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AIRCRAFT ENGINE SUMP-FIRE STUDIES

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SUMMARY

The problem of lubricant sump fires in aircraft engines is examined, and pertinent background subjects are discussed (i.e., the basic conditions required to start fires, the flammability limits for lubricant vapors, the importance of engine sump sealing systems, and the engine operating parameters that affect fires). Results of ongoing experimental studies are reported in which a 125-millimeter-diameter-advanced-bearing test rig simulating an engine sump is being used to find the critical range of conditions for fires to occur. Design, material, and operating concepts and techniques are being studied with the objective of minimizing the problem. It has been found that the vapor temperature near a spark ignitor is most important in determining ignition potential. At temperatures producing oil vapor pressures below or much above the calculated flammability limits, fires have not been ignited. But fires have been routinely started within the theoretical flammability range. This indicates that generalizing the sump-fire problem may make it amenable to analysis, with the potential for realistic solutions.

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INTRODUCTION

Lubricant sump fires have been encountered in high-temperature operation of aircraft engines during flight, in engine ground studies, and in advanced laboratory studies of lubrication systems (ref. 1) and mainshaft seals (ref. 2). There is evidence that at least 31 incidents of sump fires or excessive heat in a bearing sump have occurred over a recent 5-year period in one widely used aircraft engine. Despite the reality of fires and near fires in operational aircraft engines, the environment found in engine sumps, with their high oil-recirculation rates, leads to the inherent contention that sumps in general are too oil rich for fires to occur in them. However, the trend toward developing engines with higher speeds and higher pressure ratios and their resulting higher energy levels suggests an impending increase in the frequency of sump fires.

Past sump fires have resulted from a number of different causes, which shows the need for study in this problem area. First, we must find the ranges of the principal operating parameters that are potential causes of sump fires and then experimentally

and analytically explore various operating, materials, and design concepts and tech-
›s to reduce the fire potential. Accordingly, NASA is sponsoring a continuing re-
.rch program at SKF Industries (contract NAS3-19436) to realize these objectives, wherein various means to mitigate sump fires are being studied on a 125-millimeter-diameter-advanced-bearing test rig. This paper presents the status of this program and its significant highlights.

The ultimate targets of this program are, by fiscal year 1978, (1) to acquire a comprehensive understanding of sump-fire problems and (2) to develop methods for eliminating, reducing, or controlling fires in current and proposed aircraft engines.

BACKGROUND

Before we discuss the past, current, and planned experimental sump-fire studies, let us first consider background subjects important to this problem area. These include the basic conditions required for fires to start, the flammability limits for lubricant vapors, the importance of the engine sump sealing systems, and, finally, those engine operating parameters that affect fires.

Basic Conditions for Fires

Three basic conditions are required in an aircraft engine oil sump for fires to occur. First of all, there must be a proper mixture of air and oil in vapor, mist, or droplet form. If there is insufficient oil in the mixture (too lean) or excessive oil in the mixture (too rich), a fire cannot start. Data taken from a report by Kuchta and Cato of the U.S. Bureau of Mines (ref. 3) show that for an MIL-L-7808 (type I ester) lubricant, fires cannot be ignited if air-oil weight ratios are above 29 to 1 or below 5.5 to 1.

Secondly, the air-oil mixture temperature must be above a critical value. The mixture temperature must be above the flash point of the oil before a fire can be ignited and above the fire point before a fire will continue to burn in the absence of an ignition source. At temperatures above the autoignition temperature (AIT), no external ignition source is required to start a fire. For the type II ester oil being used in the test program the flash point, fire point, and AIT are 525 K (485° F), 558 K (545° F), and 705 K (810° F), respectively (ref. 4).

Thirdly, there must be the presence of an ignition source of sufficient energy level when the mixture temperature is below the AIT. Ignition sources include frictional sparks and component surfaces heated by frictional rubbing, as well as hot chamber walls and hot gases. Primary ignition sources within a sump are frictional heating of failing seals, bearings, and other rubbing parts plus the leakage of high-temperature compressor discharge air into the sump area.

Flammability Limits for Lubricant Vapors

The concept of flammability limits for lubricant vapors is important and is illustrated in the lubricant flammability diagram shown in figure 1. At a given system temperature and pressure, there is an upper ratio and a lower ratio of oil vapor to air, known as the upper flammability limit (UL) and the lower flammability limit (LL), respectively, within which self-sustaining or self propagating flames can be produced by an ignition source. At oil concentrations above the UL, the mixture is said to be too rich to burn; below the LL, it is too lean to burn (refs. 5 and 6).

It is worth emphasizing that it is the oil concentration in the vapor state that defines the flammability of the oil-air mixture. The maximum concentration of oil vapor is determined by its equilibrium vapor pressure at any given temperature. The equilibrium oil-air ratio is therefore the ratio of the vapor pressure of the oil to the air pressure in the chamber. The flow rates of air and liquid oil do not determine flammability except to the degree that they influence the temperature and thereby the vapor pressure. However, flow rates can profoundly influence the severity and propagation characteristics of a fire once it has been ignited.

Maximum burning velocity is achieved when a stoichiometric ratio C_s of oil vapor and oxygen exist in the chamber. This ratio is equivalent to the molar ratio of oil and oxygen in the balanced chemical equation for complete combustion of the oil. The stoichiometric ratio is always within the flammability range of the oil. It has been shown for many hydrocarbons that at 297 K (75° F)

$$LL_{297K(75^\circ F)} \approx 0.55\ C_s \tag{1}$$

$$UL_{297K(75^\circ F)} \approx 4.8\ C_s \tag{2}$$

The flammability range increases with temperature according to the following equations:

$$\left.\begin{aligned} LL_T &\approx LL_{297K}\left[1 - 7.2 \cdot 10^{-4}(T - 297)\right] \\ \text{or} \quad LL_T &\approx LL_{75^\circ F}\left[1 - 4 \cdot 10^{-4}(T - 75)\right] \end{aligned}\right\} \tag{3}$$

$$UL_T = UL_{297K}\left[1 + 7.2\times10^{-4}(T - 297)\right]$$

or

$$UL_T = UL_{75^oF}\left[1 + 4\times10^{-4}(T - 75)\right] \tag{4}$$

By definition, oils will not burn below their flash point. Therefore, for oils with flash points higher than 297 K (75° F), the LL and UL at 297 K (75° F), calculated from equations (1) and (2), have no physical meaning but can be used in equations (3) and (4) to estimate flammability limits above the flash point. The calculated LL line should intersect the vapor pressure-temperature curve near the flash point of the oil, and this temperature, T_L, is defined as the lower flammability temperature at equilibrium vapor pressure conditions. Similarly, an upper flammability temperature T_U exists where the calculated UL line intersects the vapor pressure-temperature curve.

The relation of calculated flammability limits to temperature for the type II ester lubricant is shown schematically in figure 1. Lubricant vapor pressure and concentration are given as a function of temperature. The region enclosed by the vapor pressure curve, the flammability limits, and the AIT line defines the temperatures and lubricant vapor partial pressure in air for which ignition sources can produce a self-propagating fire. Above the AIT, no ignition source is required.

Importance of Engine Sump Sealing

The potential fire conditions in an aircraft engine are greatly influenced by the efficiency of the engine sump sealing system. Figure 2 is a cross-sectional view of the sump for a typical engine bearing compartment. Here the essential problem is to protect the bearing sump from the hot environment, which is compressor discharge air at temperatures to 922 K (1200° F) and pressures to 242 N/cm² (350 psi). (The compressor discharge air is used to cool the high-pressure-turbine disks.) A buffer type of seal system is used and this requires three sets of labyrinth seals on each side of the bearing. Figure 3 is a simplified schematic of this sealing system. The buffer gas is seventh-stage compressor bleed air with a relatively low pressure of 55 N/cm² (80 psi) and temperature of 478 K (400° F); therefore, it can be allowed to leak through the inner labyrinth seal directly into the bearing compartment. This buffer gas thermally insulates the bearing compartment. The buffer system requires an overboard vent. The buffer gas flowing into this vent prevents the hotter compressor discharge air from getting into the bearing compartment. In some engines, the labyrinth seals next to the bearing compartment have been replaced with face-contact seals. This reduces leakage and results in lower specific fuel consumption. However, failure of either the labyrinth or face-contact seals could create conditions that would result in a sump fire (i.e., a rubbing friction ignition source and a hot air-oil mixture). This fact stresses the importance of developing better and more reliable seals that could reduce the probability of sump fires occurring.

Engine Operating Parameters Affecting Fires

The basic parameters that control fire conditions in an engine bearing sump and the range of operating values that are being studied in the program are shown in table I. The parameters that can affect the ratio and temperature of a combustible mixture are

(1) Oil flow rate into the sump

(2) Oil inlet temperature

(3) Air leakage rate to the sump

(4) Air inlet temperature

(5) Shaft or bearing speed

(6) Ignition source and duration

Other parameters, such as sump volume and geometric configuration as well as bearing, shaft, seal, and housing temperatures and lubricant flammability, can also affect sump-fire susceptibility. In addition, the ratio of air leakage rate to sump volume is probably a critical parameter and should be considered for each system application.

EXPERIMENTAL ENGINE-FIRE TEST APPARATUS

In the test bearing program itself, a bearing test rig originally designed to study 125-millimeter-diameter aircraft main-shaft thrust bearings at high temperatures and speeds was modified to simulate an engine sump and to accommodate sump-fire testing. Figure 4 is a cross-sectional view of the bearing sump area. The rig was designed to create controlled rub and electric spark ignition sources and to provide for varying oil and air flows and temperatures and was instrumented to determine temperature profiles throughout the sump. Shown in figure 4 are the test bearing, a Monel baffle on the hot-air side of the bearing, the rub ignition mechanism, and the main seal life-off device that permits hot air to flow into the sump for fire ignition attempts.

RESULTS AND DISCUSSION

Preliminary Test Study

Test results from a preliminary study completed several years ago (ref. 7) had indicated that spontaneous combustion could not be obtained over the range of variables studied and that simulated engine fires could readily occur and be self-sustaining in a wide range of parameters when an electric spark ignitor was used. A spark ignitor was used in most of the fire tests as an experimental, easily controlled means of producing fires. Other significant results are as follows:

Ignition from rubs by labyrinth seals and other component materials can cause sump fires. This was shown by the fact that fires were also obtained by using the rub ignitor mechanism in the test chamber. Bearing skidding and excessive seal interferences are potential fire sources and suggest that accidental fires in engine sumps may well arise from these causes.

Fire ignition is sensitive to location. It is likely that significant real differences in air-oil ratios exist in the various parts of the sump, which makes it difficult to achieve significant data on air-oil ratios. Indications from oil degradation products were that sump fires begin in localized and small regions of the sump and are influenced by baffles. Combustible volume grows slowly with the duration of the fire in response to local gas and oil mass flow conditions.

Nitrogen blanketing was effective in the immediate extinguishing of every test run fire once the fire had been detected.

A fire-baffle (Monel sheet) mitigation device on the hot side of the bearing not only prevented fire propagation, but also prevented bearing thermal seizure due to hot (922 K; 1200° F) gas flow directly into the bearing. Such baffles have practical significance.

Freon-113 flame snuffer injected into the lubricant flow was only marginally effective in controlling fires.

Current Test Study

In our current work in this program we are using some of the experimental techniques and testing facilities from the preliminary study. The objectives of this phase of the program are to make a more definitive determination of the critical ranges of lubricant and hot-air flow rates and other operating variables and thus find the flammability range of conditions (or envelope) where fires are likely to occur.

Results and conclusions from the current program to date are as shown in figures 5 to 7, where the basic parameters were varied over their full ranges in different combinations and a spark ignitor was used. Figure 5 presents hot-air flow rates as a function of temperature increase in the sump at a constant oil flow rate of 0.45 m^3/hr (2 gal/min) and a temperature of 441 K (335° F). The higher the air flow rate, or the seal leakage, the more severe were the resulting fires. At low air flow rates, only minor fires if any were ignited. At medium air flow rates, non-self-sustaining fires were experienced, but at high air flow rates, self-sustaining fires were started. These self-sustaining fires spread more generally throughout the sump, with temperature increases as high as 556 K (1000° F) before extinguishment. However, fires could be ignited at all air flow rates evaluated under the proper set of conditions.

As illustrated in figure 6, where oil flow rates are plotted against air-oil mixture temperatures at a constant high air flow rate of 41 m^3/hr (24 stdft^3/min), the mixture temperature decreases with increasing oil flow rate. This suggests that more oil is mixing with the air. This difference was more pronounced at the higher air flow rates, pointing to a greater mixing of the oil and air at higher air flows.

No fires could be ignited when the mixture temperature was below the flash point temperature of the oil. However, the converse was not always true. Fires could not always be ignited when the mixture temperature was well above the flash point. (Refer again to fig. 6.) In one case, where no fire occurred when the air-oil mixture temperature was 611 K (640° F) at an oil flow rate of 0.23 m^3/hr (1 gal/min), an increase in the oil flow rate resulted in fires as the mixture temperature was decreased but not below the flash point temperature.

It is significant that all fires fell within the range of operating parameters for the flammability limits as predicted from combustion principles. If the vapor mixture temperatures can be held below the flash point of the lubricant in any regions of the engine where potential ignition sources are located, the fire problem will be much less acute, if not even eliminated.

As shown in figure 7, a series of runs were made at increasing oil inlet temperatures and with constant air flow rates as high as 41 m^3/hr (24 stdft^3/min) and air inlet temperatures as high as 814 K (1005° F). No fires could be ignited when a 0.45-m^3/hr (2-gal/min) oil flow was maintained except when oil inlet temperatures exceeded about 419 K (295° F). It should be stressed that these data are for specific stoichiometric conditions and results might differ for other combinations of air and oil flows and temperatures. If proper engine heat management can be achieved by using heat exchangers and other devices, the oil inlet temperature can be held to such a level that oil vapors will be at temperatures below the lower flammability limit.

Although there was evidence that the air-oil mixture in the sump was often too vapor rich to burn, it is presently considered that the best approach to minimizing sump fires is to design to produce mixtures too vapor lean to burn. This could possibly be done by injecting more oil (e.g., by increasing the oil recirculating rate) or by incorporating a device to provide more equal dispersion of the oil, such as baffles in the sump. The injection of more oil would have the effect of reducing mixture temperatures, which is in the proper direction to suppress fires.

Since the experimental data and the flammability theory coincide fairly well in this study, it appears that generalizing the sump-fire problem may make it amenable to analysis. If analysis can predict flow fields and temperature distribution within the sump, the presence or absence of conditions within the flammability limits can be determined from lubricant vapor pressure-temperature data and combustion principles.

CONCLUDING REMARKS

As a logical extension to this work, further studies directed toward reducing sump-fire problems are planned. These include further spark ignition tests, where the effectiveness of novel sump baffles will be studied to produce excessively vapor-lean environments adjacent to the bearing, as well as a study of the effect of higher oil flow rates or perhaps a combination of the two. Also, additional rub ignitor tests will be performed using improved honeycomb seal and rub shroud materials that should reduce rub temperatures. Use of less-flammable lubricants in the system is another area of interest for this program. Also, a computerized analysis of the test results is planned to assist in assessing the effects of arbitrary engine sump geometric variations and flow patterns. The goal of this analytical study is to develop, concurrent with test procedure, a preliminary prototype analytical tool to predict sustained combustion in terms of critical flow and sump geometric parameters.

In closing, we would like to reiterate that improving seals for use in engine sumps could solve sump-fire problems by preventing the occurrence of conditions that are conducive to fires. The NASA Lewis Research Center is currently working on designs toward that purpose.

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TABLE I. - PARAMETERS THAT CONTROL FIRE CONDITIONS IN ENGINE BEARING SUMPS

PARAMETER	OPERATING VALUES BEING STUDIED
OIL FLOW RATE INTO SUMP	0.23-0.45 m^3/hr (1-2 gal/min)
OIL INLET TEMP	353-441 K (175^0-335^0 F)
HOT AIR LEAKAGE RATE TO SUMP	7-48 m^3/hr (4-28 stdft^3/min)
HOT AIR INLET TEMP	739-833 K (870^0-1040^0 F)
SHAFT OR BEARING SPEED	7 000-14 000 rpm
IGNITION SOURCE & DURATION	UP TO 60 sec
OTHER PARAMETERS	-------------------------

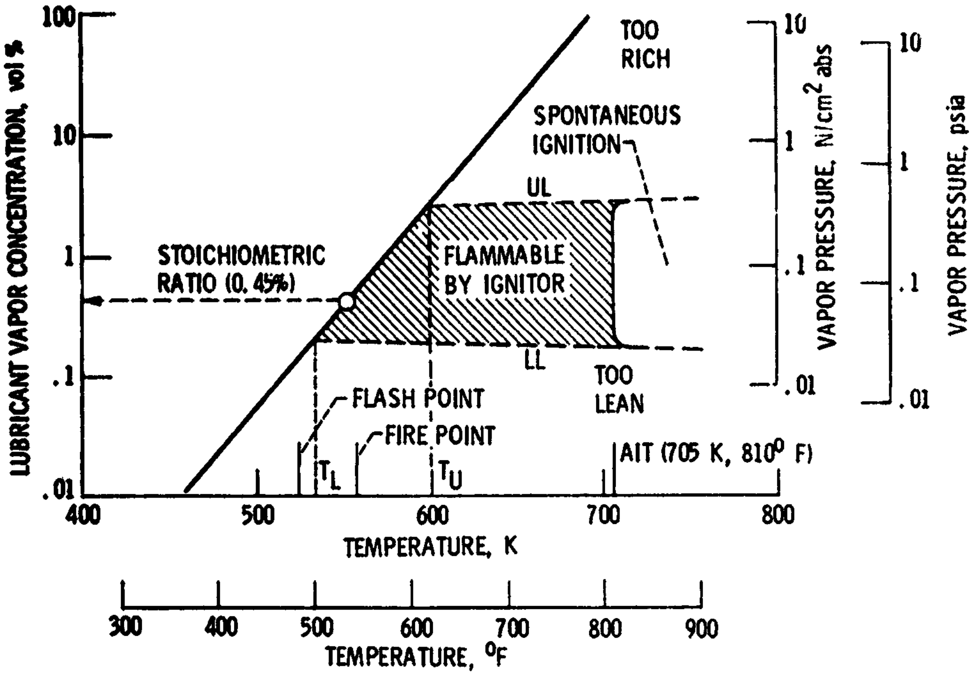

Figure 1.- Flammability diagram for type II ester lubricant, MIL-L-23699.

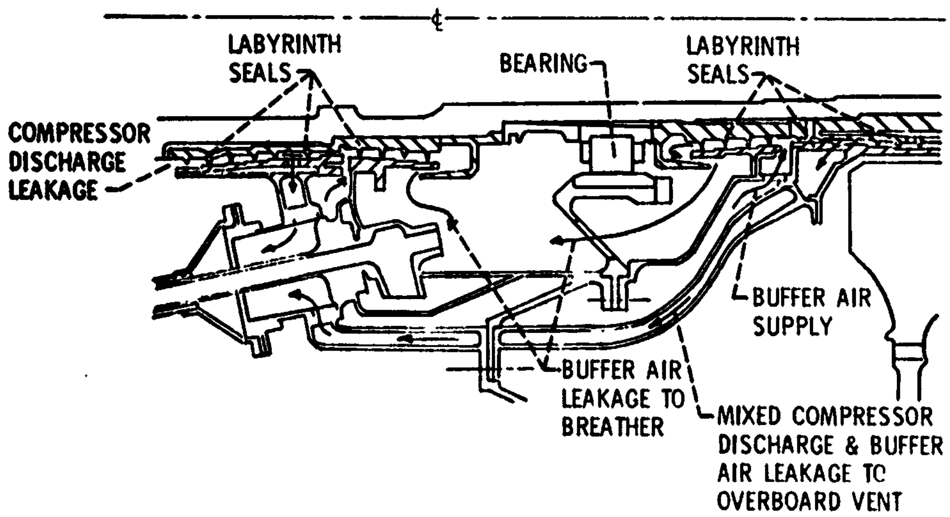

Figure 2.- Typical engine bearing sump.

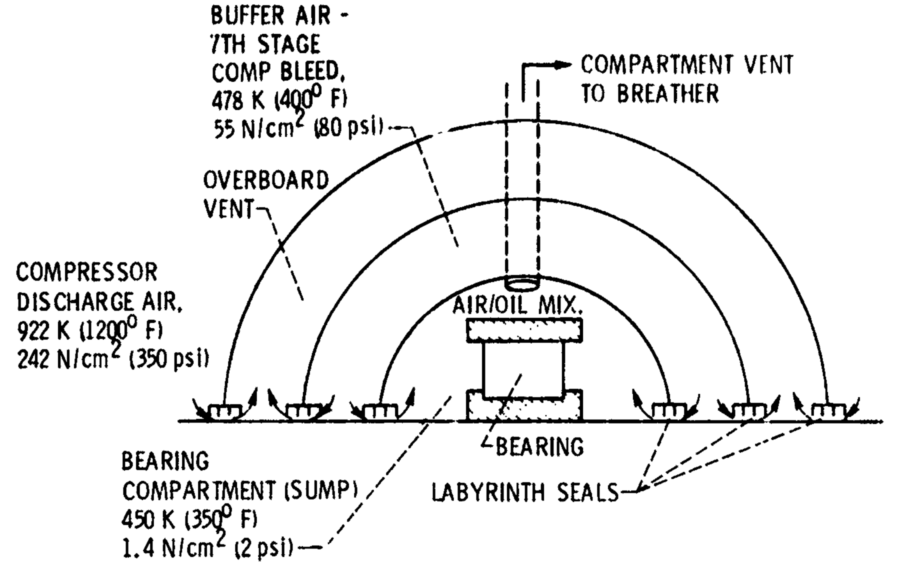

Figure 3.- Schematic of typical aircraft gas-turbine-engine sump seal system.

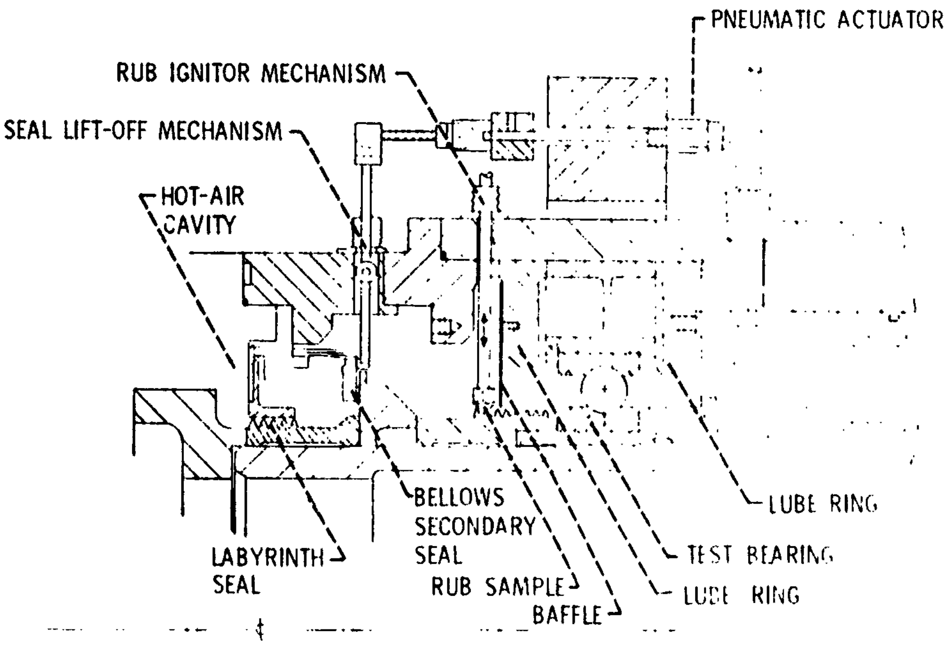

Figure 4.- Sump-fire test rig.

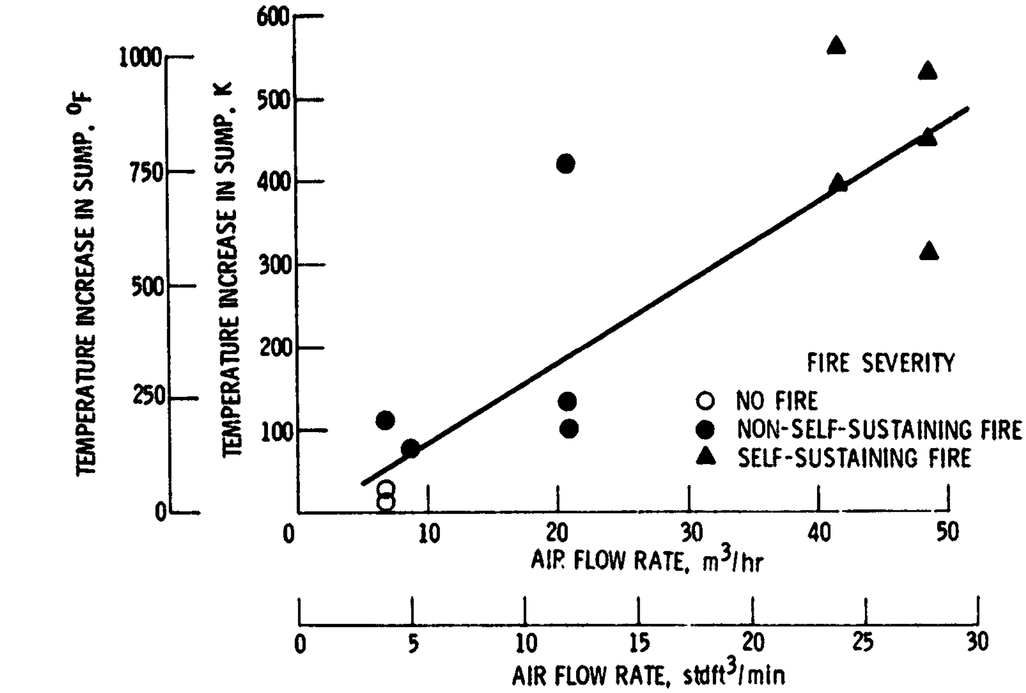

Figure 5.- Effect of air flow rate on fire severity. Oil, type II ester; oil flow rate, 0.45 m^3/hr (2 gal/min) at 441 K (335° F); air inlet temperature, 789 to 814 K (960° to 1005° F); ignition source, spark; speed, 14 000 rpm.

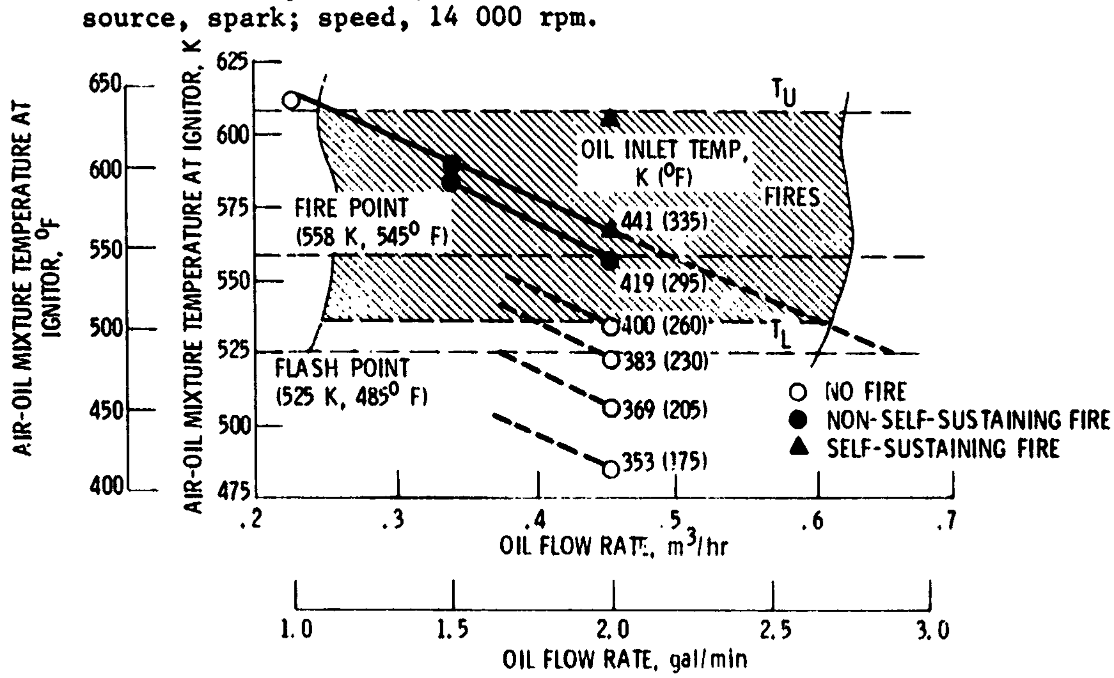

Figure 6.- Effect of oil flow rate on air-oil mixture temperature and combustion at various oil inlet temperatures. Oil, type II ester; air flow rate, 41 m^3/hr (24 stdft^3/min) at 789 to 814 K (960° to 1005° F); ignition source, spark; speed, 14 000 rpm.

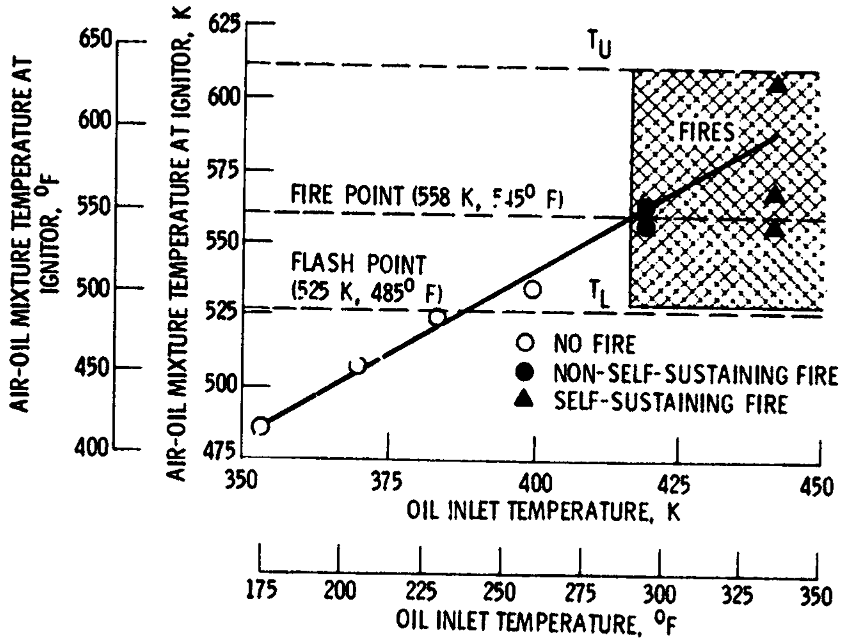

Figure 7.- Effect of oil inlet temperature on air-oil mixture temperature and combustion. Oil, type II ester; oil flow rate, 0.45 m^3/hr (2 gal/min); air flow rate, 41 m^3/hr (24 stdft^3/min) t 789 to 814 K (960° to 1005° F); ignition source, spark; speed, 14 000 rpm.