INVESTIGATION OF FIRES ORIGINATING IN AIRCRAFT VACUUM SYSTEMS

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SUMMARY

Aircraft fires originating within faulty vacuum systems have been investigated in the laboratory.

Bench tests and tests in full-scale engine installations of an operating vacuum system have been conducted to determine conditions within the system resulting from blockage of the suction and/or pressure lines combined with malfunctioning of the suction and/or pressure relief valves.

A simple bench test was developed to duplicate the internal fire conditions which were obtained in earlier tests, but without destroying a vacuum pump in each investigation as occurred in those tests. Control of conditions was refined until tests could be easily and accurately duplicated. Various vacuum piping systems, including systems in use and those proposed for future use, were compared to determine the relative abilities of the systems to withstand internal fire.

A final series of bench tests was conducted which led to the development of a means for preventing internal vacuum system fires. This comprises a fusible plug in the pressure side of the pump housing which fuses and relieves excessive pressure before fires occur, but does not render the system entirely inoperative.

INTRODUCTION

Several fires in flight have been traced to malfunctioning of the aircraft vacuum or air pumping system. In one instance, there was evidence that such malfunctioning developed into an internal fire within the vacuum system. Subsequent failure of the vacuum system plumbing to withstand this internal fire apparently permitted the fire to break out into the accessory section.

An investigation of the entire matter of malfunctioning of the vacuum system was suggested by the Air Transport Association and undertaken by the Technical Development and Evaluation Center.

PURPOSE

The purpose of the vacuum system tests was:

1. To determine pressure and temperature conditions within the vacuum system, with blockage of the suction and/or pressure lines combined with functional failure of the suction and/or pressure relief valves.
2. To determine whether those conditions could result in fire within the vacuum system.
3. To determine practical means to reduce the hazards arising from malfunctioning of the vacuum system by:
   - (a) developing or determining plumbing systems capable of withstanding internal fires, and/or
   - (b) developing means for preventing occurrence of fire within the vacuum system.

TEST PROCEDURE AND EQUIPMENT

Tests were conducted on the vacuum system installed in a B-29 engine installation under simulated flight conditions. Temperatures were obtained on the vacuum and pressure sides of the pump, under normal operating conditions, at a differential of eight inches of mercury on the vacuum side, and a differential of 18 inches of mercury on the pressure side. Pressures and temperatures also were taken on this installation with the vacuum side completely blocked. These data provided a basis for establishing a bench test which would closely resemble actual flight conditions.

Test No. 1

A Pesco Type 211 vacuum pump was mounted on a block and connected directly to a 20 horsepower, 3,490 rpm electric motor. See Figs. 1 and 2. An aircraft oil pump driven by a one-half horsepower electric motor delivered SAE 60 oil to the pump at 80 psi, these conditions being identical to an actual engine installation of this vacuum pump. A one-half horsepower electric motor and

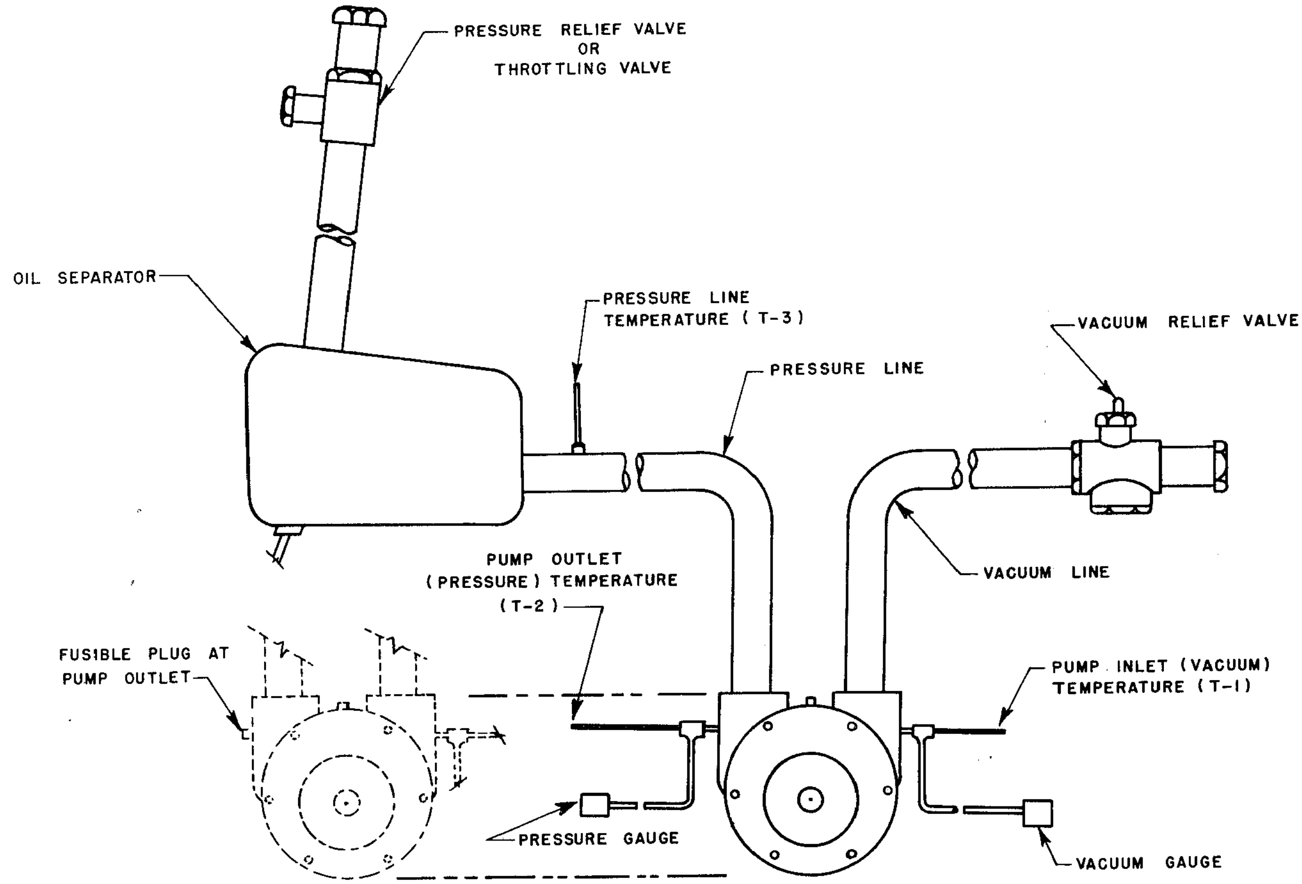

Fig. 1 Diagrammatic Sketch of Vacuum System Bench Test

blower supplied cooling air to the vacuum pump, giving cooling conditions similar to that provided by the blast tube on the B-29 installation. This setup was used to:

1. Determine temperatures and pressures resulting from complete blockage of the vacuum relief valve.
2. Determine temperatures and pressures resulting from partial and complete blockage of the pressure relief valve.
3. Determine whether these conditions could result in fire within the vacuum system.
4. Determine practical means for reducing the hazards arising from malfunctioning of the vacuum system.

Temperatures and pressures were taken at the two ports of the pump through one-eighth-inch pipe tapped holes, which are plugged on a normal pump installation. The vacuum port of the pump and the vacuum relief valve were connected by aluminum alloy tubing and hoses. The pressure side of the system included an oil separator and a pressure relief valve connected by aluminum alloy tubing and hose connections.

When blockage of the pressure side was simulated, the aluminum tubing between the pump and oil separator was replaced by an equal length of copper tubing and connected to the pump with a compression fitting instead of the hose connection. This alteration was necessary because the hose connection between the pump and aluminum alloy tubing occasionally failed from heat alone before internal ignition occurred. A thermocouple was located within this line 2 1/2 feet downstream of the pump and six inches upstream of the separator.

Blockage of the vacuum side of the system was accomplished by obstructing the intake screen of the vacuum relief valve. Partial or complete blockage of the pressure

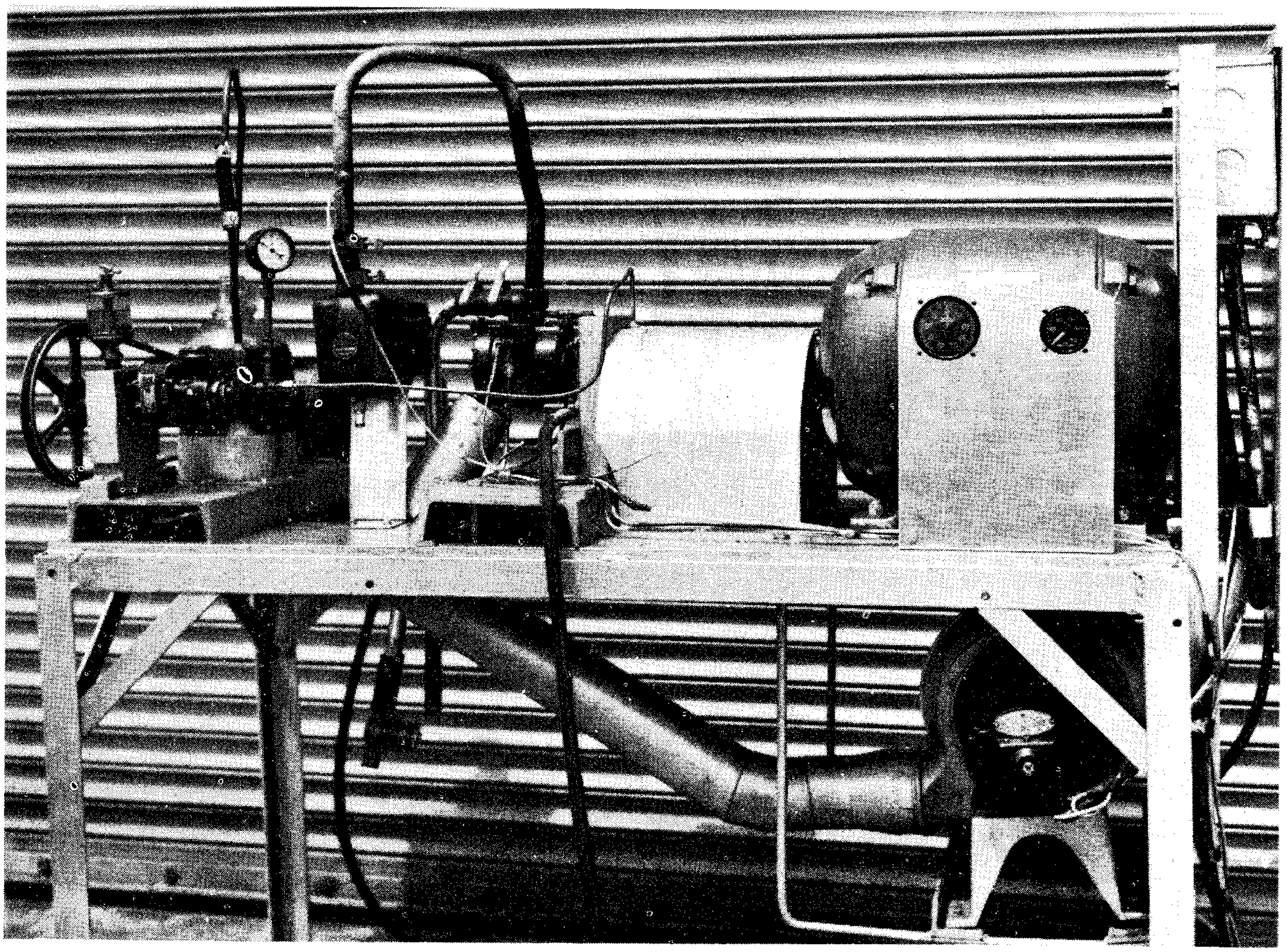

Fig. 2 Vacuum System Bench Test

side of the system was obtained by substituting an orifice or a plug in place of the pressure relief valve.

The practicability of a fusible blow-out plug was determined by inserting such a plug in a three-eighths-inch pipe tapped hole in the pressure port of the pump. Two types of plugs with three different fusible alloys were tested. These plugs were the modified AN-816-8D nipple and the modified AN-840-8D adapter. The three alloys were:

(a) binary eutectic mix with a melting point of 351° F,
(b) binary eutectic mix with a melting point of 390° F and,
(c) pure tin with a melting point of 450° F.

Since the normal drive usually shears before the pump pressure reaches 90 psi, the tests were conducted using sufficient blockage to produce 90 psi. None of the fusible plugs tested will prevent fire when pressures suddently rise to 120 psi or more. However, such conditions are extremely remote since the normal drive will shear at pressures well below 120 psi. Three types of blockages of the pressure side of the system were investigated:

1. Gradual blockage. Under these conditions, the fusible plug operated at the minmum temperatures as shown in Table I.
2. Rapid blockage of a pump operating at normal temperatures, viz., 280° F air temperature and 200° F body temperature. Under these conditions, the fusible plug operated at the maximum temperatures as shown in Table I.
3. Rapid blockage of a pump operating at high normal temperatures, viz., 375° F air

temperature and 250° F body temperature. Under these conditions, the fusible plug operated in the shortest possible time, and at temperatures between the minimum and maximum shown in Table I.

Test No. 2

The bench test shown in Figs. 3 and 4 was developed to expose various plumbing systems to internal fire, as produced by a malfunctioning vacuum system without the necessity for damaging or destroying a vacuum pump in each test. In this manner, test conditions could be accurately controlled and various plumbing systems could be compared under identical conditions. Compressed air and lubricating oil were pumped into the combustion chamber in metered quantities. External heat applied to the combustion chamber provided ignition. The resulting internal fire passed through the test hose assemblies through an orifice, to maintain pressure in the hose, and exhausted through a tail pipe.

Temperatures and pressures during these tests were maintained at values that could occur during actual system failures. This arrangement was used to compare relative endurance of hoses, tubing, and fittings now in use or proposed for future use, in order to determine whether a practical system could be built to withstand such internal fires.

RESULTS AND DISCUSSIONS

Test No. 1

As indicated from the fire tests of the B-29 engine installation under simulated flight conditions, the air temperature in the system reached a maximum of 250° F in the pressure port of the pump and somewhat less in the suction port. With the vacuum side completely blocked, a maximum temperature of approximately 550° F was obtained in the pressure port, and a somewhat lower temperature in the suction port. The bench tests reproduced these conditions.

In some aircraft, under normal operating conditions, air temperatures in the discharge port of the pump as high as 367° F have been attained. This fact particularly was kept in mind while conducting tests on fusible plugs. Even though relatively high temperatures result when the vacuum side of the system is blocked, fire is very improbable because excessive oil makes the air/fuel ratio too rich to initiate combustion. When the vacuum relief valve is blocked, various blockages of the pressure side are irrelevant because the pressure drops to zero.

Simultaneous blockage of the vacuum and pressure sides of the pump results in a no more severe condition than blockage of the pressure side only. The most severe fire hazards occur when the vacuum relief valve operates normally and conditions on the pressure side are varied from partial to complete blockage.

Complete blockage of the pressure side was omitted in the final tests because such a condition either sheared the pump drive or stalled the 20 horsepower motor. Pressures of over 120 psi were obtained by complete blockage of the pressure side of the system.

TABLE I

CONDITIONS REQUIRED TO OPERATE FUSIBLE PLUG
(Maximum Pressure in Exhaust Port of Pump - 90 psi)

	Air Degrees F		Body Degrees F		
Type of Plug and Melting Point of Alloy	Minimum Gradual Blockage	Maximum Rapid Blockage	Minimum Gradual Blockage	Maximum Rapid Blockage	Minimum Time Seconds
AN-816-8D					
351° F	580	795	400	515	33
AN-840-8D					
351° F	500	690	350	400	11
390° F	575	790	410	440	17
450° F	640	890	460	490	26

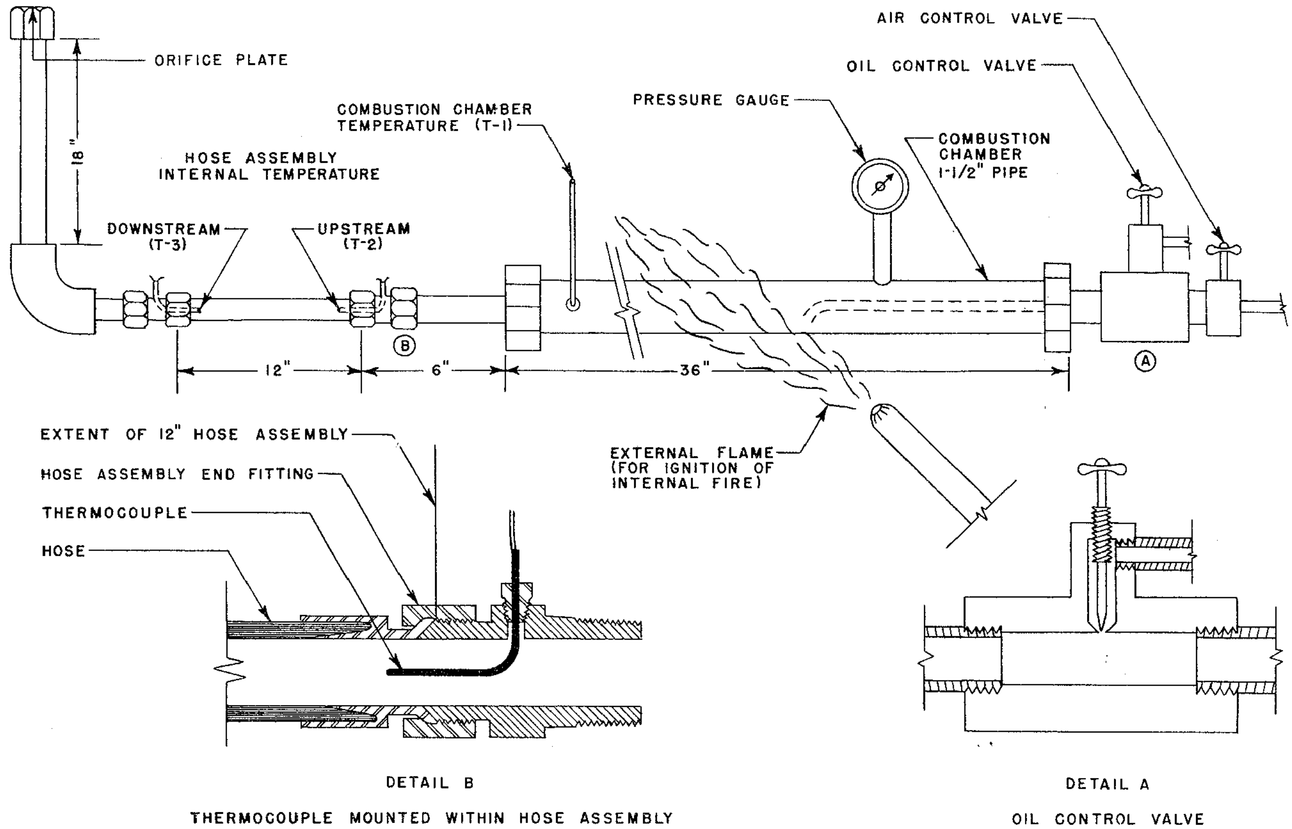

Fig. 3 Diagrammatic Sketch of Arrangement for Subjecting Hose Assemblies to Internal Fire

It appears that internal fire can be caused only when the air temperature within the system rises to above 780° F, and the proper ratio of air to oil vapor is present.

Vacuum pumps vary considerably in oil consumption. However, it is possible for most any pump to have (at sometime or another) the proper air/fuel ratio necessary for combustion; depending upon the amount of air being passed and the engine oil pressure on the pump at the time, when sufficiently high temperatures exist.

Various stages of blockage of the pressure line were used in these tests. As the blockage was increased, both the pressure and temperature increased. As the body temperature of the pump increased, the pressure dropped for any particular size orifice. For example, with an orifice of 0.1405 inch diameter, an initial pressure of 60 psi resulted, but, after a few minutes of operation, the pressure dropped to about 40 psi. Fire can be initiated at pressures as low as 25 psi, this becoming possible when the temperature reaches 780° F. After ignition, the temperature inside the pressure line can rise to above 2,400° F. In one test, the oil separator exploded. In this case, the test lasted 75 seconds. In other tests, less than 30 seconds elapsed from the time of blockage of the pressure line to the time of internal ignition. Fig. 5 shows a typical failure of the oil separator. The conditions required to melt the fusible plug located in the vacuum pump exhaust port boss under a maximum pressure of 90 psi are given in Table I.

In order to ascertain that the fusible plug would not fail prematurely under the most extreme conditions encountered in normal operation, it was subjected to:

(a) seven hours and fifty-five minutes of operation with pump outlet air temperature at 370° F and pump body temperature at 240° F,
(b) five minutes of operation at an

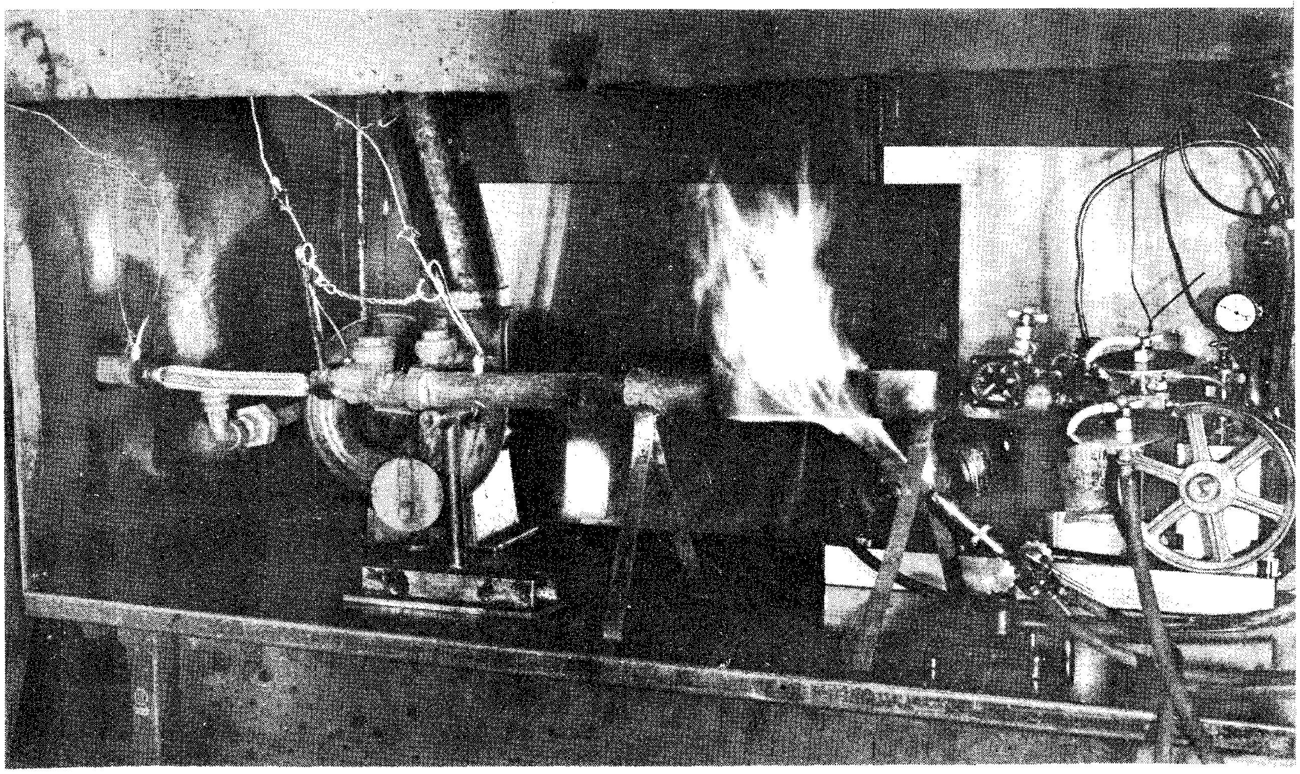

Fig. 4 Bench Test for Subjecting Hose Assemblies to Internal Fire

outlet air temperature of 400° F and a pump body temperature of 325° F and finally,

(c) rapid blockage of the pressure side of the pump to 90 psi. The plug operated in 15 seconds at 560° F outlet air temperature and 365° F pump body temperature.

The plug assembly used in this test was the modified AN-840-8D adapter with a 351° F alloy slug installed. A six-foot length of one-half inch I.D. hose was clamped to the adapter. Apparently this arrangement will not operate prematurely due to prolonged exposure to relatively high normal temperatures.

Fig. 6 illustrates how an improper fusible plug and overboard discharge line (AN-816-8D nipple with fixed-end-fitting hose) can fail to give the proper protection. This photograph shows that the alloy slug, after being properly released from its housing at the left, started tumbling as it passed through the overboard line (removed) and lodged crosswise in the entrance to the downstream fixed-end hose fitting at the right.

In designing a fusible plug installation with overboard line, it is essential that the design be such that the alloy slug can pass through the downstream portion of the plug body freely and, that the remaining overboard line and fittings are of sufficiently large internal diameter to allow the plug to tumble without danger of lodging.

The above results show distinct advantages in using the modified AN-840-8D adapter (Fig. 7) with one-half inch I.D. hose and hose clamp on the Model 211 pump, and the AN-840-6D adapter with three-eighths I.D. hose and hose clamp on the Model 207 pump rather than using the modified AN-916 nipple with fixed-end-fitting hose attached. These advantages are due to the following contributing factors:

1. The AN-840 fitting has less metal and less cooling surface in contact with the air than the AN-816 fitting with the fixed-end fitting of the attached hose. Therefore, the temperature of the AN-840 fitting will be closer to the temperature of the pump body than that of the AN-816 fitting.

2. The plug assembly using the AN-840

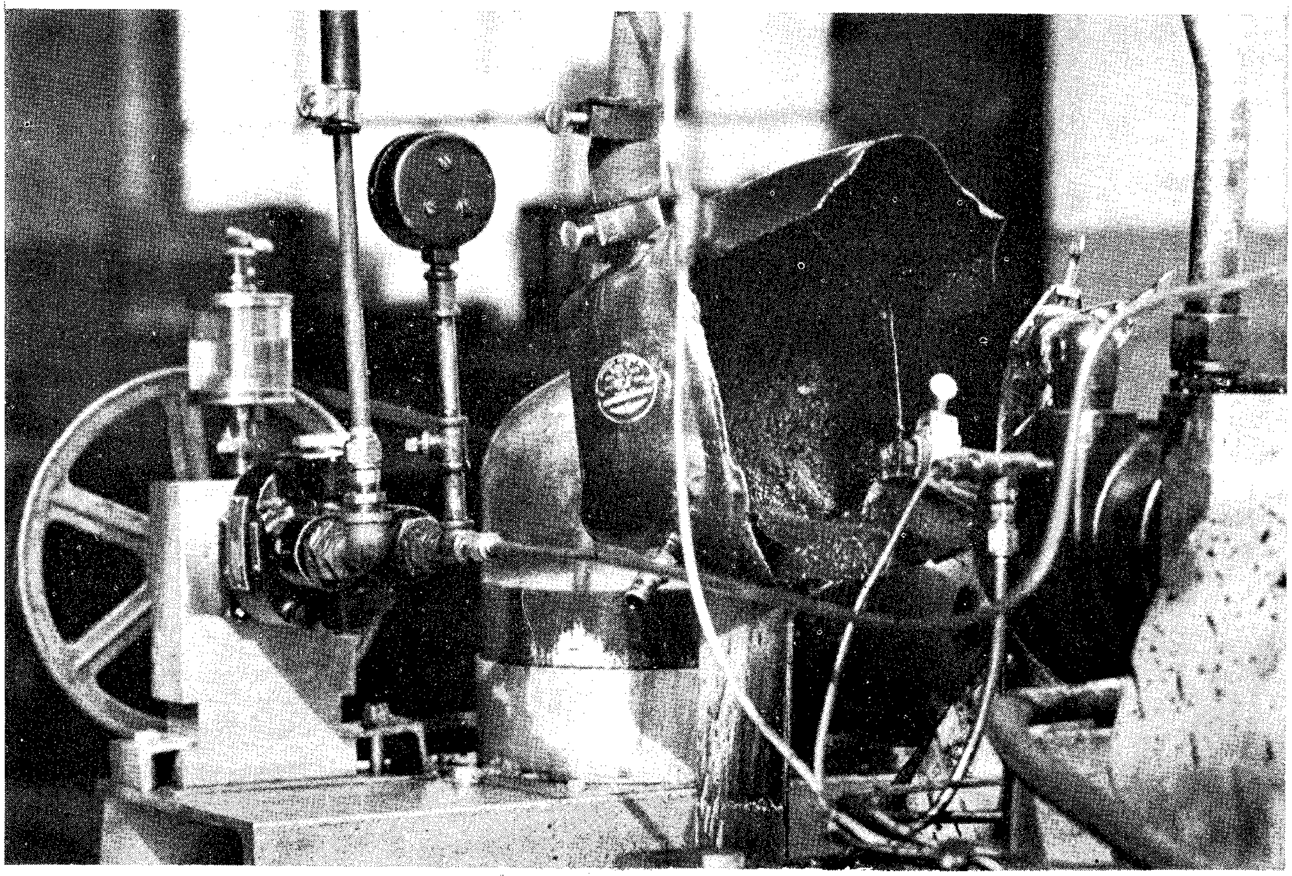

Fig. 5 Oil Separator Damaged by Malfunctioning of Vacuum System

fitting includes a small slug which requires less latent heat of fusion to operate and, therefore, operates in less time.

3. The use of the AN-840 fitting elimnates the need for checking and possibly reaming the bore of the fixed-end fitting on the hose to assure that the alloy will be expelled freely.

4. The use of the AN-840 fitting eliminates the possibility of the alloy slug lodging crosswise at the entrance of the downstream fixed-end fitting due to tumbling in the hose, even though precautions (item 3) have been taken. See Fig. 6.

Additional tests were conducted to determine the best location of the fusible plug assembly. A Pesco Model 207 pump with the one-eighth-inch pipe tapped hole in the exhaust port boss enlarged to a one-fourth-inch pipe tapped hole was mounted on the test stand. A fusible plug as shown in Fig. 7 was used. Table II compares the operating characteristics of identical fusible plugs in three different installations.

From these results, it can be seen that the safety provided by the fusible plug is doubtful unless it is placed directly in the exhaust port boss of the pump body.

A typical example of the protection offered by a fusible plug installation in a vacuum system is illustrated in Fig. 8. The first curve shows that 30 seconds after partial blockage (causing 90 psi in the pressure side of the system) was imposed on the system, a temperature of 800° F was reached. This resulted in fire as indicated by the rapid temperature rise. Temperatures above 2,400° F have been recorded as a result of such ignition.

The second curve shows that after 14 seconds of partial blockage (90 psi) a temperature of 590° F was reached, at which time the fusible plug operated, relieving the excessive pressure; thereby allowing the temperature to return to normal.

TABLE II

EFFECT OF INSTALLATION ON FUSIBLE PLUG OPERATING TEMPERATURE

Installation	Maximum Air Temperature °F	Maximum Body Temperature °F	Time Seconds
In exhaust port boss of pump body	590	385	15
In brass T fitting attached to exhaust port boss	720	475	32
In brass hexagonal adapter attached to exhaust port boss	780	495	31

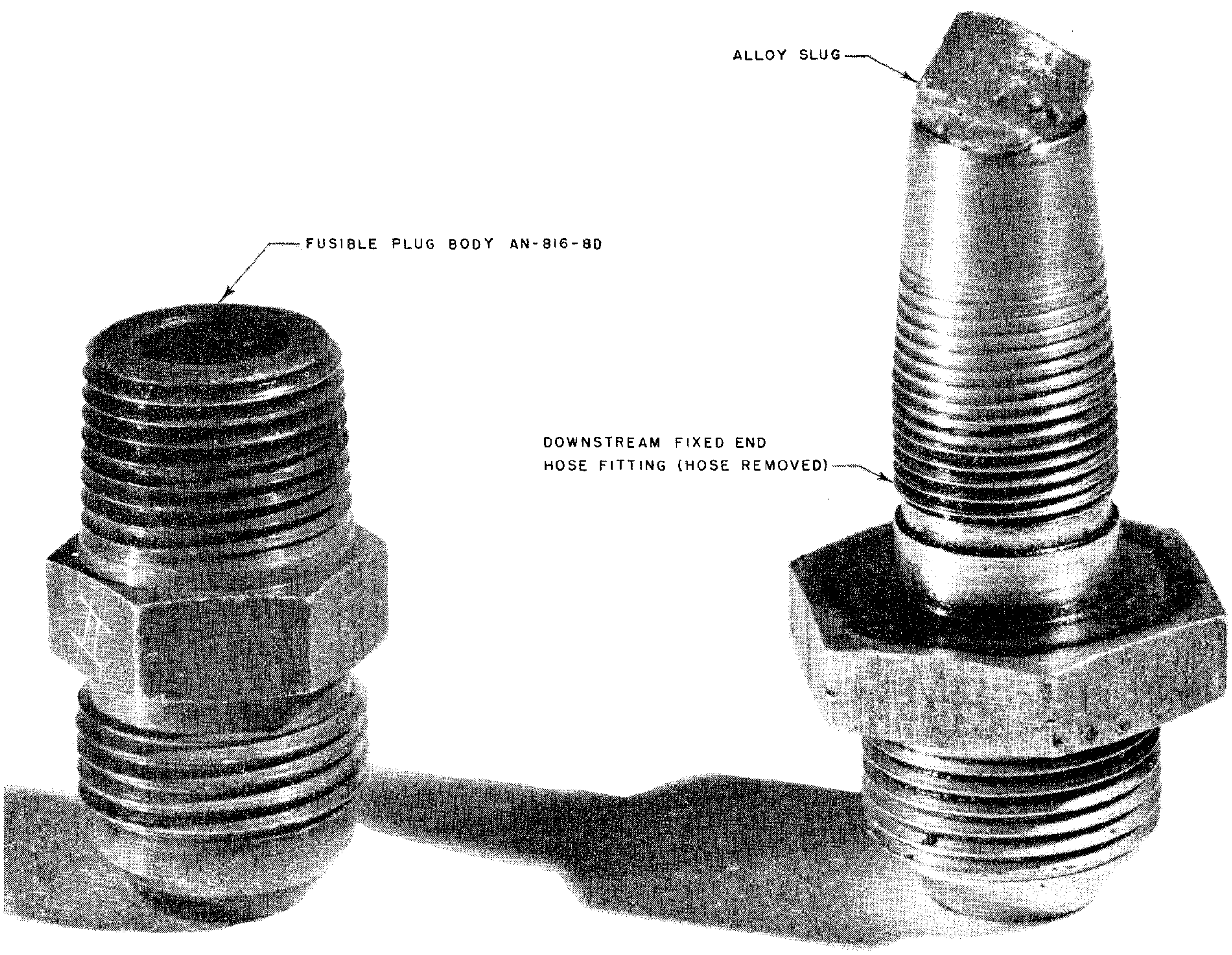

Fig. 6 Failure Due to Limited Clearance Between Slug and Overboard Drain Line End Fitting

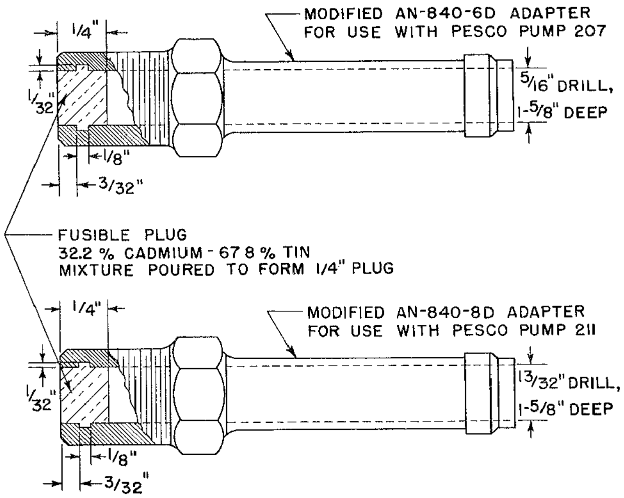

Fig. 7 Vacuum System Fusible Plugs

A suitable fusible plug properly installed is no substitute for a properly designed vacuum system. It is intended to protect the vacuum system and prevent fire, similar to the installation of a fuse in a properly designed electrical circuit for over-all protection of that system.

Test No. 2

A temperature of 1,600° F was selected for testing endurance of the components of vacuum system lines because it is within the range of fire temperatures normally experienced and low enough to obtain a measurable time of endurance. A pressure of 15 psi was selected for safety. Previous experience had shown that hose assemblies would withstand similar internal fires for equal periods of time whether operated at the 15 psi selected, or at the 40 psi experienced under actual failures.

Table III shows a comparison of the results of the internal fire (1,600° F at 15 psi) on various types of vacuum system plumbing. Under these conditions, aluminum alloy tubing was destroyed in two minutes and aluminum alloy end fittings were destroyed in five minutes. The appearance of the fittings before and after the tests is shown in Fig. 9.

CONCLUSIONS

1. Complete blockage of the vacuum side of the pump can produce vacuum system air temperatures above 550° F, but is not likely to result in fire.

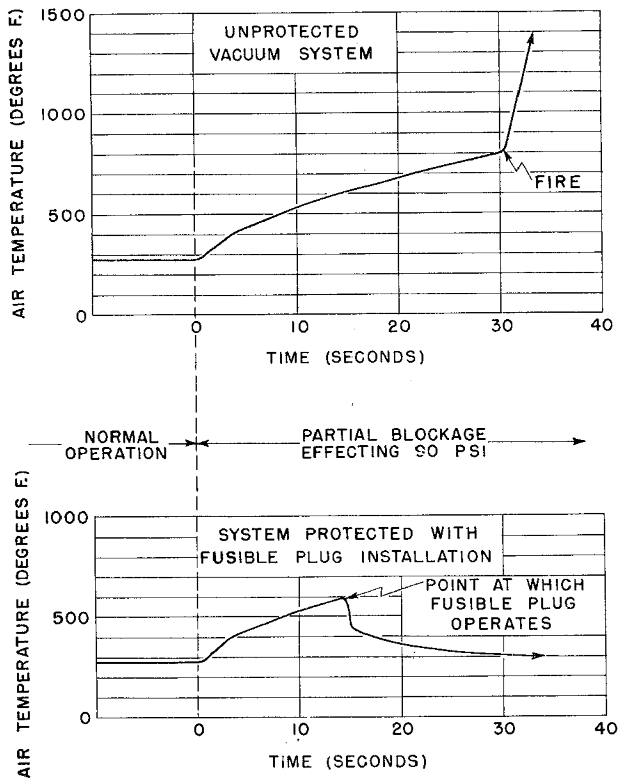

Fig. 8 Typical Time-Temperature Curves Illustrating Effect of Fusible Plug on Malfunctioning Aircraft Vacuum System

2. Partial blockage of the pressure side causing a discharge pressure of 25 psi or more can result in air temperatures above 780° F and readily cause internal fires in the discharge line.
3. Complete blockage of the pressure side can cause pressures of 120 psi or more and generally results in shearing of the pump drive before fire can occur.
4. Flexible steel lines between the pump and oil separator are desirable and eliminate one possible source of system blockage. However, they do not prevent fire from occurring; and, while they will retain fire within themselves, they will not prevent fires from spreading to other components or lines since the oil separator and the vacuum pump housing can fail and allow the fire to attack other vulnerable portions of the accessory section. See Figs. 5 and 10.
5. A properly designed fusible plug installed in the exhaust port boss of the pump will relieve the pressure when excessively high

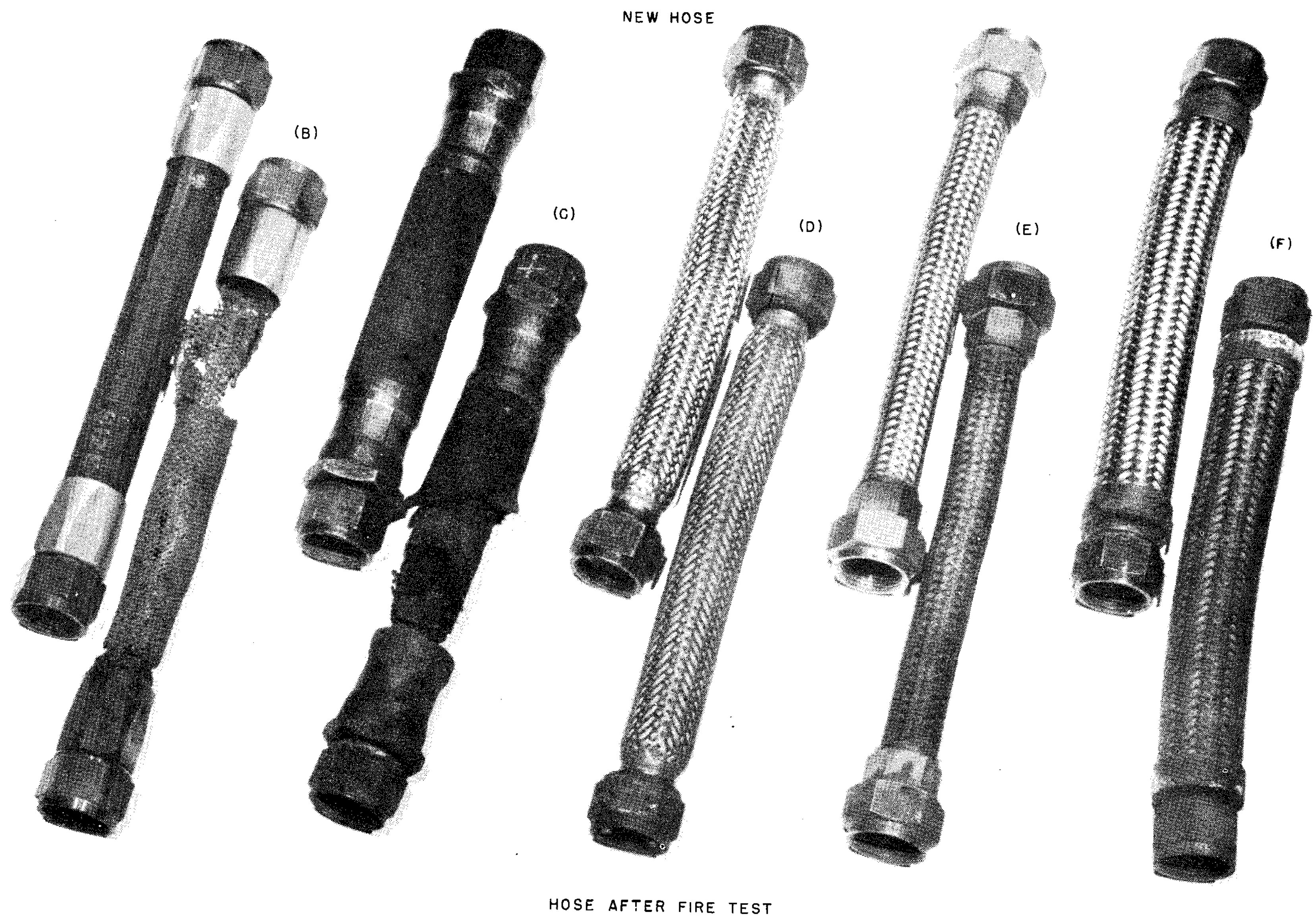

Fig. 9 Effects of Internal Fire (1600° F) on Various Plumbing Systems

TABLE III

RESULTS OF BENCH TESTS SUBJECTING HOSE ASSEMBLIES TO INTERNAL FIRE

Sample	Composition	Fittings	Approx. Weight 12-in Assembly	Endurance Time
A	Rubber, cotton braid, asbestos braid	Al. Al.	0.9 lb	1 min
B	Rubber, one metal braid	Al. Al.	0.75 lb	2 min
C	Rubber, two metal braids	Steel	2.4 lb	5 min
D	Corrugated S. S. tube, S. S. wire braid	Steel	1.0 lb	10 hr (undamaged)
E	Corrugated inconel tube, inconel braid	Steel	1.25 lb	10 hr (undamaged)
F	Corrugated S. S. tube, S. S. wire braid	Steel	1.6 lb	10 hr (undamaged)
G	Corrugated S. S. tube, S. S. wire braid	Steel	1.7 lb	10 hr (undamaged)

Note: 1. These results compare the abilities of various flexible connections to withstand internal fire, but do not reflect their abilities to withstand the external fires for which most of them were designed.

2. All test hoses were of one inch-nominal diameter. In actual flight operation, the currently used composition liner hoses become embrittled due to high operating temperatures. This causes pieces of lining to flake off and block oil separator screens and other parts of the system.

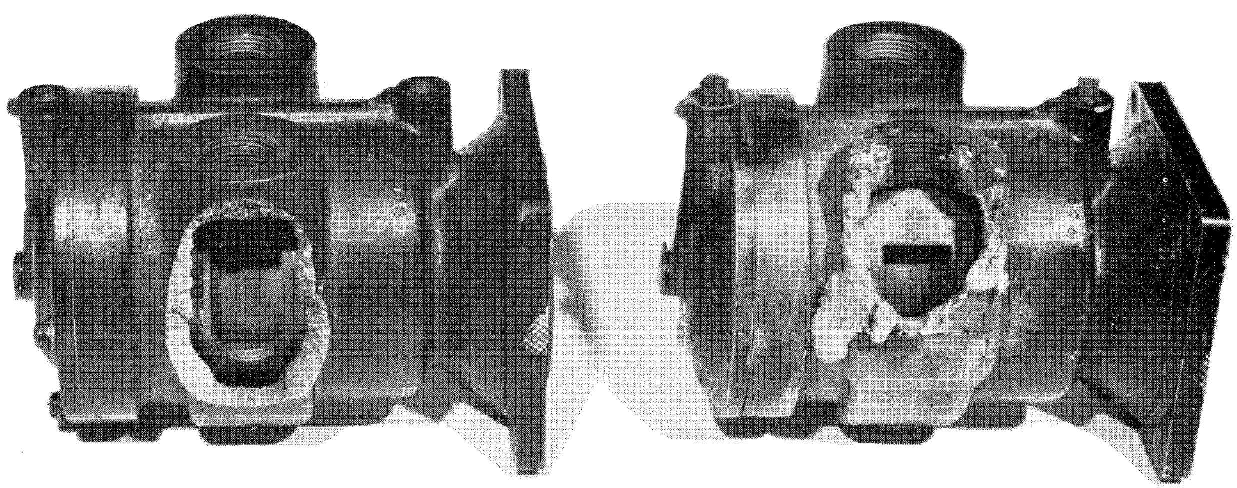

Fig. 10 Vacuum Pump Housing Damaged by Malfunctioning of Vacuum System

temperatures are attained, thereby lowering the temperature before internal ignition can occur and yet not rendering the vacuum system completely useless.

RECOMMENDATIONS

It is recommended that:

1. A suitable fusible plug be used in the pressure side of all vacuum pumps. The pressure relief line from the plug should discharge overboard, completely free of the aircraft.
2. Highly fire-resistant flexible lines be considered for use in any location which can be subjected to internal or external fire.
3. Fire-resistant plumbing developments be continued with consideration given to internal as well as external fire resistance.
4. A properly installed fusible plug be used as an emergency safety device, and not as a substitute for a properly designed vacuum system.
5. Fusible plugs designed in the future should be tested under conditions that will result in fire unless the plug gives proper protection.

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