The Extinction of Fires in Aircraft Jet Engines — Part I, Small-Scale Simulation of Fires

R. HIRST and P. J. FARENDEN
Graviner Ltd.
R. F. SIMMONS
University of Manchester
Institute of Science and Technology

Three modes of combustion are possible in an aircraft engine fire, and these have been simulated separately in a small wind tunnel.

INTRODUCTION

SPECIFICATIONS adopted by British and United States authorities for fire extinguishing systems on aircraft are accepted almost throughout the world, despite a difference in approach in the two countries. Requirements of the British Civil Aviation Authority and Ministry of Defence specify that a given concentration of agent must be reached within 2 sec of the start of its discharge and maintained for an additional 2 sec at least. Thus, for a given installation, these requirements do not directly control the quantity of agent to be used nor the total duration of the discharge. In contrast, United States authorities require the use of a specific quantity of agent for a given installation and that it be discharged within 2 sec, but the actual quantity depends on a subjective judgment of the smoothness of the nacelle and the airflow. They also have requirements for high rate discharge systems, which again specify an amount of agent; but for such systems, the discharge is limited to 1 sec. The specifications for these latter systems also require that a given concentration of agent be maintained for 0.5 sec throughout the fire zone and that this be checked by a suitable instrument, such as a Statham analyzer.

Despite these differences in approach, both the British and the United States specifications for a given extinguishing agent are based on a concentration that should extinguish any fire present in the fire zone. The modern extinguishing systems use agents that interfere chemically with the combustion reactions, so that lower concentrations are required to extinguish the fire than if an inert diluent such as carbon dioxide is used.

Until now, the concentrations specified in the British regulations have been derived from the concentration that will prevent a flame from propagating through any mixture of a typical fuel (usually hexane) and air. The United States authorities have taken the results of actual fire tests into consideration when framing their regulations. Thus the original concentration specified for methyl bromide (MB), Halon 1001, by the British authorities was 17.5 percent (by volume), which is 1.4 times the "peak" concentration on which it is based.[1] Burgoyne and Williams-Leir,[2] however, have reported a much lower peak concentration, which would lead to a requirement of only 9.9 percent if the safety factor was maintained at its original level. The latter value was obtained using the method developed by the U. S. Bureau of Mines,[3] and this method is usually accepted as the standard procedure for determining limits of flammability and peak concentrations. The higher value was obtained by observing the pressure rise following the ignition spark in a closed vessel.

That such differences exist clearly makes this approach to the problem unsatisfactory. The use of the higher concentration may imply that excessive protection has been provided (with a consequent weight penalty), while the adoption of the lower figure might lead to inadequate protection, particularly if the safety factor of 1.4 times the peak concentration is insufficient. There are also a number of other doubts that arise through the use of a peak concentration for this purpose. First of all, these peak concentrations refer to premixed gases, whereas the flames encountered in a typical fire may be essentially diffusion in character. The concentrations of agent required to extinguish premixed and diffusion flames on a laboratory scale are very similar,[4] but this has not been established for combustion on a larger scale. Again, the peak concentrations refer to a situation in which the agent is fully vaporized, but in the practical situation, the agent probably leaves the spray nozzle partly as a liquid. Thus there is the possibility that droplets of the agent can pass through the critical region of the fire zone before they can become effective.

In principle, tests in which fires are burned in a full-scale replica of the aircraft power plant over the full range of operating conditions should give the required concentration of agent. Unfortunately the results obtained can only apply to the particular range of conditions that have been covered in the tests, and these do not necessarily include the most stable fire that can be encountered in practice. This latter condition must be simulated, since this will require the highest concentration of extinguishing agent, and it is almost impossible in this type of testing to ensure that the most severe fire condition has been attained.

In an aircraft fire, combustion occurs in what is essentially a large turbulent diffusion flame. A crack or a leaking joint in a high pressure fuel pipe can lead to a spray of burning fuel or, alternatively, the fuel may burn as it flows as a thin film over a heated surface. Finally, fuel may collect in a puddle, in which case the fire is essentially a liquid surface diffusion flame. In all these cases any neighboring obstruction in the air-

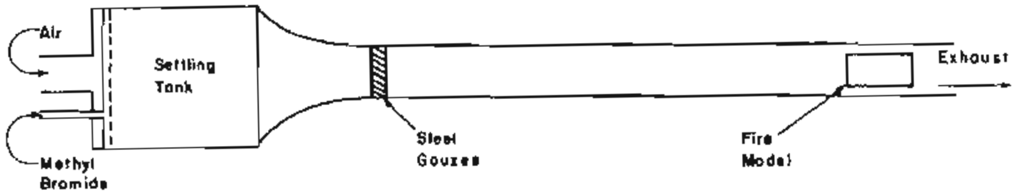

Figure 1. Schematic plan of wind tunnel.

flow can act as a flame holder, so that the practical fire condition is a very complex situation to simulate.

This problem has been avoided in this study by adopting an alternative approach, in which these three modes of combustion have been simulated separately. In each case, the experimental conditions have been optimized in terms of the concentration of MB required to extinguish the flame. This agent was chosen since it was widely used on British aircraft at the time the present work was carried out, and much practical experience in its use was available. In the present paper, it will be shown that the highest concentrations are required for the liquid surface diffusion flame burning behind a flame holder. This mode of combustion represents the worst fire condition that can be encountered in practice. In subsequent work, to be published later, this mode of combustion has been used to determine the maximum concentrations that will extinguish the flame for a range of agents, since these concentrations must be the best basis for any practical installation.

EXPERIMENTAL

A small-scale wind tunnel was used in which air velocities up to 80 ft sec^{-1} could be obtained, and this is shown diagrammatically in Figure 1. Air was fed from a centrifugal fan through a venturi flow meter into a settling tank, where some equalization in local differences in the air velocity was achieved before it was accelerated through a bell-mouth into a length of 1-ft square ducting. The working section was positioned 10 ft from the settling tank, and steel mesh gauzes were positioned at the beginning of the square ducting to ensure laminar flow conditions in the working section. This was confirmed by a pitot examination. The required mode of combustion was obtained by burning commercial kerosine in a suitable model placed centrally in the working section.

The extinguishant was stored in a 1000-gal tank, and the pressure was maintained at 20 psig by external heating of the tank. This enabled the agent to be fed into the wind tunnel at a constant vapor density, as enough vapor was available throughout the determination to ensure there was no significant decrease in the pressure in the tank. The agent was fed into the upstream end of the settling tank through a sparge pipe so that it became well mixed with the air by the time it reached the fire zone; concentration measurements in the vicinity of the model showed that this arrangement gave a uniform concentration across the tunnel.

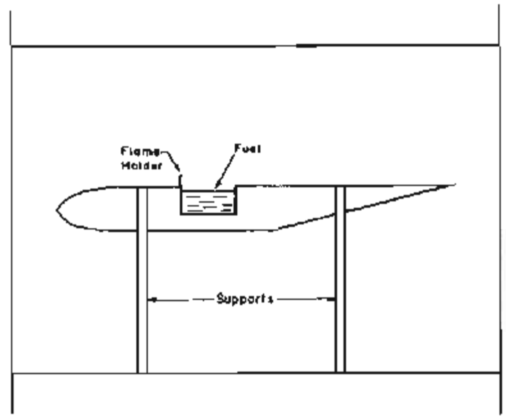

Figure 2. Section of fire model and working section of the wind tunnel.

In a given determination, the fuel was ignited, the airflow adjusted to the required level, and the agent introduced in increasing amounts until the flame was extinguished. As soon as the flame became unstable, the rate of increase in the flow was diminished, so that the final concentration was approached slowly. In these final stages the small time lag for the agent to travel from the injection system to the fire zone was allowed to lapse before the concentration was increased any further. The final concentration of agent was determined directly from the known flows of air and agent as measured on the flow meters.

To simulate a pool of burning fuel, the model shown diagrammatically in Figure 2 was used. This was essentially the same as that used earlier[5], and it consisted of a fuel tank 8 in. wide and 2 in. deep in an aerofoil section with an eliptically shaped nose and a faired-off trailing edge. The length of the fuel tray could be varied up to a maximum of 20 in., and there was provision for a flame holder in the shape of a flat obstruction at the leading edge of the fuel tank. The same model was also used to simulate the burning of a thin film of fuel as it flows over a heated surface, but in this case the model was mounted so that it sloped downwards towards the trailing edge at an angle of approximately 5°. In addition, the fuel tank was blocked off by a steel plate, which could be heated from the underside. Fuel was fed from ten holes (each of 0.04-in. diameter) spread over a distance of 6 in. and positioned at the root of the flame holder.

To simulate a burning spray a range of air blast atomizing nozzles were used in conjunction with the flame holder shown in Figure 3. These

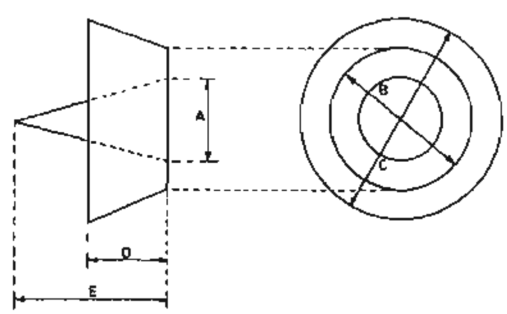

Figure 3. Flame holders used for spray fires. (See Table 1 for dimensions)

were located in a 6-in. diameter circular section connected to the same air supply as used with the larger tunnel. The flame holder was similar to those found in ram jets and the combustion chambers of some jet engines. This particular shape, which was evolved by trial and error, appeared to give the most stable flame in the present experimental arrangement; other simple shapes were found to be less satisfactory. It is not claimed that the present flame holder has the greatest stability that can be attained, but experience suggests that it would have been impossible to improve the burner to such an extent that the concentration of MB required to extinguish the flame would have been greater than that for the burning pool of fuel.

RESULTS

From the point of view of extinguishing aircraft fires in flight, the installation must be capable of extinguishing the fire even under the most favorable conditions for the combustion of the fuel. The concentration of agent required will depend on the stability of the flame and thus, throughout the present study, the effect of experimental variables has been examined in detail. In this way, the most favorable conditions for the combustion of the fuel have been established, and hence the minimum concentration of agent that will extinguish all fires has been obtained over a range of airflows.

A Burning Pool of Fuel

At the lower airflows the appearance of the flame had the characteristics expected for a normal diffusion flame.[6] The flame was inclined at a slight angle to the model and was very luminous over most of its surface, except for the blue zone at the tip of the flame just behind the flame holder. As such, it was a typical liquid surface diffusion flame.[5] As the airflow was increased, the flame became more ragged and less luminous. It progressively exhibited the appearance of turbulent premixed flame. This change can probably be attributed to changes in the recirculation zone behind the flame holder, since it is known[7-9] that the recirculation zone of premixed gases burning in the wake of a bluff body changes as the Reynold's number increases from 10^3 to 5×10^4. Within this range there is a change from laminar to turbulent flow conditions. It is interesting to note that the Reynold's number of the airflow in the present work was in the range 10^4 to 4×10^4.

The stability of the flame will be governed by the size of the pool of fuel, the airflow over the pool, the height of any obstruction that can act as a flame holder and the temperature of the bulk fuel. Increasing the fuel temperature above the level it usually reaches in the fire reduced the concentration of extinguishant required; whereas, if the temperature was decreased by deliberate cooling of the fuel, there was hardly any change in the concentration required to extinguish the flame. In considering the dimensions of the pool, only the length is likely to have any significant effect

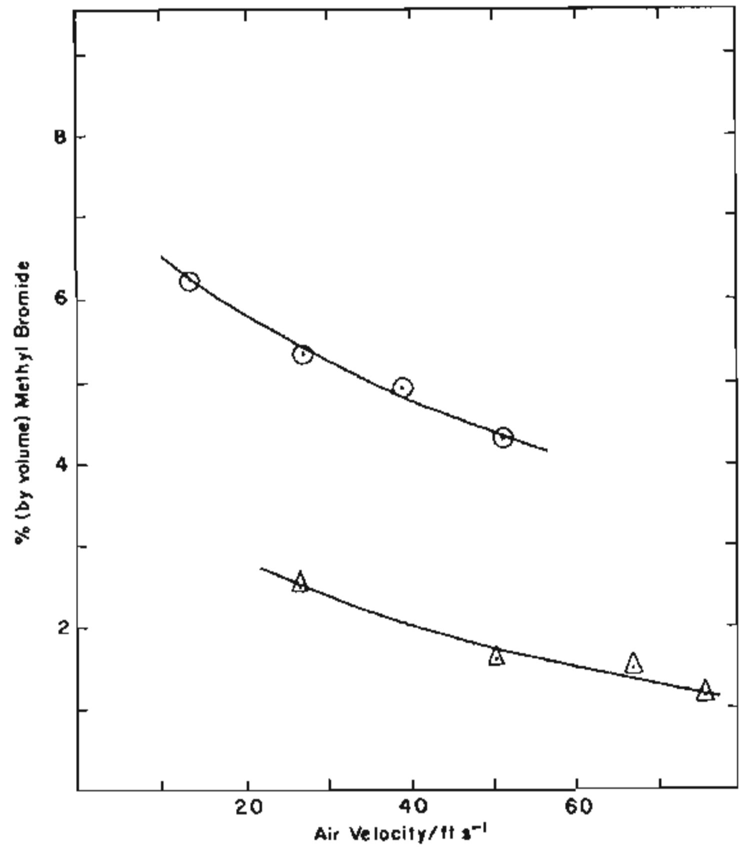

Figure 4. Comparison of the concentration of methyl bromide required to extinguish a burning pool of kerosine and a spray fire.

on the stability of the flame. Varying the width of the pool would only alter the dimension of the flame along the flame holder, but the length of the pool, in conjunction with the height of the flame holder, will control the amount of fuel entering the flame. The length of the fuel tray was varied from 2 to 20 in. The concentration of MB initially increased as the length of the tray was decreased, but below 4 in. the concentration fell again. With these very short tray lengths, there is presumably some restriction on the amount of fuel entering the flame, and it is striking that the optimum length of tray was approximately 4 in. for all airflows. Similarly, the use of flame holders between 0.375 in. and 2.5 in. showed that the most stable flame was obtained with a 1-in. obstruction. When some turbulence was deliberately introduced into the air stream, it was found that extinction of the flame was achieved with a lower concentration of MB.

Using these optimum conditions for the stability of the flame (i.e. a fuel tray 4 in. long with a flame holder 1 in. high, a laminar airflow and allowing the fuel temperature to reach its equilibrium value), the concentration of MB to extinguish the flame was determined as a function of airflow. Figure 4 shows that, at the higher flows, this concentration appears to be

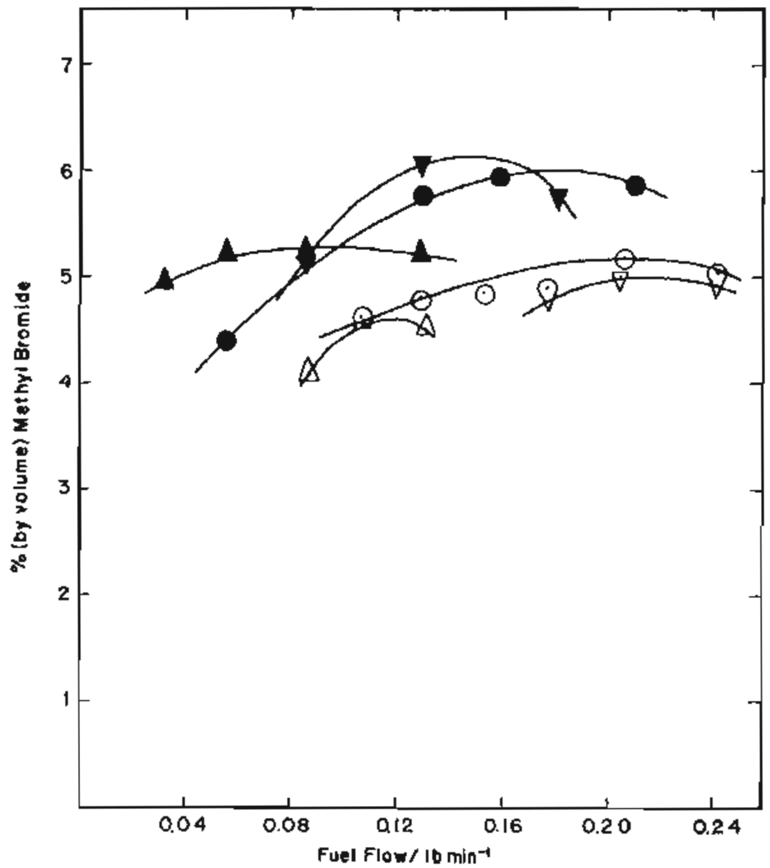

Figure 5. Effect of fuel flow and temperature of fuel on the concentration of methyl bromide required to extinguish a burning film of kerosine.

leveling off at between 4.0 and 4.5 percent MB, but as the air velocity drops this concentration increases. Over the range of flows examined in this study, however, there is no indication of any maximum in the curve, and if one occurs, it must do so at an air velocity below 10 ft sec^{-1}. Unfortunately with the experimental arrangement used in this work, it was not possible to obtain meaningful results at lower velocities.

A Burning Film of Liquid Fuel

In many respects, this mode of combustion is very similar to that which occurs with a burning pool of fuel, but in this case, evaporation of the fuel must be somewhat easier, since it is flowing over a heated surface. One of the experimental variables in this case is thus the temperature of the heated surface, while another is the flow of fuel over the surface. The stability of the flame will also be affected by the height of any flame holder, and thus a 1-in. obstruction was used, since this had been the optimum height for the burning pool of fuel. Figure 5 shows the effect of fuel flow and surface temperature on the concentration of MB required to extinguish the flame for two typical airflows. In each case, the concentrations tend to a limiting value. With an airflow of 17 ft sec^{-1}, this concentration is 6.0 percent, while with an airflow of 30 ft sec^{-1}, it is 5.1 percent MB. These two values are very close to the corresponding concentrations required for the burning pool; namely 6.25 percent and 5.1 percent MB respectively.

A Burning Spray of Fuel

The stability of the flame was first of all examined in terms of the air:fuel ratio at which blowoff occurred for a range of flame holder sizes and atomization pressures for the sprays. In all, three spray nozzles of 0.026-in., 0.040-in. and 0.052-in. diameter were used. These preliminary experiments showed that the smallest flame holder gave the most stable flame. There was little difference between the air:fuel ratio at blowoff for the two smallest flame holders at the lower air velocities, but the former gave consistently higher values at the higher airflows. The effect of atomization pressure showed that this should be used in conjunction with an atomization pressure of 100 psig. This is presumably connected with the formation of a spray of fine droplets, which will approximate the formation of a premixed gaseous mixture.

To produce the most stable flame in terms of the concentration of MB required for its extinction, it is also important that the optimum air:fuel ratio should be used, and thus the effect of this variable was examined at two representative airflows. Air velocities of 33 and 66 ft sec^{-1} were used for this purpose. With each flow, the concentration of MB required was a maximum for an air:fuel ratio of 12.0. This corresponds to a slightly fuel rich mixture, since the stoichiometric ratio for kerosine is 14.7. This fuel:air ratio of 12.0, therefore, was used to examine the concentration of MB required to extinguish the flame as a function of the airflow. The results obtained are summarized in the lower curve in Figure 4. This also shows the concentration of MB required to extinguish the burning pool of fuel. It will be seen that the latter concentrations are approximately twice those required to extinguish the burning spray.

DISCUSSION

The results show that a burning pool of fuel or a thin film flowing over a heated surface require the same concentrations of MB to extinguish the flame at a given air velocity. The experimental conditions in these two types of combustion, however, are very similar, so that this result is not unreasonable. In contrast, the spray fire needs a much lower concentration, and thus the flame from the spray is less stable than those from the other two modes of combustion. At first sight this result is a little surprising, but an examination of the physical processes involved in the two cases shows that such a result might be expected.

The physical processes involved in spray combustion depend on the droplet size.[10] In the first case, where the droplet size is small ($< 10\mu$), the flame is essentially a gaseous flame with a continuous flame front, the droplets vaporizing and the vapor produced diffusing to give a homogeneous mixture with air in the preheating zone of the flame. With a coarse spray ($> 45\mu$), no continuous flame front is formed, but each droplet gives rise to an envelope of diffusion flame, which is transmitted from droplet to droplet through the suspension. When the size of the droplets is intermediate between these two extremes, there is presumably some vaporization of the fuel and mixing in the preheating zone, so that the flame is partially premixed and partially diffusion in character. The drop size distribution of the sprays used in the present study have not been examined, but the appearance of the flame under the optimum conditions, i.e. a high atomization pressure, suggests it contains a large proportion of small droplets. Thus it is essentially a premixed system, and the stability expected for the flame can be considered in terms of the known behavior of such systems.

In the absence of a flame holder, a premixed flame is blown out when the linear air velocity exceeds the burning velocity. The maximum value of the latter for hydrocarbon-air mixtures is only about 2 ft sec^{-1}. Hence no stable flame would have been obtained in the present work in the absence of a flame holder, since the airflows were in the range 33 to 66 ft sec^{-1}. The function of the flame holder is to give a region where the local air velocity is substantially lower than the velocity in the main gas stream, so that the flame can anchor itself in this region. The addition of an inhibitor, such as MB, reduces the burning velocity of a premixed flame and thus, at the extinction point, the burning velocity has dropped below the local air velocity behind the flame holder. The concentration of MB required to extinguish the burning spray depends on this local air velocity. At a limit of flammability, the burning velocity is approximately 4 in. sec^{-1}, even when a halogen inhibitor is present,[11] it seems unlikely that the local air velocity behind the flame holder will be this low in the present work, as the velocities in the main gas stream were an order of magnitude higher. The flame is likely to be extinguished, therefore, by a concentration of MB that is somewhat lower than might be expected from limits of flammability determinations. In this respect, it should be noted that the first addition of MB reduces the burning velocity very considerably, but as the concentration increases the relative decrease in the burning velocity becomes less marked.[12, 13] As a result it is not surprising that the burning spray is extinguished relatively easily in terms of the concentration of MB required.

The situation that exists with the burning pool of fuel is somewhat different. In this case, the flame is essentially a liquid surface diffusion flame in which radiation from the flame vaporizes the fuel, and the mixing of air and fuel vapor immediately behind the flame holder is predominantly by a diffusion process. The stability of the flame will primarily be governed by the burning velocity of this pocket of premixed gas in relation to the local gas velocity. Even with the lowest airflows used in the present work (13 ft sec^{-1}), the air velocity above the flame holder was high compared with the expected value for the maximum burning velocity (2 ft sec^{-1}). But the gas velocity just below the top of the flame holder will have been relatively low, since it was the flow induced by the vaporization of the fuel. The local gas velocity immediately behind the flame holder for the burning pool of fuel was much lower than that with the burning spray, and the concentration of MB required to extinguish the flame was correspondingly higher.

From the practical point of view, the importance of eliminating as many flame holders as possible from an engine nacelle at the design stage is clear. Hirst and Sutton[5] found that a projection of only 0.125 in. high was sufficient to double the air velocity at which blowoff occurred in the absence of any inhibitor. A further indication comes from the concentrations of MB required to extinguish the flame at an airflow of 15 ft sec^{-1}. With an obstruction 0.625 in. high, 5.5 percent MB is required, while for a 1.0 in. obstruction this concentration has risen to 6.5 percent. In the absence of any obstruction a velocity of 15 ft sec^{-1} is sufficient to blow the flame out on its own.[5] Thus it is not unreasonable that a lower concentration of extinguishing agent should be specified when the design ensures a smooth nacelle. Unfortunately there is quantitative data available on the reduction in concentration that can be tolerated and, at the same time, ensure that the fire is extinguished.

When some turbulence was deliberately introduced into the airflow, the concentration of agent required to extinguish the fire was reduced, but it is doubtful if this observation can be utilized in any practical sense. Unlike the experimental arrangement used in the present work, it is likely that the deliberate introduction of turbulence will be at the expense of introducing flame holders. The resultant increase in the stability of the flame will more than outweigh any beneficial effect of the turbulence. The importance of these experiments in which turbulence was deliberately introduced lies in the fact that they ensure that the most stable flame was obtained in the present work.

Thus for any given airflow, the concentration of MB that will extinguish any flame has been obtained. This concentration increases as the airflow decreases, however, and with the experimental arrangement used in this part of the work, the practical lower limit for the air velocity was 10 ft sec^{-1}. At that velocity there was no indication that the concentration of MB was approaching a maximum value, and for any practical fire situation, it is this maximum value that is needed. The concentrations of various agents required for air velocities < 10 ft sec^{-1} will be reported in a subsequent paper.

CONCLUSIONS

The results discussed here show that the most stable type of flame to be encountered in an engine fire in an aircraft is a liquid surface diffusion

continued on page 289

REFERENCES

[1] Geyer, G. B., "Evaluation of Aircraft Ground Firefighting Agents and Techniques," Technical Report AGFSRS 711 (February 1972).

[2] Sparrow, E. M. and Cess, R. D., *Radiation Heat Transfer* (Brooks/Cole Publishing Company, Belmont, California, 1966).

[3] Salzberg, F. and Campbell, J., "Aircraft Ground Fire Suppression and Rescue Systems," current technology review, IIT Research Institute, ASWF Technical Report, AHFSRS 701 (October 1969).

[4] Welker, J. R. and Sliepcevich, C. M., "Bending of Wind Blown Flames from Liquid Pools," *Fire Technology*, Vol. 2, No. 2 (May 1966).

[5] Atallah, S. and Allan, D. S., "Safe Separation Distances from Liquid Fuel Fires," *Fire Technology*, Vol. 7, No. 1 (February 1971).

[6] Blinov, V. I. and Khudiakov, G. N., "Certain Laws Governing Diffuse Burning of Liquids," Doklady Academy Nauk SSSR, 11B, 10941098 (1957).

[7] Chicarello, P. J., Krasner, L. M., and Shpilberg, D. C., "Aircraft Ground Fire Suppression and Rescue System Analysis and Fire Protection Evaluation," Factory Mutual Research Corporation, Norwood, Massachusetts (1972).

---

continued from page 275

flame from a pool of fuel burning behind an obstruction in an airflow. The conditions required for optimum stability of this flame have been determined. The concentration of MB required to extinguish the flame varied from 4.3 percent at an air velocity of 50 ft sec^{-1} to 6.2 percent when the air velocity was 13 ft sec^{-1}. The results clearly show the advantage, from the safety aspect, of eliminating flame holders in the engine installation.

ACKNOWLEDGMENT: The authors wish to thank Mr. R. Eyre for his assistance with the experimental work. This work was carried out with the support of the Procurement Executive, Ministry of Defence.

NRC-CNRC

CISTI Document Delivery Order Form

Commande de service de fourniture de documents de l'ICIST

ORDER NO. : CI-776542-6

TECHNICAL CENTER LIBRARY
US FEDERAL AVIATION ADMINISTRATION
INTERNATIONAL AIRPORT
ATLANTIC CITY. NEW JERSEY
USA 08405

FIN NO. :
CISTI NO. : AZ138084
ACCOUNT NO.: DD705938
SENT VIA : GEOFOCLC

PHONE : 609/485-5124
FAX : 609/485-4329

SUBMITTED : 07-12-95 12:00:00 AM
PRINTED : 07-13-95 7:36:50 AM

2	Periodical	Regular

TI : FIRE TECHNOLOGY.
AU : HIRST. R . FARENDEN. P.J. AND SIMMONS. R.F.
SO : -
V/I : VOL 12
DA : PART 1 1976
PG : 266
TI ART : THE EXTINCTION OF FIRES IN AIRCRAFT JET ENGINES
PE : ›BOSTON. MASS.! . NATIONAL FIRE PROTECTION ASSOCIATION.
NU : ISSN 0015-2684
SO : OCLC 1569307 OCLC
NO/CL : 9861436 /INGERSON. DOUG. X54945
MODE : GEOFOCLC

INSTR : MAX COST $WI. PAY SHIP TO: ILL DEPARTMENT/FAA TECHNICAL CENTER LIBRARY/ACL-1L TE

REPLY VIA: OCLC

The estimated copyright charge for this document based on 10 pages is $0.00 .

If you have any questions or problems, please contact our Client Assistant.

En cas de problèmes ou si vous avez des questions, communiquez avec le bureau d'aide aux clients.

Phone/Téléphone : (613) 993-9251
Fax/Télécopieur : (613) 952-8243

National Research Council Canada
Conseil national de recherches Canada

Canada