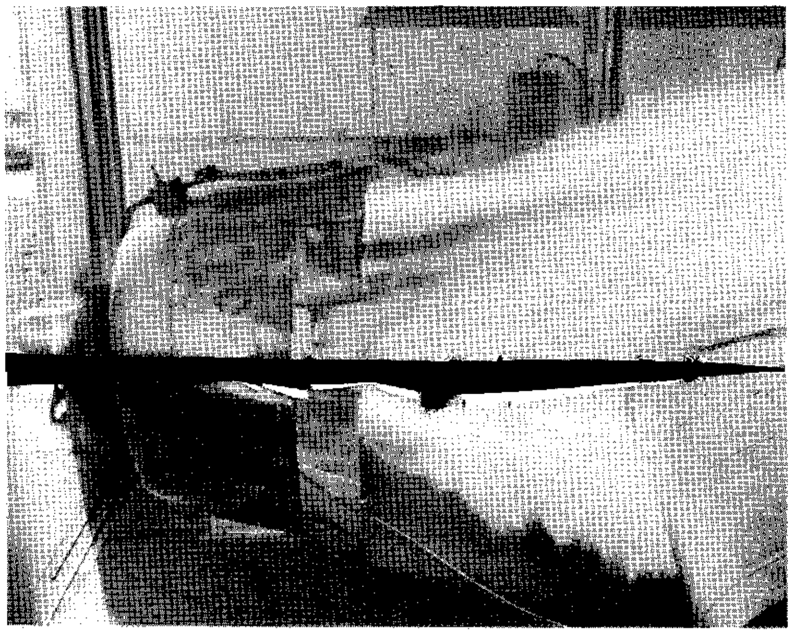
The results of bench tests conducted to date are not directly applicable to the problem of air flow in the B-29 exhaust stack well because the well was not duplicated on the bench However, they appear to lend support to the observations made in connection with the B-29 tests that, at a given temperature of the hot stack, if the air speed is above a certain value, ignition will not occur.

In the bench tests, the stack is a smooth cylindrical tube and the duct is smooth-surfaced and of square cross section With this comparatively unrestricted arrangement, the air speeds required to prevent ignition are much lower than those required in the well of the engine installation.

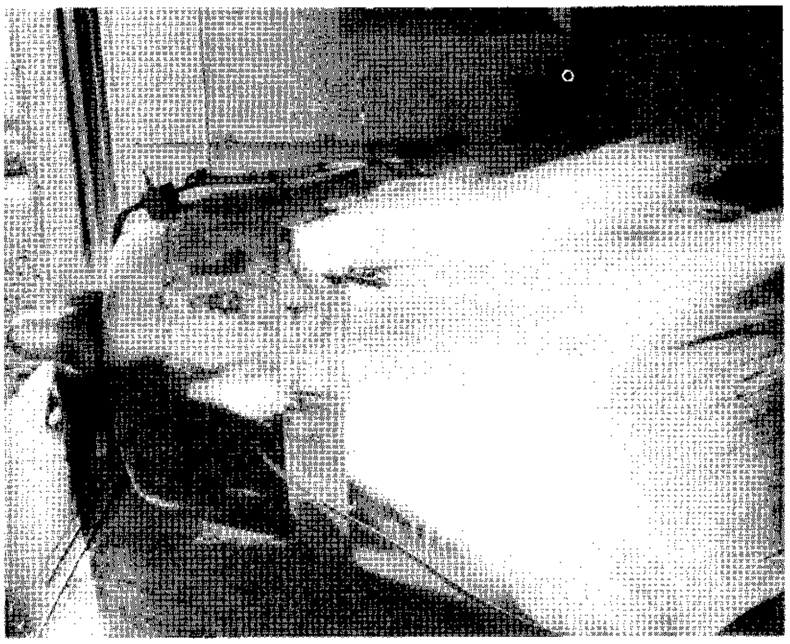
The results of 89 engine exhaust stack well tests, using gasoline for fuel, are shown graphically in Fig 10, using the same coordinates as for the temperature plots of



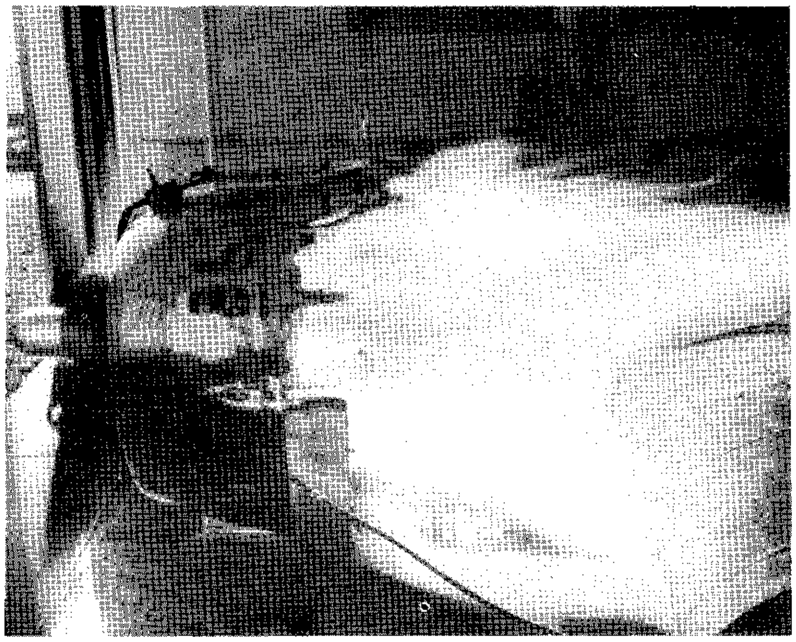
BEFORE THE FIRE



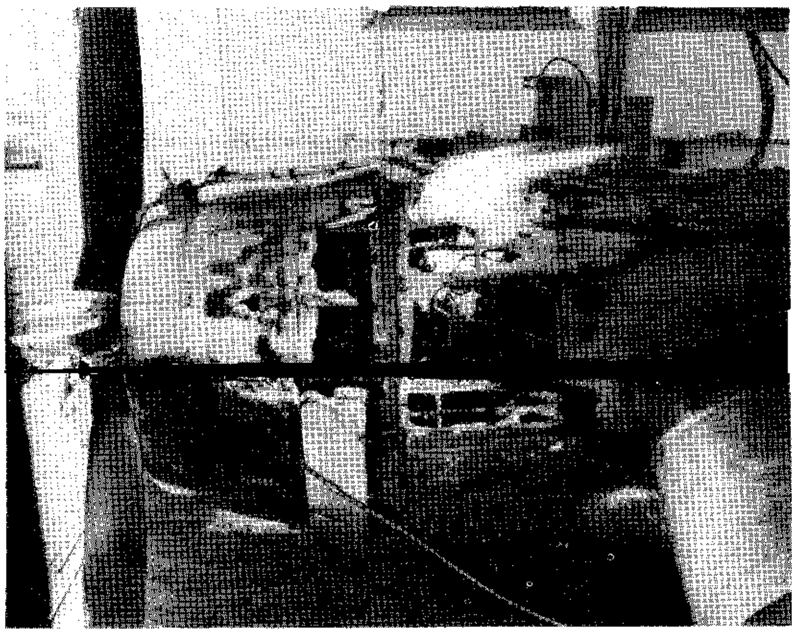
15 SECONDS FROM START



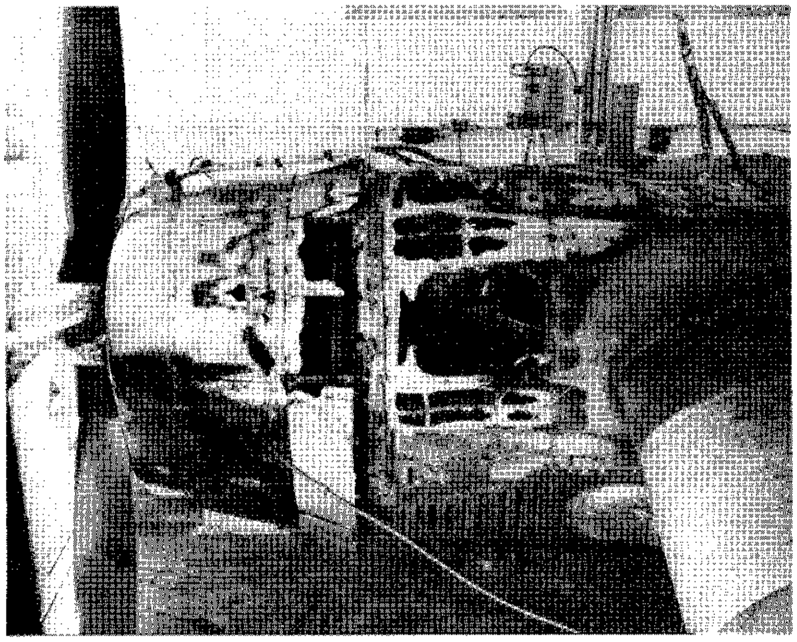
35 SECONDS FROM START



45 SECONDS FROM START



100 SECONDS FROM START



AFTER THE FIRE

Fig. 14 Progress of Fire During Final Test

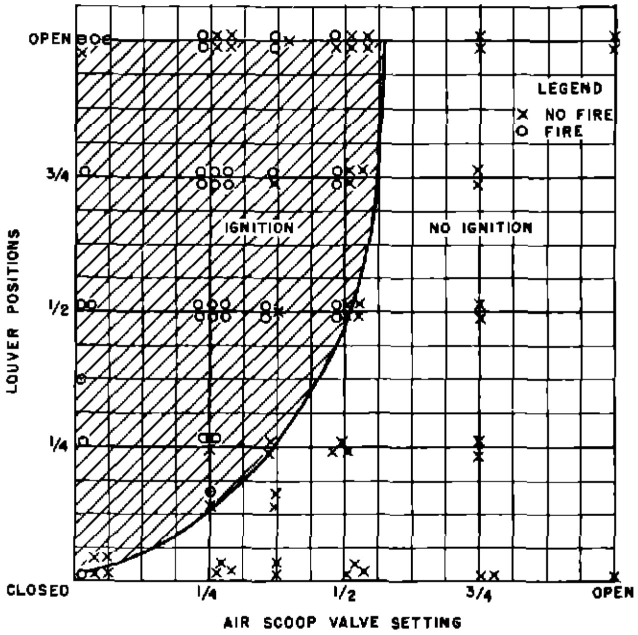


Fig. 10 Effect of Character of Air Flow Through Exhaust Stack Well on Ignition of Gasoline by Exhaust Stack

Fig. 9 In Fig 10, a circle represents a test in which ignition occurred and an x represents a test in which no ignition occurred. The location of the mark shows the relative conditions of air flow existing in the stack well during the test as determined by the position of the valve in the added air intake scoop and of the louver cover All other conditions are unchanged except the location of the fuel nozzle and the rate of fuel flow. Two positions were used for the nozzle, one inside the accessory section secured about 5 in above the shroud at the overlapping joint previously referred to (just forward of the flanged connection between stack and turbosupercharger), and the other position within the stack well, 7 in forward of the forward edge of the turbosupercharger cooling bell, 1 in below the upper surface of the stack well, and 4 in inward from the well cover In the first position, the rate of gasoline flow was about 0 5 gpm, in the second about 0 2 gpm (through a nozzle having a No 60 drill hole).

The regions of the plot in which ignition occurs and in which no ignition occurs are quite well defined by the line drawn to represent the borderline conditions In general, low linear air flow and high turbulence are conducive to ignition, and the opposite characteristics, to greater safety

A comparison between this plot and that of Fig 9 shows that the boundary line of ignition deviates from the constant temperature lines most sharply in the range of minimum turbulence and in the direction of greater safety (less likelihood of ignition) This deviation substantiates what might be theoretically reasoned, viz., that turbulent air in a region of potential ignition does double duty in facilitating ignition by increasing surface temperature and by more thoroughly distributing the fuel around the surface and encouraging the existence of localized explosive mixtures.

As a further commentary regarding shrouded and unshrouded exhaust stacks, it is well to note that not a single case of ignition occurred in 28 tests where fuels were directed upon the ring in Zone 1 although the ring was heated to a bright cherry red The open smooth air blast past it apparently made ignition impossible.

A brief series of tests was conducted to investigate the possibility of ignition by an overloaded motor or pump inside Zone 2 The propeller feathering pump was used for the tests and a manual shutoff valve was placed in the outlet line of the pump so that by closing the valve and operating the pump a condition of overload on the pump and motor could be obtained Gasoline was allowed to flow onto the motor and pump during each test from a one-fourth inch tube located directly above the motor During this overload condition, a thermocouple on the motor indicated a maximum temperature of 350° F and a thermocouple on the pump indicated a maximum of 160° F After four tests with a total running time of 16 minutes, the motor was inoperable, the paint on the motor casing was badly blistered and two 200 amp fuses were blown A 325 amp fuse was used for the final test However, the gasoline running over the motor and pump was not ignited in any of the tests Work of this nature is planned in the bench tests where more accurate and controlled conditions can be obtained.

CONCLUSIONS

1 The double layer of metal separated by an air space, which forms the shroud between

the exhaust stack well and the accessory section, is effective in shielding the accessory section from the heat of the exhaust stack

2 For maximum benefit, the double layer of metal should be continuous and should be so designed that the space between the two layers can be drained

3 Failure of the exhaust stack can cause a dangerously high temperature inside the accessory section near the region where the failure occurs

4 Increased air flow through the stack well is effective in reducing the temperature in that region and in preventing ignition.

5 Complete blockage of the pressure side of a vacuum pump while in operation can produce a sufficiently high operating temperature within the pump to create an ignition source

6 Gasoline leakage inside the accessory section will drain away harmlessly in most instances except when the leakage gains access to the turbosupercharger through the shrouding Fire then can occur and spread back into the accessory section

7. Overloaded pumps and motors did not generate sufficient heat to become ignition sources in the tests

THE IGNITABILITY OF AIRCRAFT FLUIDS

The purpose of this investigation was to determine the relative ignitability of a number of aircraft fluids in an effort to find new fluids which would be less hazardous than those currently used. Hydraulic fluids, lubricating oils, and gasolines are all highly flammable, but, with the exception of the latter, do not need to be It is conceivable that even gasoline might be made more safe Hence, a number of tests have been conducted using all the available fluids

One series of tests was completed in which comparisons were made of seven hydraulic fluids All were exposed to various types of ignition sources to determine their relative flammability under flight conditions In the B-29 installation, under simulated flight conditions, four types of ignition sources were provided hot stack, hot gases, spark, and a previous fire (presumed to have originated elsewhere in the installation) One fluid tested was the standard hydraulic fluid currently used in aircraft The remaining fluids were developed by various companies in an effort to find a fluid which is less flammable than the standard The results of these tests have been reported.[6]

Another series of tests were conducted using SAE 10 oil, 100-octane gasoline, kerosene, and a few low volatility fuels The latter are special fuels which have a sharply defined boiling range In laboratory tests conducted by a few oil companies, these fuels appeared to be less hazardous than 100-octane gasoline However, the tests consisted of spilling or splashing the fuels near ignition sources such as an open flame, a hot stack, or an electric arc No tests had been conducted in which the fuels were released in the presence of ignition sources in aircraft power plants operating under flight conditions Tests of this nature, therefore, were undertaken in connection with the ignition source investigation conducted on the test power plant installation.

PROCEDURE

The test equipment used in this investigation already has been largely described under the previous section of this report titled 'Fire Ignition Sources " However, instead of a single nozzle being employed, as many as four nozzles were used - one for each of the fuels being compared at the time The nozzles were mounted together in such a manner that one fuel after another could be sprayed and tested with the same ignition source Each nozzle was connected by one-fourth inch OD copper tubing to its own aircraft fuel pump, which, in turn, was connected to its own supply drum

During the course of this series of tests, the engine was operated usually at 2,400 rpm and 31 in manifold absolute pressure The cylinder head temperatures were intentionally kept high at 350 to 450° F The wind tunnel produced a 112 mph air blast through and over the nacelle

Once the nozzles had been mounted in a particular position in the nacelle, it was possible to proceed through a series of indi-

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[6] Power Plant Section, 'Determination of Ignition Characteristics of Hydraulic Fluids Under Simulated Flight and Crash Conditions," CAA Technical Development Report No 64, April 1947

vidual tests of the several fluids under a number of different engine operating conditions. After completing one cycle of tests the nozzles were moved as desired and the testing resumed The sequence and operation time of various units in the test system such as the fuel pumps, the fire detectors, and the extinguishers were recorded

In an individual test of a particular fuel, the proper pump was operated for a one minute period unless fire occurred The pump produced a flow of 0 5 gpm at the nozzle If fire occurred, the pump was stopped and the flow to the nozzle terminated. Usually the cessation of the flow was sufficient to extinguish the fire, but occasionally the fire persisted necessitating the use of carbon dioxide from the stand-by system

DISCUSSION

A series of 35 tests was conducted in which SAE 10 oil was the flammable fluid used The tests were conducted in a similar manner to the tests involving gasoline and the results are plotted in Fig 11 using coordinates similar to those of Fig. 10 for gasoline. Comparison of the two plots shows a larger area of potential ignition for oil because two fires were ignited with the air scoop one-half open and the louvers closed. In general, this substantiates the results of other investigations, including Zone 1 tests described later in this report

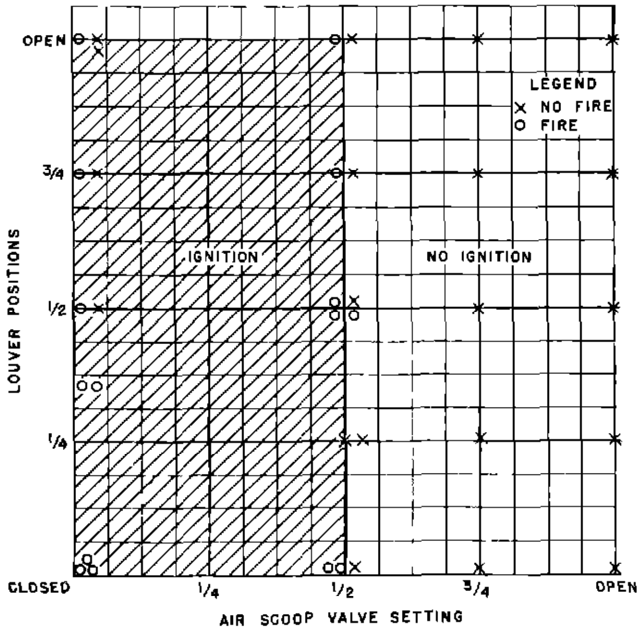

Fig 11 Effect of Character of Air Flow Through Exhaust Stack Well on Ignition of Oil by Exhaust Stack

In comparing the relative ignitabilities of low volatility fuels with gasoline in any group of tests, no consistent differences were found An apparently superior performance of gasoline in one group of tests would be nullified by an opposite performance in another group It was generally observed, however, that the lower volatility fuels were less predictable in their reactions to a given set of conditions than was gasoline and thus, in this somewhat negative sense, were more hazardous

In a separate series of 359 tests in which the various fuels were more directly compared under different conditions, the results again indicated that no adequate grounds exist for rating one type of engine fuel as safer than another with respect to engine fires in flight Table II summarizes the results, showing the number of tests resulting in fires and the number resulting in no fires as well as the percentage of fires to tests for each fuel and for each type of ignition source tried Each test consisted of the ejection of a fuel into the specified ignition source for from 30 seconds to one minute unless fire broke out in less time

For the collector ring tests, the nozzles were mounted just forward of the rear collector ring approximately aft of cylinder No 5 (right center of engine), directed rearward so that the fuel impinged directly on the ring surface For the stack and turbosupercharger tests, the nozzles were inside the exhaust stack well and they ejected the fuels directly onto the stack in some tests and onto the turbosupercharger casing in others. For the spark tests, a shielded spark plug was placed in the air stream outside the nacelle and the nozzles directed the fuel toward it In different tests, the engine speed ranged from 800 to 2,400 rpm and tunnel settings ranged from low to maximum

A slightly lower percentage of fires to total attempts is shown for the low volatility fuels than for gasoline and kerosene, but the difference cannot be considered to constitute a positive safety factor It also was observed that the low volatility fuels and kerosene burned with consistently less violence than

TABLE II

RELATIVE IGNITABILITY OF FUELS

Fuel	Boiling Range °F	Ignition Sources								
		Collector Ring			Stack and Turbosupercharger			Spark		
		Fire	No Fire	Per Cent Fires To Tests	Fire	No Fire	Per Cent Fires To Tests	Fire	No Fire	Per Cent Fires To Tests
100 Octane		0	8	0	31	19	62	36	27	57
High-Flash	300-400	0	8	0	17	14	55	21	21	50
High-Flash	300-400 + Propane	0	8	0	22	17	56	26	28	48
High-Flash	200-300	0	4	0	6	5	55	6	9	40
Kerosene		-	-		9	2	82	10	5	67

did gasoline in the brief fires of these tests, but this too is of slight significance since ample experience has shown that even heavy engine oil can burn with great violence and heat when started, especially in the presence of an air blast. There appears to be no significant difference between the performances of the three types of low volatility fuels tested

CONCLUSIONS

In the event of engine failure in flight, which releases quantities of flammable fluids amid the ignition sources about the engine,

(a) Low volatility fuels would be nearly as hazardous as 100-octane gasoline,
(b) SAE 10 oil would be more hazardous than 100-octane gasoline
(c) Kerosene would be more hazardous than 100-octane gasoline or low volatility fuels

FIRE DETECTION

A fire detecting program for the B-29 airplane was conducted concurrently by another fire test group under contract to the U S Air Force[7] Therefore, detection problems were not included in these investigations However, some information which would be helpful in designing a fire detecting system for this airplane was sought Also, two types of detectors were given preliminary tests

DETECTING SYSTEM DESIGN DATA

Tests were conducted in the B-29 engine installation to determine the maximum temperatures and the maximum rates of temperature rise of the air at the cowl flap openings during normal and severe engine operating conditions In the accessory section, an attempt was made to discover some particular region or regions which would be consistently exposed to the heat of fires originating anywhere in the zone so that a detector system could be simplified by the location of a minimum number of detectors in the most advantageous places

Seven thermocouples were installed in the cowl flap openings, spaced uniformly around the engine to record the temperature changes during operations which would supposedly produce the highest temperature or the greatest change in temperature

These operations included landing and cutting the engine, and propeller pitch reversal Both operations were simulated Since the propeller on this particular test installation could not be reversed, this procedure was simulated by releasing a current of air from a compressed-air line through an expanding horn placed just aft of the top cowl

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[7] C-O-Two Fire Equipment Company "Aircraft Power Plant Fire Protection" Final Report on A A F Contract No W-33-038-ac-8489, February 1948

flaps directed forward

For each test, the engine was run for from 10 to 25 minutes with the cylinder head temperature at about 450° F To make the conditions more severe in some tests, the cowl flaps were closed to about three-fourths inch opening immediately upon shutting down

The results obtained from the cowl flap thermocouples in three representative tests are reproduced as curves in Fig 12 The maximum rate of temperature rise obtained in any test was about 450° F per minute, but this rate lasted only four seconds, and the average change of temperature was approximately 100° in all tests The maximum temperatures and maximum rates of rise occurred in the top sector of the engine and in the regions adjacent to the two exhaust stacks A series of six Edison type detectors mounted in the top of the cowl flap opening did not operate during any of the tests

In the accessory section, four groups of detectors were mounted at selected regions, one group in each region Each group consisted of four Edison type detector units connected in series The four locations were

1 At the top of the zone, above the air intake ducts to the carburetors
2 At the sides of the zone just below the access doors (two detector units on each side, but all connected together)
3. At the bottom of the zone, two or three inches above the upper surface of the main air duct
4. At the approximate center of the zone, just aft of the starter

The extreme rear end of the zone, it was thought, would undoubtedly require localized coverage and was not included in this study

With the wind tunnel operating at full power (112 mph), but without the engine running (propeller feathered), small running gasoline fires were ignited in various parts of the zone. Records were made of the detector groups which operated and the time required to signal an alarm

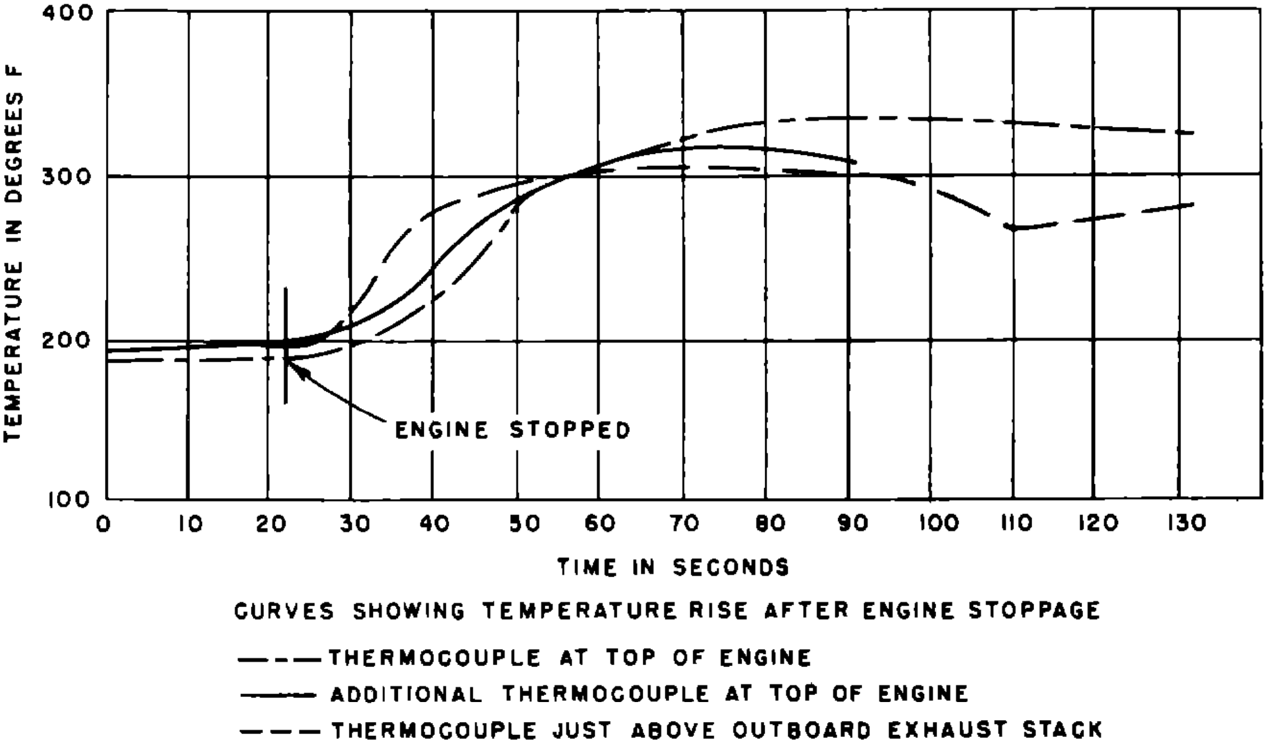
In tests with fire originating at seven different locations in Zone 2, no one group of unit detectors operated consistently Reacting times in general were poor, ranging from 7 to 34 seconds However, none of the fires was located very close to any group Fires located far forward at the bottom of the zone were not detected at all, and most of the fire appeared to be emerging to the outside of the nacelle through cracks between the air seal diaphragm and the cowling In 20 tests, group one operated most frequently, 13 times, group two operated 9 times, group four operated 7 times, and group three not at all

PRELIMINARY TESTS OF TWO TYPES OF DETECTORS

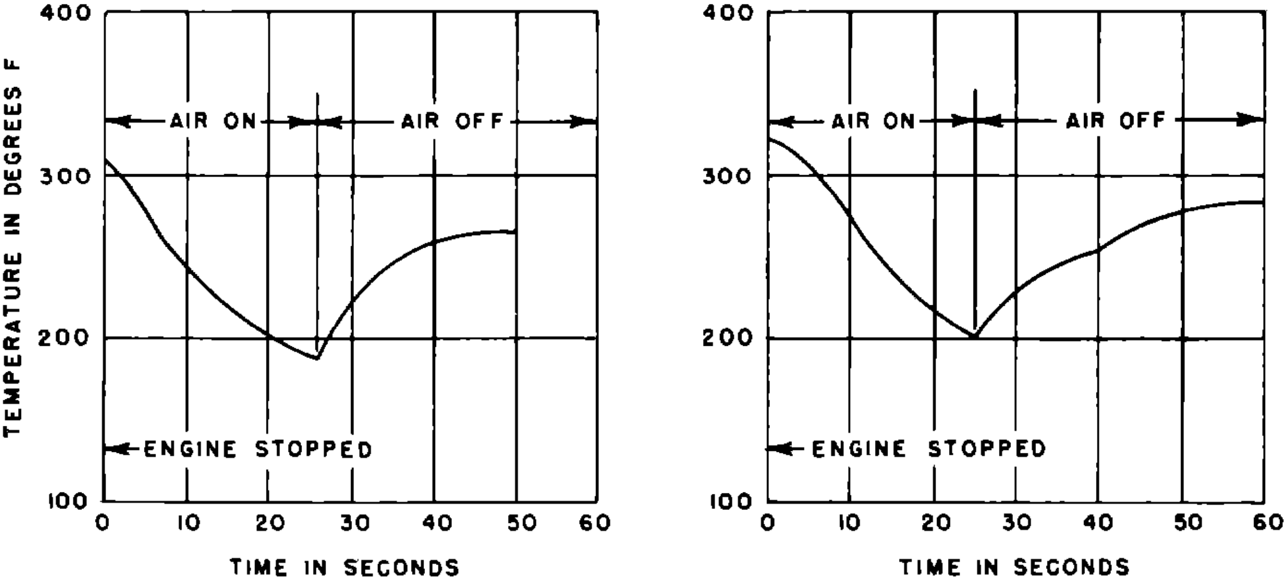
Tests of a preliminary nature were conducted with two types of detectors to determine their reliability and limitations The first was a flame detector designed by Minneapolis-Honeywell Regulator Company, and the second was a light detector designed by Photoswitch, Inc

The Minneapolis-Honeywell detector consisted of a standard 1/16 in stainless steel stranded control cable which was mounted on the side of the nacelle and underside of the wing by means of standard commercial standoff porcelain insulators. The principle of operation required that flames be carried backward along the outside surface of the nacelle or under the surface of the wing by the air stream in such a way as to impinge on both the aircraft skin and the detector wire simultaneously The flames, being ionized, completed an electric circuit which caused a warning light to operate and thus indicate the presence of fire Gasoline fires were used in some tests and hydraulic fluid fires in others. Both the wind tunnel and the engine were in operation during these tests.

The Photoswitch detector (trade-mark "Fireye") used a photocell One photocell unit was placed in the power section near the cowling at about Station -30 (see Fig 19) and radially at about Cylinder No 4 (see Fig. 13) It was pointed to observe the area downward and rearward of that point Fires were originated at a number of different points, both in front and in back of the engine, simulating failure at cylinders on the right side of the engine The other photocell was located just below the accessory door at about Station 15 on the right side of the accessory section and pointed to observe the opposite side of the nacelle Fires were originated at a number of points on the right side of the accessory



CURVES SHOWING TEMPERATURE RISE AFTER ENGINE STOPPAGE



CURVES SHOWING TEMPERATURE DROP AT TOP OF ENGINE DUE TO INDUCED REVERSED AIR FLOW AFTER ENGINE STOPPAGE, THEN TEMPERATURE RISE WHEN REVERSED AIR FLOW WAS STOPPED

Fig 12 Curves Showing Temperature Changes in the Region of the Cowl Flaps During Engine Operation

section also, thus increasing the difficulty of detection

The units were connected to a warning light and to a sequence recorder. Air at

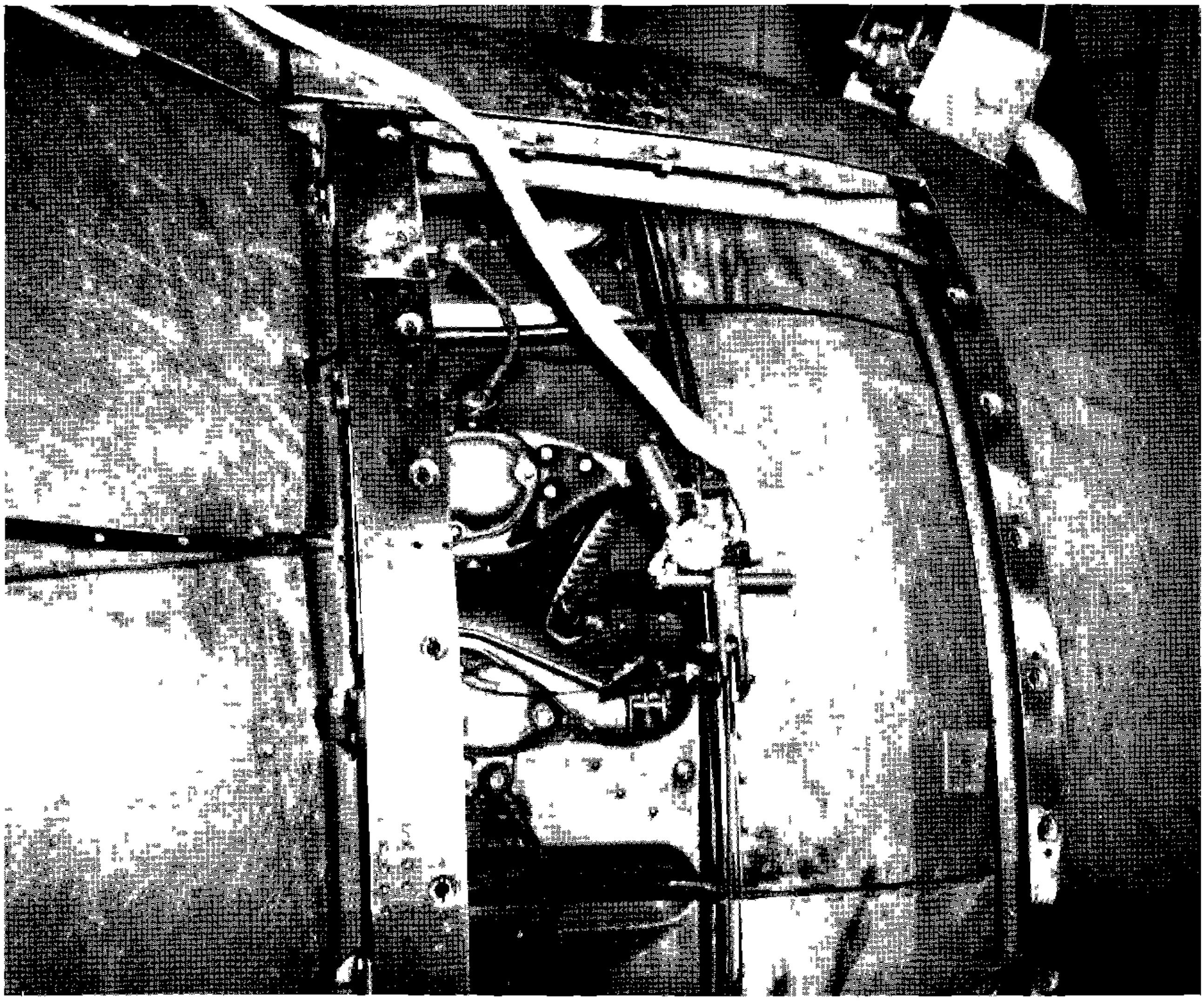


Fig 13 Photoswitch Detector Mounted on B-29 Engine for Tests

maximum speed provided by the wind tunnel was used to simulate flight conditions The engine was not operated during these tests

The Minneapolis-Honeywell detector was successful in detecting all fires which were large enough to impinge simultaneously on both the detector wire and the adjacent airplane surface However, an unusual reaction occurred when silicone hydraulic fluid was burned This fluid left a heavy white coating (SiO_2) on all exposed surfaces and, being a good insulator, made the detector inoperative in the region affected Other hydraulic fluids which were tested left no deposit while burning and these fires were detected During prolonged fires, the resistance of the detector wire to ground reduced considerably, probably due to a coating of carbon on the insulators

The range of vision of the "Fireye" detector units was such that a single photocell was capable of detecting any fire originating on the right side of the engine from Cylinder No 18 to Cylinder No 7 or an area equal to nearly half of the engine This being the case, it would seem that two units would suffice as a detecting system for this power plant However, it is desirable to arrange for more than a single unit to survey a region of possible flame egress, so, the minimum number which should be considered for use in the power section is four. In the accessory section, a single unit was capable of detecting nearly every fire originating in this zone On the same theory that overlapping coverage is desirable, two units should be considered as minimum in the accessory section Additional units should be used if special areas do not appear to be adequately attended

CONCLUSIONS

1 The maximum rate of temperature rise at the cowl flaps during normal ground operations was 450° F per minute. This was not enough to cause the Edison type detector system to sound an alarm.

2 The average change of temperature during ground operations was approximately 100°

3 Maximum temperatures and maximum rates of rise occurred at the top of the engine and near the two exhaust stacks.

4 Adequate coverage of the accessory section could not be secured with any localization of units in particular regions, but required a fairly uniform dispersion of units throughout the volume However, some concentration of units toward the forward and upper sectors seems warranted

5 The sensitivity of the Minneapolis-Honeywell detector varied, depending on the thickness and type of coating deposited on the wire, insulators, and airplane surface

6 The minimum number of "Fireye" units which can be used in the B-29 power section to give complete coverage is four However, a larger number would be desirable

7 The minimum number of "Fireye" units which can be used in the B-29 accessory section to give adequate coverage is two, unless special regions are to be monitored

THE B-29 POWER SECTION INVESTIGATION

Tests were undertaken to determine the character of the fire, the possible sources of ignition, and the problems of detection and extinguishment when ignition occurs forward of the cylinders in Zone 1 of the B-29 power plant Following many fire tests, studies of the nacelle were made to learn what parts were most vulnerable and what improvements could be made to prevent the spread of fire from Zone 1 to other zones, thus allowing more time for extinguishment

PROCEDURE

Most of the experimentation in this particular part of the investigation took place on the left side of the power plant, where the fires could be carefully observed Three Fenwal fire detector units were installed on the air seal diaphragm in the region of the left-hand exhaust stack shroud One unit was mounted below the shroud adjacent to the cowl flap control arm in that sector, one just above the shroud, 18 in. above the first unit, and a third, 7 in. above the second unit All three units were connected together to the same signal light

One of the extinguisher rings previously mentioned under Description of Test Equipment was connected to a 12 6-lb bottle of carbon dioxide such as is normally used in aircraft extinguisher systems The ring was located just inside the cowling at a station approximately adjacent to the forward side of the front row cylinder heads. It was fabricated of one-inch copper tubing perforated with nine slots, each 1/16 by 15/16 in located so that discharge would be radially inward The ring was supplied at one point with one-inch OD tubing 27 feet long In these tests, the carbon dioxide was released from the container under high pressure at approximately 70° F through a Kidde one-inch flood valve

While the discharge of carbon dioxide at high pressure is superior in effectiveness to its discharge at low pressure, it is generally considered that a ring arrangement is inferior to a nozzle arrangement However, since the design of extinguishing systems was not included in this program, no attempt was made to design a system in accordance with best-known practice, but rather to use a system typical of those in general service In one or two tests, this high pressure system was tried for the purpose of comparing it with the low pressure stand-by system ordinarily used in the test work when needed

In order to use oil directly from the engine for the fires and thereby simulate actual fire conditions as closely as possible, a special double outlet fitting was attached to the front oil pump sump outlet (return to tank) and a line installed from that point to the oil nozzle A remotely controlled valve was placed in this line which, being normally closed, allowed all the oil to follow its usual route During a test fire, however, when the valve was opened, the oil was divided between the fire and the return to the tank, but, since the inlet to the tank was at the top of the nacelle, most of the oil went to the fire In the last test of this series, a spring-loaded check valve was placed in the return line to the tank to cause all oil to go to the fire, even with the nozzle located near the top of the engine

During each test, the special oil valve was opened to start the oil flow, and kept open, so that the oil flow continued until the engine was stopped The oil nozzle was simply the open end of a seven-eighth inch tube, the same size as the outlet of the sump The gasoline nozzle was a one-eighth inch diameter hole in a fitting which permitted a flow of 0 75 gpm

In all tests, the engine was operated at 2, 300 rpm and 38 5 in manifold pressure (1, 760 bhp), with approximately 3 7 in cowl flap opening and 470° F cylinder head temperature The tunnel was operated at full air speed of 112 mph.

DISCUSSION

Gasoline alone did not ignite on the engine in any of the tests Oil alone would ignite consistently, when released in the lower left region of the engine, in from 2 to 20 seconds after the start of oil flow Ignition undoubtedly took place on the hot exhaust stack in the stack well and worked forward When released higher in the engine, forward of Cylinder No 16, however, the oil did not ignite in six different tests in which flow continued for from 15 to 45 seconds

In three tests, the gasoline nozzle was placed forward of Cylinder No 12 (lower left sector of engine) so that the stream of gasoline divided and went partly back through the engine to the cowl flaps and partly into the space around the forward collector ring, then through the exhaust stack shroud to the turbosupercharger well The fires which resulted were not detected in any of these tests About 75 to 90 per cent of the fire was inside the stack shroud, the remainder of the fire issued through the cowl flap opening in the region of the detectors The flames were stratified and, although they appeared to pass within two or three inches of the detector units, they did not set them off. In all tests, fire could be seen through small cracks in the Zone 1 cowling in the region of the exhaust stack between the front and rear collector rings The cowling was burned out in two of the fires in this region

Detection of three oil fires occurred in from two to five seconds after ignition, when the oil nozzle was placed so that all the oil went back through the cowl flaps

In six tests, in which the fuel to the fire was shut off either by closing valves or feathering the propeller, the fires went out without use of extinguisher In two of these, however, in which gasoline was ejected into the space around the front collector ring, the fire, though small, hung on in the region around the exhaust stack shroud between the front and rear collector rings for about a minute after the gasoline was shut off Other fires went out in from 15 to 30 seconds after fuel flows were stopped

In five tests, the propeller was not feathered after the engine was cut in order to simulate failure of the feathering system and the propeller continued to windmill and pump oil to the fires These fires were sharply reduced by shutting off the engine and one fire went out completely while the propeller was still turning In two other cases, the fires were ignited in the stack well and spread only into the cowl flaps in this immediate region These fires persisted as long as the propeller turned even though, in one instance, carbon dioxide was released in Zone 1

In a fourth test in which the propeller was permitted to windmill, a fire which was originally very large in Zone 1 was knocked down by the discharge of 12 6-lb of carbon dioxide forward of the cylinders in Zone 1, but very small flames persisted around the cowl flap control arms until the oil flow was stopped In this test, the engine was cut 45 seconds after ignition and the extinguisher was released five seconds later The propeller was finally feathered about three minutes later, but small flames continued for another three minutes

In the final test of this series, a very large and damaging fire was experienced (See Fig 14) Both gasoline, at 0 75 gpm, and engine oil at the full flow from the front pump, were used The fuel nozzles were located forward of Cylinder No 16 (upper left sector of the engine) and the fuel flowed for 40 seconds before being ignited by a spark from an igniter From the beginning, the fire was very large and hot, reaching well back of the wing trailing edge and covering the entire left side of the engine After 20 seconds of unabated burning, the engine was cut, but the propeller feathering was not begun for another 40 seconds Twelve and six-tenths pounds of carbon dioxide were released in Zone 1, 15 seconds after the engine was cut, but since the discharge was through the ring located forward of the cylinders, no appreciable effect on the fire was noticed and the fire continued to reach about half-way over the wing as long as the propeller windmilled The propeller was stopped completely 1 1/2 minutes after the start of fire During the 30 seconds required to accomplish the feathering the fire steadily diminished and 10 seconds after the propeller stopped the fire in Zone 1 was completely out

In this brief period, practically the entire aluminum skin area on the left side and top of Zone 2 was burned away and fuel lines around the carburetor and injector pumps were opened so that flames hung on in these regions and were unaffected by a continuous discharge of low-pressure carbon dioxide into the zone When all gasoline was turned off, both to the nozzle and to the engine, the fire burned itself out

Sometime during the first 20 seconds of fire, a major structural member of the nacelle, an aluminum longeron running through the upper left part of Zone 2, was severely burned and weakened so that it failed in tension and shear at a point about one foot aft of the air seal diaphragm The member pulled apart at this point about 1 in After the test, it was found that the engine apparently had started to drop, for excessive weight was being held by the emergency suspension cable on the left side Fig 15 shows the extent of damage to the structural member

The facts revealed in this single test should be noted carefully This fire, which was fed by fuel from the engine itself, was capable of destroying the power plant supporting structure in less time than was required to feather the propeller But the propeller had to be feathered in order to prevent engine rotation and the attendant pumping of oil to the fire

Obviously, a feathering operation requiring 30 seconds is undesirable and should be avoided in aircraft However, many existing B-29 aircraft and other types of aircraft are equipped with propellers which require excessive time to effect complete feathering As long as such a condition exists there will be a need for adequate Zone 1 fire protection

The Zone 2 fire extinguishing system, with which the test installation was equipped when it arrived in the laboratory for tests, was wholly inadequate It consisted of a single ring perforated with a number of small holes Such a system provides no protection against power section fires, and very little protection against accessory section fires

It is realized that many fires can be eliminated by the simple process of shutting down the affected engine, stopping the flow of flammable fluids, and feathering the propeller In fact, this procedure has been recommended in combating an engine fire in flight[8] However, a power zone extinguishing system should be capable of extinguishing a fire even if the engine has not stopped. Hundreds of past tests have proven that this can be done[9, 10, 11] Some benefit will be achieved by initiating the shutdown procedure prior to releasing the extinguishing fluid

A further observation to be made from this fire test is the amount of damage resulting to the cowling, skin, structure, and accessory section equipment from relatively long exposure to fire The damage which occurred seriously affected the air flow conditions and increased the difficulty of extinguishment with reasonable quantities of agent Moreover, a study of the record of flight fires indicates that the damage to accessory section structure can lower the nose of the power plant to the extent that serious difficulties are encountered in controlling the aircraft because of aerodynamic changes Such fires occurring on an inboard power plant frequently damage the landing gear as well

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

[9] See footnote 1

[10] See footnote 2

[11] See footnote 3

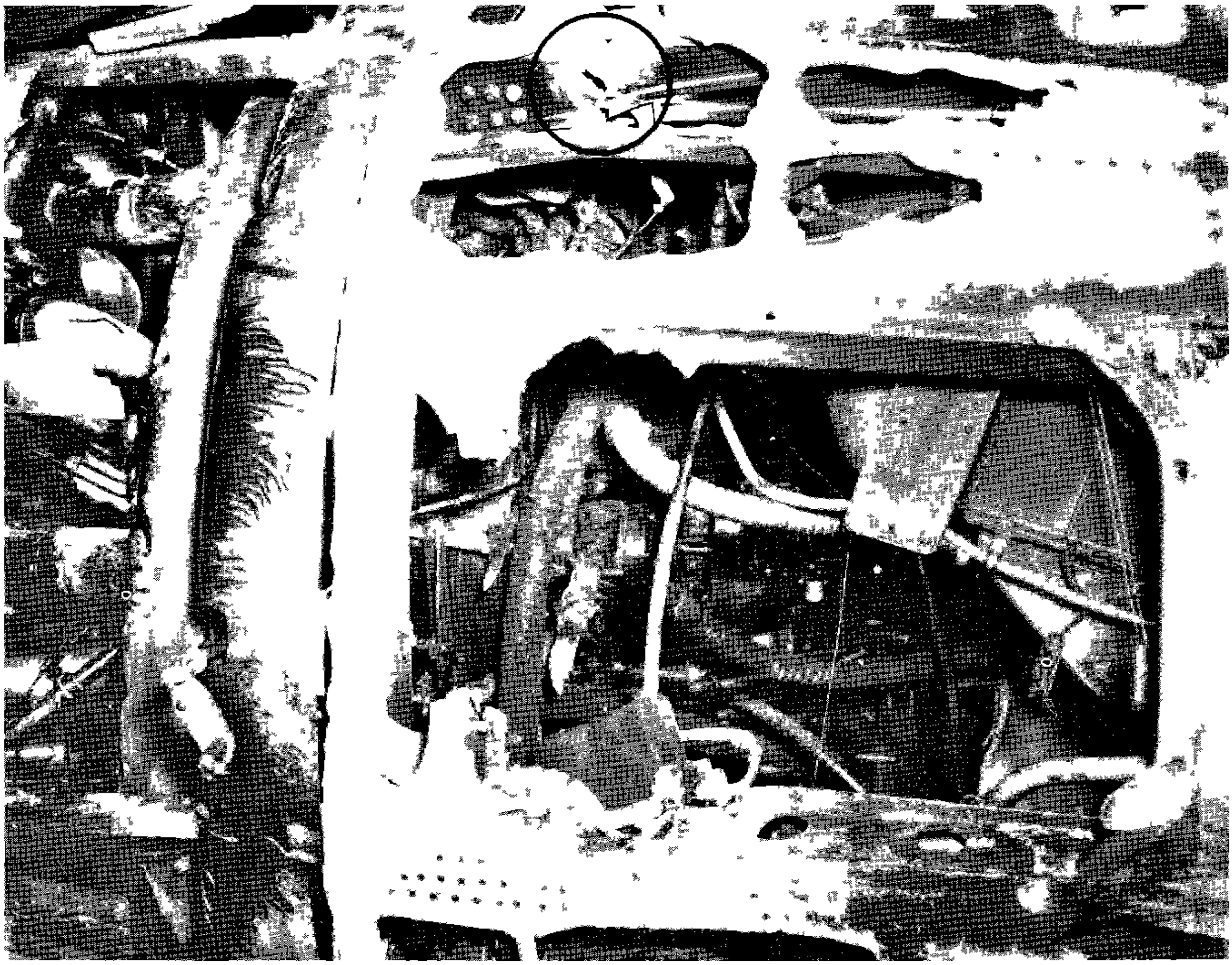

Fig 15 View Showing Failure of Structural Member as a Result of Fire

As an added safety measure, therefore, stainless steel should replace the aluminum alloy skin on the accessory section, the nacelle aft of the fire wall, and the wing for approximately one foot to each side of the nacelle Fig 16 was prepared to show the area which should receive this additional protection Stainless steel also should replace, or at least protect, the aluminum alloy structural members within the accessory section and the nacelle aft of the fire wall

During a series of runs to measure the baffle pressure drop through the engine, an accidental fire occurred which revealed several significant facts relative to Zone 1 fire protection The fire was occasioned by the loss of the magnetic sump plug in the front oil pump Oil poured back through the lower portion of the cowl flap openings and ignited, presumably on the exhaust system, within about ten seconds after oil was first seen Although the engine was shut down as soon as the fire was discovered, the propeller could not be feathered because the valve in the oil line supplying the feathering pump had been closed while work was being done on the engine prior to the tests and had not been reopened It could not be opened remotely and the air blast from the wind tunnel continued to windmill the propeller Far from blowing out the fire, the air blast spread the fire until practically the whole nacelle was enveloped in flames Low pressure carbon dioxide was released through rings (see Description of Test Equipment) in Zones 1 and 2 without appreciable effect on the fire The fire was finally extinguished by totally flooding the test cell with carbon dioxide after

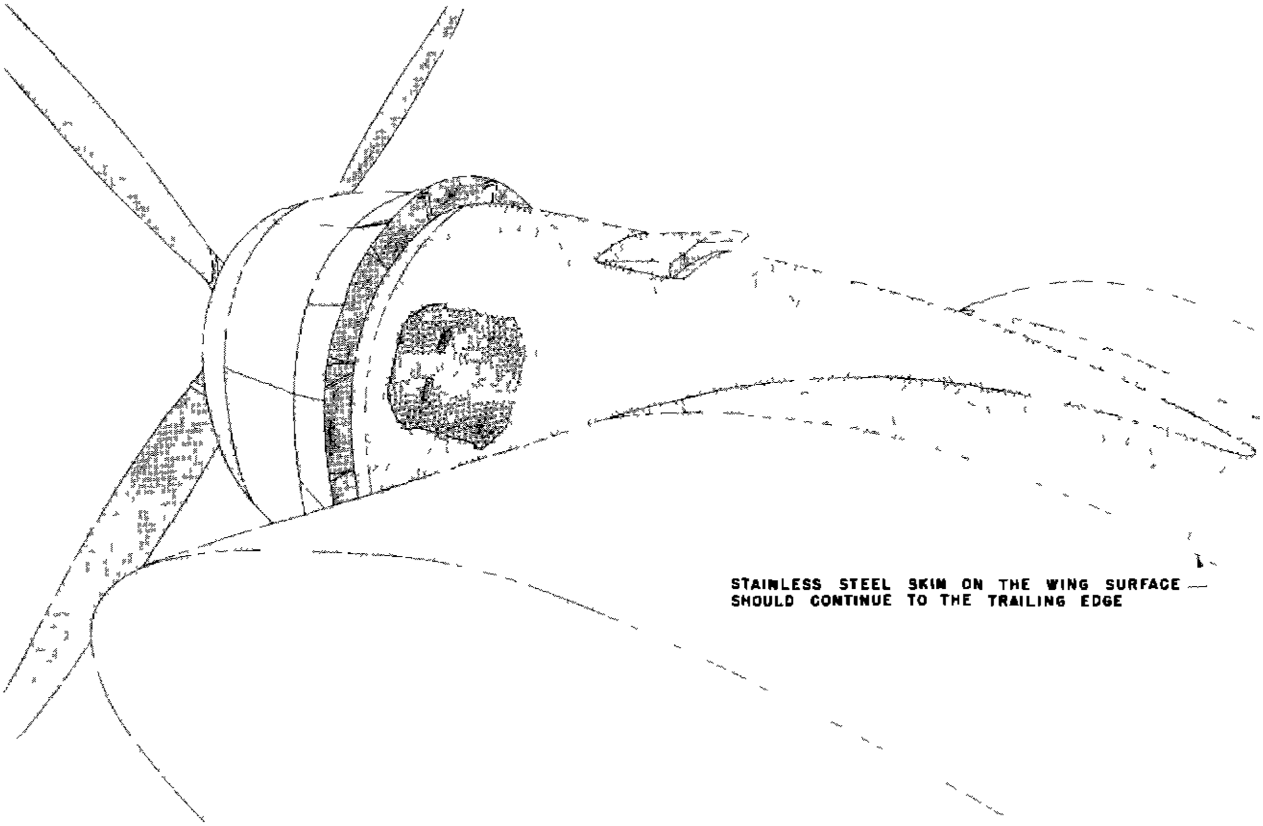

Fig 16 Sketch of B-29 Nacelle with Portion Dotted to Indicate Where Aluminum Alloy Skin and Structural Members Should be Replaced or Protected by Stainless Steel

the wind tunnel was shut down and the test chamber doors closed

The pertinent observations made in this instance were that

1 the source of fuel feeding the fire (the front sump) could not be stopped by valves, but only by feathering the propeller, and
2 the propeller could not be feathered

Ordinarily, either fuel and oil valves must be closed or the propeller must be feathered, or both, in order to effect extinguishment without an adequate Zone 1 extinguishing system If this accident had occurred in flight, it undoubtedly would have proved disastrous

In this particular instance, the inability of the propeller to be feathered did not result from any damage to the propeller feathering system However, it illustrates what might be expected to happen in a flying aircraft if the feathering mechanism should fail Since so much depends on proper functioning of this accessory, it follows that every effort should be made to assure that the feathering system is maintained in good working order and that it is well protected against possible damage by fire, at least until it has had an opportunity to do its all-important work

The fire spread into Zone 2 by burning out a piece of the main ring cowl air duct near the air seal diaphragm In not more than two minutes after the start of the fire, it had burned out a rubber hose at the fuel strainer drain outlet, releasing a large flow of gasoline in Zone 2 A number of other hoses, wires, and blast tubes were severely burned inside the accessory section Air valves inside the main air duct were burned and the oil cooler was severely damaged Both of the fuel injection pumps leaked at the gaskets, the left one leaking severely enough to require extensive repair The oil cooler, as well as a number of hoses and one cowl flap adjusting arm, required replacement The canvas flexible joint in the intercooler air intake duct was completely burned out The outer skin of the nacelle suffered practically no damage

In the region of contact between the air seal diaphragm and the ring cowl air duct, the provision for air and fire sealing was very inadequate The fire and unburned oil apparently were able to get past this seal in great quantities and enter directly into Zone 2 By the additional burning of some thin aluminum and rubber strips, entrance was gained into the oil cooler and the air induction system

The connection between the ring cowl air duct and the air seal diaphragm is closed with a strip of asbestos, but this is only a loose flap which can be easily disturbed by vibration and air blast Also, a hot flame plus vibration will disintegrate the asbestos quite rapidly Normally, an opening of about one square inch exists at one point along this joint, and this, plus burned out asbestos, was all the passage that could be directly seen after the fire The damage done behind this, however, proved that a long and hot, though not very widespread flame issued past this region, indicating that a larger opening must have existed during the fire

It should be noted that this fire was situated too low in the nacelle to burn out any of the aluminum cowling over the upper part of the accessory section, and the stainless steel over the lower part of the nacelle remained entirely intact, so that the only possible access into Zone 2 was through the air seal diaphragm A general tightening and true sealing of this diaphragm obviously is required and is very important

It also is pertinent, in connection with this fire, that the distribution of steel and aluminum around the nacelle apparently is determined by the proximity of the part to normal engine heat, and that, with few exceptions, no consideration is given to the possibility of a part forming a barrier to the spread of fire by having it made of fire-resistant material

Hoses, especially those carrying flammable fluids, should receive their full share of attention As the first step toward improvement, all clamped hose connections should be replaced with fixed-end-fitting hoses, and, as a further step, all rubber hoses should be replaced with flexible stainless steel hoses as soon as any such hoses have proved satisfactory in all respects

Tests of stainless steel hoses are reported elsewhere [12] In these tests, the conditions resulting from a malfunctioning vacuum system were simulated for the purpose of subjecting hoses and tubing to internal fires The commonly used fixed-end-fitting hoses withstood internal fires up to five minutes, but several types of flexible stainless steel hoses with fixed-end fittings were still undamaged after undergoing ten hours of internal fires

Objections have been made to the use of flexible stainless steel hoses on the grounds of excessive weight and poor performance records in vibration and torsion However, the weight has been found to compare quite favorably with most of the conventional type hoses. With no particular consideration being given to reduced weight, a one-foot length of flexible stainless steel hose with fixed-end fittings weighed one pound, while a comparable conventional hose of the same length weighed 0 9-lb, and one which was supposed to be particularly fire-resistant (it burned through in five minutes) weighed 2 5-lb As for poor vibration and torsion characteristics, there is every reason to believe that these will soon be overcome by continued development Since this is the one truly fireproof component in aircraft, its development should be encouraged

CONCLUSIONS

1 Gasoline and oil readily ignite on the hot exhaust stack inside the louvered well at either side of the nacelle.

2 Gasoline and oil are difficult or impossible to ignite on the unshrouded exhaust collector ring in Zone 1

3 Fires which originate far forward in the engine and enter the exhaust stack shroud may escape detection by detectors located near the cowl flaps

4. Fires in Zone 1 burn out if the flow of fluid feeding the fire can be stopped, even

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[12] See footnote 5

though considerable damage has been done to the cowling in the meantime.

5 The proper functioning of the propeller feathering system is of utmost importance in the control of power section fires

6 Power section fires can severely damage downstream structure of aluminum alloy in very few seconds

7 While small fires can be extinguished by feathering the propeller and stopping the flow of combustible fluids feeding the fires, the only sure means of providing complete protection is by the use of an adequate and properly designed extinguishing system.

8 The seal between the air seal diaphragm and ring cowl air duct is not sufficiently fireproof to prevent the spread of fire from Zone 1 to Zone 2

9 The aluminum alloy skin covering the accessory section does not provide sufficient protection to the structural members in this compartment

10 Rubber hoses fastened with hose clamps are very vulnerable to fire and should not be used to carry flammable fluids

THE SIMULATED L-49 INVESTIGATION

The power plant originally scheduled for study in the fire test laboratory was the Constellation L-49 However, by the time the laboratory was ready to begin operations, it was agreed that this airplane should yield to the B-29 Both the L-49 and the B-29 use the Wright R-3350 engine, and it was felt that, in the course of the tests, modifications could be made to the B-29 power plant such that it would adequately simulate the L-49 This course of action was desirable in that it obviated the necessity of installing an entire L-49 nacelle in the test chamber for the purpose of conducting a relatively brief series of tests

This portion of the report deals with the test program conducted on the simulated L-49 configuration to determine the character of fire, the possible sources of ignition, and the problems of detection and extinguishment when ignition occurs forward of the cylinders in Zone 1

PROCEDURE

The B-29 power plant was modified by removing the connecting stack on the right side of the engine between the forward and rear collector rings In its place, a short stack was connected to the forward ring This stack projected out through the Zone 1 ring cowl, bent rearward, and ended just forward of the cowl flaps. The opened connection in the rear collector ring was sealed A fairing of aluminum was added over the projecting stack as on the L-49 nacelle. (See Fig 17)

Four Fenwal detector units were mounted on the air seal diaphragm in the region aft of this revised exhaust stack One unit was mounted just below the exhaust stack shroud, another just above the shroud (12 in above the first one), and the other two, 10 and 20 in , respectively, above the second unit They were placed on the air seal diaphragm as far outboard as possible, still allowing full closing of the cowl flaps All four units were wired together to the same signal light

Two thermocouples were placed in Zone 1, one forward of Cylinder No 8 near the source of fire, and one back at the cowl flap opening adjacent to the detector unit located just above the exhaust shroud

Fuel nozzles for the fire were placed forward of the cylinders near Cylinder No 8, which is adjacent to the modified exhaust stack SAE 10 oil and 100-octane gasoline were used The flow of gasoline was at first 1 3 gpm and later reduced to 0 75 gpm The flow of oil was approximately 3 5 gpm

In all tests, the engine was operated at 2,300 rpm and 38 5 in manifold pressure (1,760 bhp), with approximately 3 7 in cowl flap opening and 470° F cylinder head temperature The tunnel was run at full speed

DISCUSSION

In the first ten tests, the fuel nozzles were so placed near the forward side of Cylinder No 8 that all of the fuel was carried back past the cylinders and out through the cowl flaps, none getting forward far enough to be carried out past the special projecting exhaust stack

In the second group of tests numbered 11 to 23, both nozzles were placed farther forward so that the fuel divided, going partly back through the engine and cowl flaps and partly into the region around the front collector ring, whence it was carried back and out

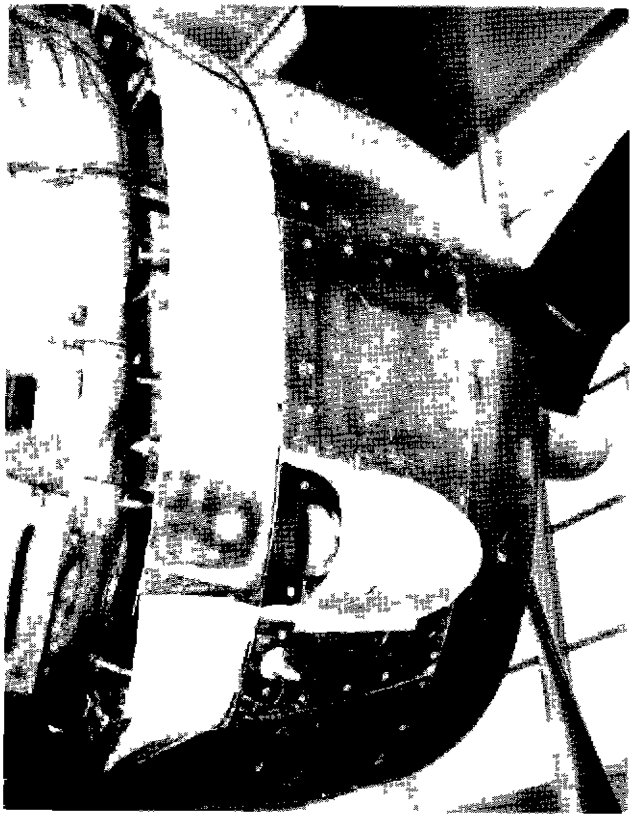

Fig 17 Modification of B-29 Front Exhaust to Simulate the L-49

around the special L-49 stack

Gasoline alone was not ignited by the engine under any conditions Oil alone was not ignited in Zone 1 in any of the tests In Test 4, a mixture of gasoline and oil was ignited in Zone 1 after the oil alone had flowed for 60 seconds and the oil and gasoline both had flowed for another ten seconds The source of the ignition was not determined

In several tests, however, oil alone was ignited inside the exhaust stack well aft of the air seal diaphragm The oil flowing back over this region went through the louvered shroud onto the stack and turbosupercharger The ignition always started as small flames around the stack, gradually growing larger and usually working forward to the cowl flaps But fire did not spread any farther into Zone 1

In several of the tests in the second group, gasoline and oil in large quantities poured out around the projecting exhaust stack, apparently mixing with the exhaust gases issuing from the stack, yet no ignition occurred

In Tests 1 to 10, with fire ignited forward of the cylinders but passing back through the engine to the cowl flaps, detection occurred consistently in from one to three seconds after ignition, with gasoline alone and with gasoline and oil together

Detection in the second group of tests was more delayed In four tests in which detection was checked, the detector operating times were 5, 5, 6, and 8 5 seconds after ignition Only a small fraction of the fire in these tests was carried through the cowl flaps where the detectors were located The greater portion was either emitted around the projecting stack or was carried back through the exhaust shroud to the turbosupercharger well

The gasoline was shut off immediately upon detector operation and, in the last three of these tests, the detector warning light went out within one second after the gasoline was shut off In the first test, however, the detector stayed on for 20 seconds for no apparent reason In the earlier group of tests, the fires were somewhat larger and longer and the detector recovery times were from 10 to 20 seconds

In all tests, the fires went out completely when the fuel was shut off, without use of any extinguisher Since both the oil and gasoline were obtained from sources outside the engine, it was not necessary to stop the engine to cut off the fire fuel Therefore, the engine was kept running during all tests until the fire was out

In Test 10, a large gasoline and oil fire was ignited forward of the cylinders which burned some cylinder baffles and cowl flaps The temperature at the cowl flap opening reached 1,780° F The fire was permitted to burn for 15 seconds and, when the fuel was then shut off, it went out almost immediately

In Test 24, the oil nozzle was placed forward of Cylinder No 4 (upper right part of engine) With the gasoline nozzle and igniter still down in the lower right sector, the fire was concentrated around the special projecting exhaust stack and fairing Two ring cowl panels were severely burned in this region as were the cylinder baffles and cowl flaps The engine was stopped and the propeller feathered at about the same time that the oil and gasoline were shut off The fire went out completely about one minute after it

Fig 18 Damage to Engine Installation Resulting from Gasoline and Oil Fire Forward of the Cylinders

was started (about 45 seconds after oil was shut off and engine stopped) It hung on longest around the projecting stack After the external fire was out, flames were seen well inside the projecting stack The engine was restarted and these flames were blown out Fig 18 shows the condition of the engine after this test

The thermocouple located forward of the cylinders, though within 3 in of the gasoline and oil nozzles and spark, did not show any temperature rise during any of the fires Also, observation of the region forward of the cylinders, both during and after the tests, showed that no fires existed in this region although it was here that the fuel leakage and ignition occurred Obviously, no fire reached over the front of the ring cowl

Fire did exist, however, around or at least behind the cylinder heads, as attested by the burned cylinder head baffles and ring cowl panels The severity of the fire apparently increased farther aft, since cowl flaps were generally damaged first and most severely

No fires in any of these tests spread into Zone 2

CONCLUSIONS

Several of the conclusions which have already been enumerated as a result of the B-29 power section investigations also are applicable to these investigations In addition, the following conclusions were reached,

1 Gasoline and oil leaking from a source far forward in the power section are not readily ignited
2 Fires originating so far forward as to enter the projecting exhaust stack shrouds may escape detection by detectors located near the cowl flaps

SUMMARY OF CONCLUSIONS

1 The double layer of metal separated by an air space, which forms the shroud between the exhaust stack well and the accessory section, is effective in shielding the accessory section from the heat of the exhaust stack
2 For maximum benefit, the double layer of metal should be continuous and should be so designed that the space between the two layers can be drained
3 Failure of the exhaust stack can cause a dangerously high temperature inside the accessory section near the region where the failure occurs
4 Increased air flow through the stack well is effective in reducing the temperature in that region and in preventing ignition
5 Complete blockage of the pressure side of a vacuum pump while in operation can produce a sufficiently high operating temperature within the pump to create an ignition source
6 Gasoline leakage inside the accessory section will drain away harmlessly in most instances, except when the leakage gains access to the turbosupercharger through the shrouding Fire then can occur and spread back into the accessory section
7 Overloaded pumps and motors did not generate sufficient heat to become ignition sources in the tests
8 In the event of engine failure in flight, which releases quantities of flammable fluids amid the ignition sources about the engine,

(a) low volatility fuels would be nearly as hazardous as 100-octane gasoline,

(b) SAE 10 oil would be more hazardous than 100-octane gasoline,
(c) kerosene would be more hazardous than 100-octane gasoline or low volatility fuels

9 The maximum rate of temperature rise at the cowl flaps during normal ground operations was 450° F per minute This was not enough to cause the Edison type detector system to sound an alarm

10 The average change of temperature during ground operation was approximately 100°

11 Maximum temperatures and maximum rates of rise occurred at the top of the engine and near the two exhaust stacks

12 Adequate coverage of the accessory section could not be secured with any localization of units in particular regions, but required a fairly uniform dispersion of units throughout the volume However, some concentration of units toward the forward and upper sectors seems warranted

13 The sensitivity of the Minneapolis-Honeywell detector varied, depending on the thickness and type of coating deposited on the wire, insulators, and airplane surface

14 The minimum number of "Fireye" units which can be used in the B-29 power section to give complete coverage is four However, a larger number would be desirable

15 The minimum number of "Fireye" units which can be used in the B-29 accessory section to give adequate coverage is two, unless special regions are to be monitored

16 Gasoline and oil readily ignite on the hot exhaust stack inside the louvered well at either side of the nacelle

17 Gasoline and oil are difficult or impossible to ignite on the unshrouded exhaust collector ring in Zone 1

18 Fires which originate far forward in the engine and enter the exhaust stack shroud may escape detection by detectors located near the cowl flaps

19 Fires in Zone 1 burn out if the flow of fluid feeding the fire can be stopped even though considerable damage has been done to the cowling in the meantime

20 The proper functioning of the propeller feathering system is of utmost importance in the control of power section fires

21 Power section fires can severely damage downstream structure of aluminum alloy in very few seconds

22 While small fires can be extinguished by feathering the propeller and stopping the flow of combustible fluids feeding the fires, the only sure means of providing complete protection is by use of an adequate and properly designed extinguishing system

23 The seal between the air seal diaphragm and ring cowl air duct is not sufficiently fireproof to prevent the spread of fire from Zone 1 to Zone 2

24 The aluminum alloy skin covering the accessory section does not provide sufficient protection to the structural members in this compartment

25 Rubber hoses fastened with hose clamps are very vulnerable to fire and should not be used to carry flammable fluids

26 Gasoline and oil leaking from a source far forward in the power section are not readily ignited

27 Fires originating so far forward as to enter the projecting exhaust stack shrouds on the L-49 configuration may escape detection by detectors located near the cowl flaps

RECOMMENDATIONS

As a result of this testing it is recommended that

1 The exhaust stack well of the B-29 aircraft be modified to

(a) Remove traps and pockets in the lower side of the well where fluids can accumulate between the two existing heat shrouds
(b) Make the double heat shrouds on the upper and lower sides of the well continuous sheets of metal or, if that is impossible, at least stagger and seal the metal joints to prevent existing access from the accessory section to the well.
(c) Double the air flow through the well, using only air ducted from the leading edge of the ring cowl
(d) Attain the smoothest possible air flow through the well
(e) Replace the louvered exhaust stack well cover plate with an unperforated cover plate

2 Various components in the accessory section of B-29 aircraft be relocated to reduce the fire hazard Specifically

(a) Reroute major gasoline and oil lines so that they do not pass over the exhaust stack shrouds and turbosuperchargers at the sides of the installation
(b) Relocate the propeller feathering oil tank and the turbosupercharger lubricating oil tank so that fluids leaking from these tanks cannot impinge on the stack inner shroud
(c) Locate tanks, lines and fittings containing flammable fluids as low as possible in the accessory section to insure that leakages drain overboard with no access to ignition sources Locate electrical equipment and lines as well as components of the exhaust system as high as possible in the installation.

3 The fire resistance of the entire B-29 nacelle be increased by the use of

(a) Stainless steel to replace the aluminum alloy skin on the accessory section, the nacelle aft of the fire wall, and the wing in the vicinity of the nacelle
(b) Stainless steel to replace, or at least protect, the aluminum alloy structural members within the accessory section and the nacelle aft of the fire wall
(c) Stainless steel to replace thin aluminum alloy, asbestos, and rubber sealing strips at the contact between the air seal diaphragm and the main ring cowl air duct and at joints in the air induction system, air seal diaphragm and the oil cooler duct
(d) Fire-resistant materials to replace the canvas flexible joint in the intercooler air intake duct
(e) Fixed-end-fitting hoses in place of clamped hose connections
(f) Stainless steel flexible hose on the pressure side of the vacuum pump

4 If possible, a fire detector be located in each exhaust stack shroud or well

5 The propeller feathering system be made as fireproof as possible in every respect and maintained to function properly at all times

6 Zone I (power section) extinguishing systems be incorporated in B-29 aircraft in accordance with CAA Technical Development Note No 31 or Aircraft Engineering Division Report No 34

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Wright Aeronautical Corporation
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U S Department of the Navy
U S Weather Bureau

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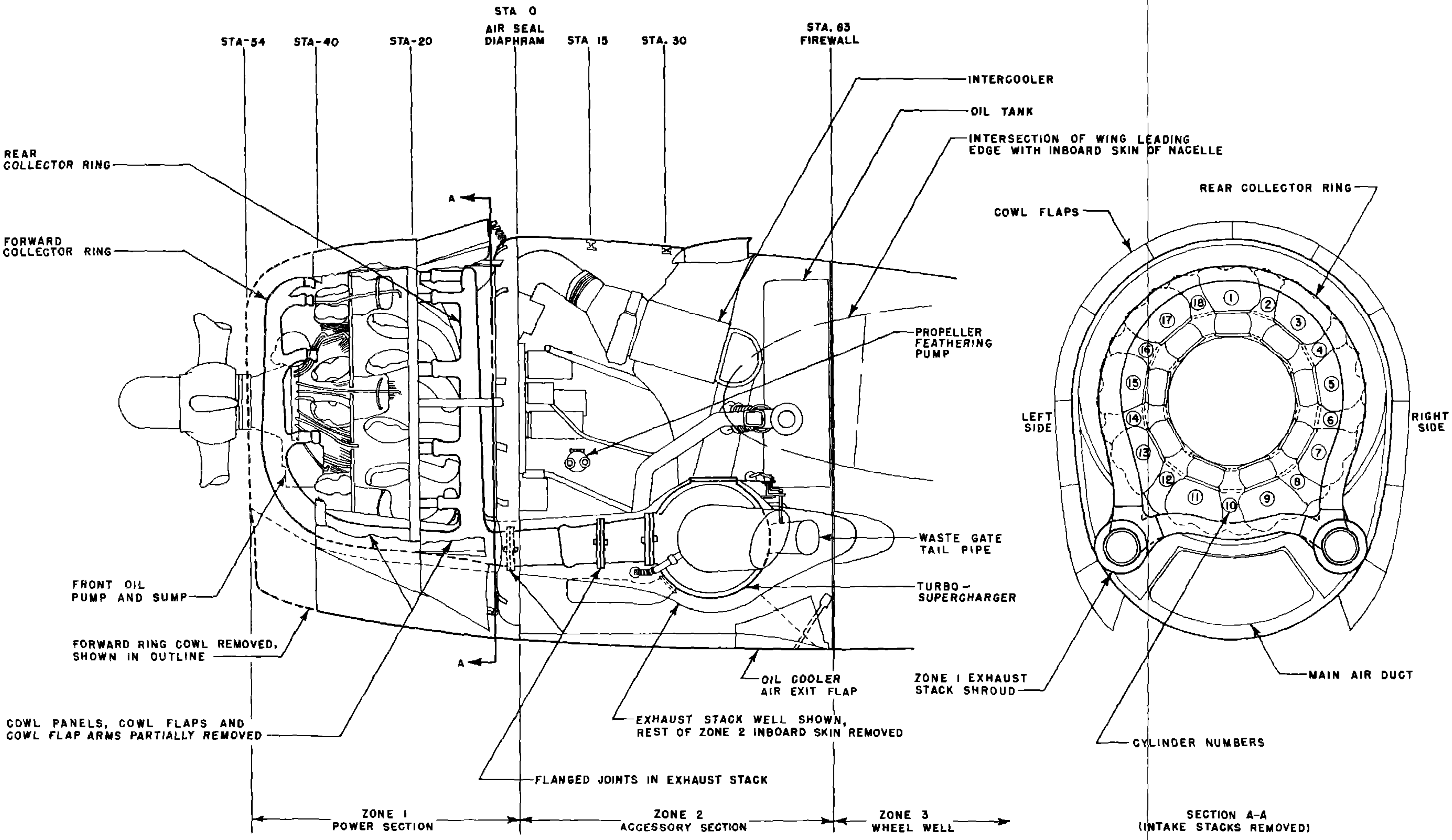

Fig 19 Cutaway View of B-29 Nacelle