The Extinction of Fires in Aircraft Jet Engines — Part III, Extinction of Fires at Low Airflows

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Minimum concentrations of methyl bromide, bromotrifluoromethane, bromochlorodifluoromethane, and nitrogen that will ensure the extinguishment of the most stable liquid surface diffusion flame burning behind a flame holder have been determined.

RESULTS presented earlier[1] show that the most stable mode of combustion obtained in an aircraft engine fire is one in which the fuel has collected in a pool and burns behind an obstruction in the airflow. The most favorable conditions for this type of combustion were established in terms of the concentration of methyl bromide required to extinguish the flame, and for these conditions, it was found that the concentration required tended to increase as the air velocity decreased. With the experimental arrangement used earlier,[1] the practical lower limit for the air velocity was 10 fps (3.05 m s^{-1}), and there was no indication that the concentration of methyl bromide was approaching a maximum value at this velocity. For any practical fire situation, it is this maximum value that is needed, since the application of such a concentration would ensure that all flame was extinguished. In the present work, therefore, the experimental conditions have been modified so that the concentrations required for air velocities below 10 fps (3.05 m s^{-1}) could be examined. Results are reported for methyl bromide (MB, Halon 1001), bromotrifluoromethane (BTM, Halon 1301), and bromochlorodifluoromethane (BCF, Halon 1211). Results are also presented for the inert diluent nitrogen.

EXPERIMENTAL

The fire model, wind tunnel configuration, and the system of flow measurement were essentially the same as those used earlier,[1] but thermo-

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couples were used to monitor the temperature of the air and extinguishant flows to achieve more accurate flow measurements. A small two-stage centrifugal fan was used to obtain the low airflows required. Control of the flow was achieved by adjusting the fan inlet and two butterfly valves, one in the main flow and the other in the pipe that carried the excess air to the atmosphere.

With these low flows (less than 10 fps or 3.05 m s^{-1}), measurements could not be made by slowly increasing the concentration of agent in the airstream and noting the concentration at which the fire was extinguished, because the time delay between changing the flow of agent and a change in concentration in the fire zone became too long. As a result, it was necessary to follow the buildup in concentration in the fire zone and determine the concentration at which extinction occurred. This buildup was achieved as rapidly as possible, usually by manual control of the extinguishant flow, so that the concentration in the fire zone increased rapidly with time until the final equilibrium concentration had been reached. With BCF, BTM, and nitrogen, this increase in concentration was followed with a thermal conductivity detector. (A trace of helium was added to the nitrogen to enable its concentration to be followed.) However, this technique had not been developed when the measurements with MB were made. In the latter case, an alternative approach was adopted in which samples were taken from the wind tunnel at predetermined times and analyzed by gas-liquid chromatography. It will be convenient, therefore, to consider the results for each agent separately.

RESULTS

METHYL BROMIDE (MB)

Preliminary experiments established that the time required to extinguish the fire, measured from the introduction of the extinguishing agent into the airflow, depended on the concentration introduced. With the higher injected concentrations (greater than 12 percent methyl bromide) at an airflow of 2.5 fps (0.76 m s^{-1}), the time to extinguish the fire was always about 8 s. (See Figure 1.) This represents the minimum time for the agent to reach the fire zone. Slight random scatter in the times probably reflects slight changes in the rate at which the flow of methyl bromide had been built up to the required level. Figure 1 also shows that there is a lower limiting concentration below which extinction cannot be achieved. But as this concentration is approached, the corresponding time to extinction exceeds 20 s, i.e., methyl bromide had been present in the fire zone for more than 10 s. As a result, these latter values are of no significance in the practical aircraft situation, since the maximum time that the concentration of agent is maintained in the nacelle is only of the order of a few seconds.

Corresponding results were obtained at all the other airflows. Thus, the analyses were restricted to tests in which the injected concentration of methyl bromide was greater than 7 percent, so that extinction occurred within a few seconds of the methyl bromide reaching the fire zone. These

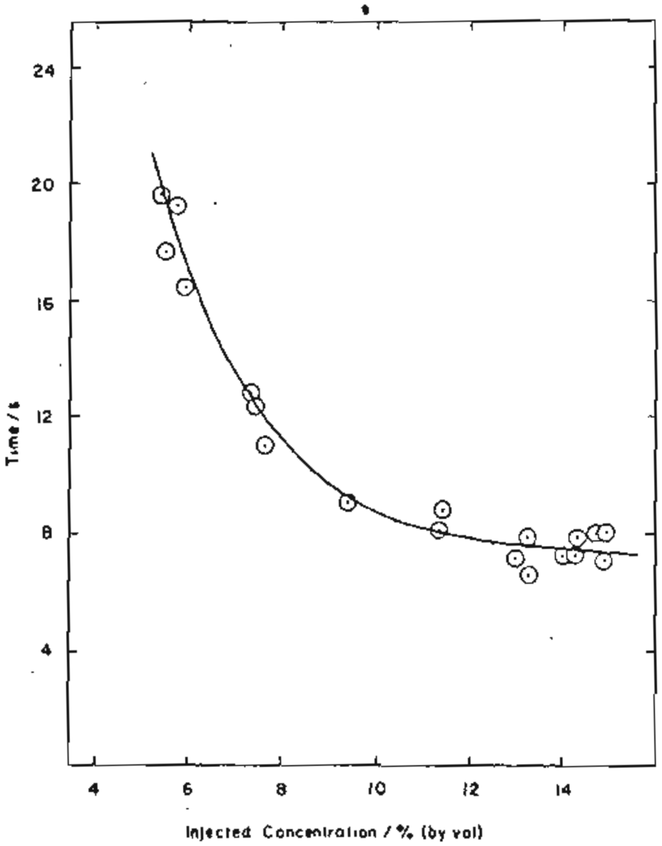

Figure 1. Time to extinguish the burning pool of kerosine as a function of the concentration of MB injected into the air stream. Air velocity, 2.5 fps (0.76 m s⁻¹).

analyses were made using duplicate experiments in the absence of a fire. A particular concentration of methyl bromide was introduced into the flow, and gas samples were taken at intervals of a few seconds around the time that the flame was known to be extinguished. Figure 2 shows the spread of values obtained at each airflow over a wide range of nominal concentrations of methyl bromide. It is striking that extinction occurred so consistently in such a narrow range of concentrations. In addition, Figure 2 shows that these concentrations are in good agreement with those obtained at the higher airflows by gradually increasing the concentration of agent.[1] The concentration of methyl bromide at which the flame was extinguished passes through a shallow maximum in the region of 1 to 4 fps (0.305 to 1.22 m s^{-1}). From the practical point of view, this maximum concentration (7.8 percent methyl bromide) should extinguish any fire that might be present.

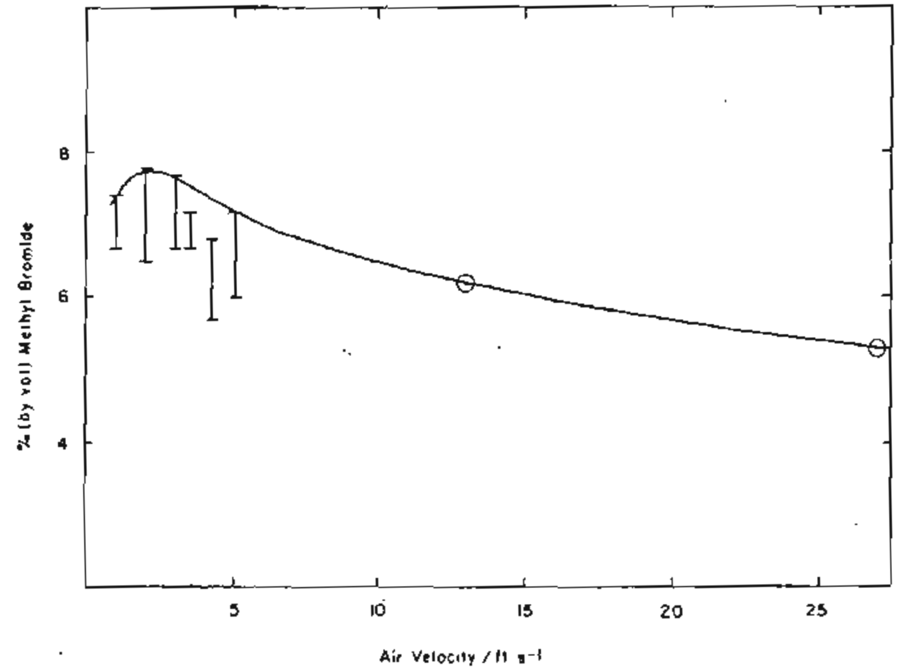

Figure 2. Variation in concentration of MB required to extinguish the flame with airflow. The bars represent the range of concentrations obtained by analysis; ⊖ concentrations obtained by slowly increasing concentration and noting that at which extinction occurred.

BROMOCHLORODIFLUOROMETHANE (BCF)

In this part of the work, an improved method of following buildup in concentration in the fire zone was used. This involved drawing samples of the flow at a constant rate through a thermal conductivity detector. This sample was taken off approximately 6 in. (15.2 cm) upstream of the fire model, so that there was no need for the duplicate experiments that had been made with methyl bromide as the extinguishing agent. The sensitivity of the detector was determined using known flows of BCF and air. Spot checks of the calibration were made each day before starting the wind tunnel tests. If the result was outside ± 2 percent of the expected value, it was usually found that soot had accumulated in the filter in the sample tube, so that the flow through the detector had been affected.

To obtain the concentration at which the flame was actually extinguished, it was necessary to determine the response time of the detector unit, i.e., the time for a particular volume of gas to pass from the tip of the sample probe to the detector. This was obtained initially by discharging some pure BCF approximately 3 in. (7.6 cm) upstream of the tip of the sample probe within the wind tunnel and noting the time at which an initial indication of BCF was obtained on the recorder. This was 2.2 s, but it took an additional few seconds for the concentration to reach its final

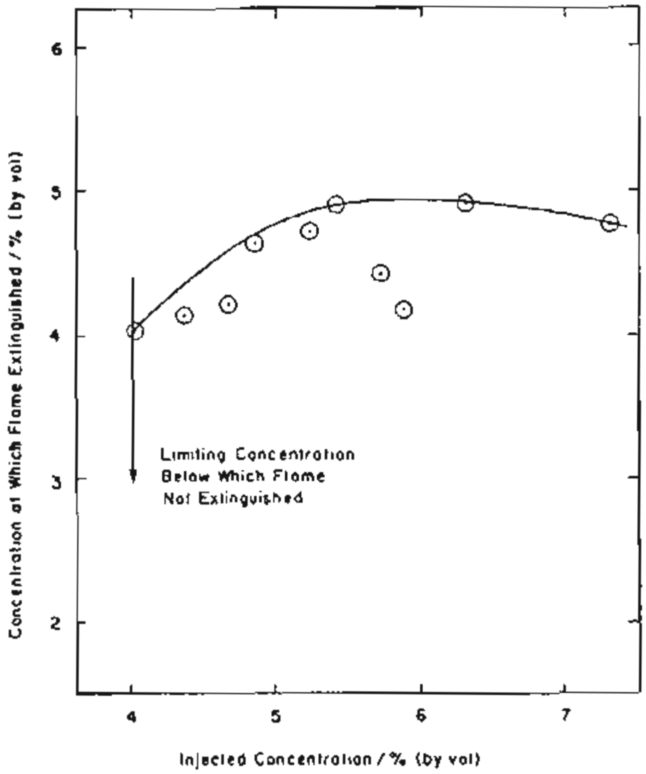

Figure 3. Concentration of BCF at which the flame was extinguished as a function of the injected concentration. Air velocity, 13.8 fps (4.2 m s^{-1}).

equilibrium level. Thus, the use of 2.2 s for the response time may underestimate the concentration at which the fire was actually extinguished, but it is convenient to use this time in an initial analysis of the results.

Figure 3 shows that, at the higher injected concentrations, the fire was extinguished before the final concentration had been attained in the fire zone, and extinction occurred within a few seconds of the first trace of BCF reaching the fire. The results show some scatter, but a detailed analysis of all the results suggests that not only the concentration of agent, but also the rate at which it is reached, affect the extinction of the flame. In general, where extinction was achieved with a relatively low concentration of BCF, it had been built up rapidly.

The results in Figure 3 show that the 2.2-s response time leads to an upper limiting value of 4.9 percent BCF for the concentration at which the fire was extinguished. Corresponding results were obtained at other airflows. Figure 4 shows these limiting values plotted as a function of airflow, together with the values obtained at higher airflows by gradually increasing the concentration of agent in the airflow and noting the value at which

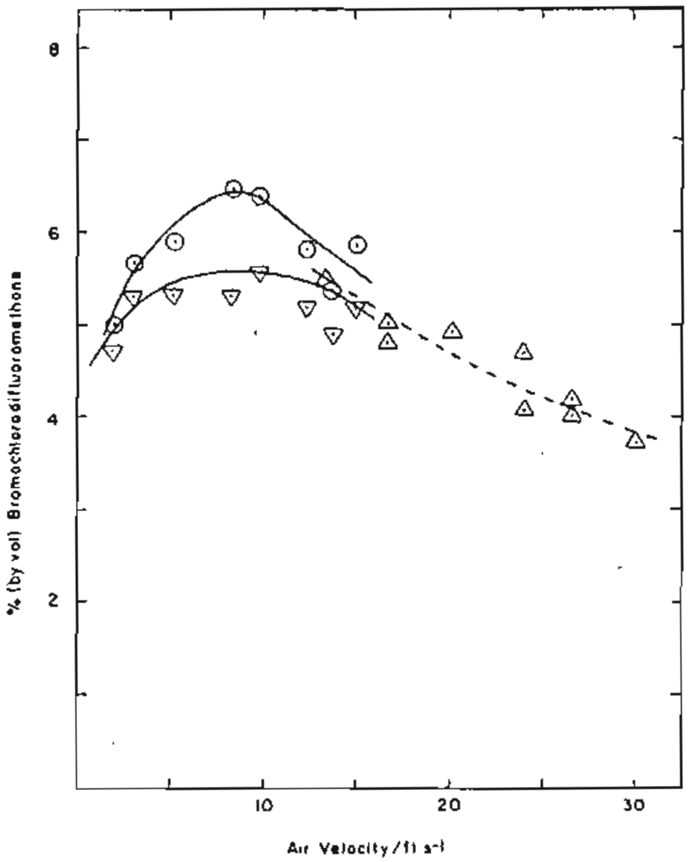

Figure 4. Variation in the concentration of BCF required to extinguish the flame with airflow. Concentration using response time of 2.2 s ▽ and 3.4 s ⊙ for the detector; concentrations obtained by slowly increasing concentration in airflow △.

extinction occurred. These two sets of data are in reasonable agreement and tend to a maximum value of 5.5 percent BCF.

As pointed out earlier, 2.2 s is the time at which BCF is first detected, and an additional few seconds is required to reach the final equilibrium concentration. Thus, an alternative measure of the response time was made in which a concentration of 8.5 percent BCF was introduced into the flow and the time noted for the indicated concentration to reach 5.5 percent (the maximum value using 2.2 s for the response time). This gave 3.4 s. The upper curve in Figure 4 was obtained from a further analysis of all the results using this higher value for the response time of the detector. The general pattern in the results was unchanged by the use of the longer time, but the maximum concentration in Figure 4 was increased to 6.5 percent BCF. It might be argued that 3.4 s is longer than the true response time, but equally, 2.2 s is an underestimate. Thus, although the value of

6.5 percent BCF may be slightly greater than that actually required to extinguish any fire, it is considered that this value should be accepted as the lowest concentration of BCF that will ensure the extinction of any fire in an aircraft engine nacelle.

BROMOTRIFLUOROMETHANE (BTM)

Essentially, the same experimental procedure was used with BTM as was used with BCF, but the hand-operated valve controlling the flow of agent was replaced by a mechanically operated valve. This enabled the required flow of BTM to be reached more rapidly than was the case with BCF. The results obtained were very similar to those for both methyl bromide and bromochlorodifluoromethane, in that, with the higher injected concentrations, the fire was extinguished very rapidly and before the final equilibrium concentration had been reached in the fire zone. Analysis of these results showed that, at a given airflow, the concentration at which the fire was extinguished tended to a limiting value. These limiting values are plotted as a function of airflow in Figure 5, which also includes the concentrations obtained by slowly increasing the concentration in the airflow. The former values were obtained by using the upper of the two response times. The two sets of data are in quite good agreement. Figure 5 shows that these concentrations pass through a maximum of 5.8 percent BTM, and as before, it is suggested that this is the lowest concentration that will ensure the extinction of any fire in the nacelle.

NITROGEN

As with the other extinguishing agents, the flow of nitrogen was built up to the required level as quickly as possible, and the time noted at which extinction occurred. Figure 6 shows a typical set of results. They are similar to the results for the halogenated agents, in that there is a lower limiting concentration below which the flame could not be extinguished. However, the actual concentrations involved are much higher, and the time to extinguish the flame again decreases as the injected concentration increases. The buildup in the concentration of nitrogen could not be followed directly using the thermal conductivity detector. It was necessary to introduce a trace of helium into the flow to obtain a suitable change in the thermal conductivity of the mixture. Adding 1.5 percent helium to the additional nitrogen gave a satisfactory response. But with the very low air velocities that had to be used to reach the maximum concentration of nitrogen required to extinguish the fire, the buildup to the injected concentration occurred slowly. For example, with an air velocity of 1.2 fps (0.37 m s^{-1}), the first trace of helium was detected after 8.5 s, but it took 33.5 s for the helium to reach 95 percent of its final concentration. With an air velocity of 0.25 fps (0.08 m s^{-1}), the latter time was about 100 s. In comparison, the response time of the detector was negligible.

Nitrogen is unlikely to be used for extinguishing engine fires, although it might be used for inerting the vapor space in fuel tanks. As a result,

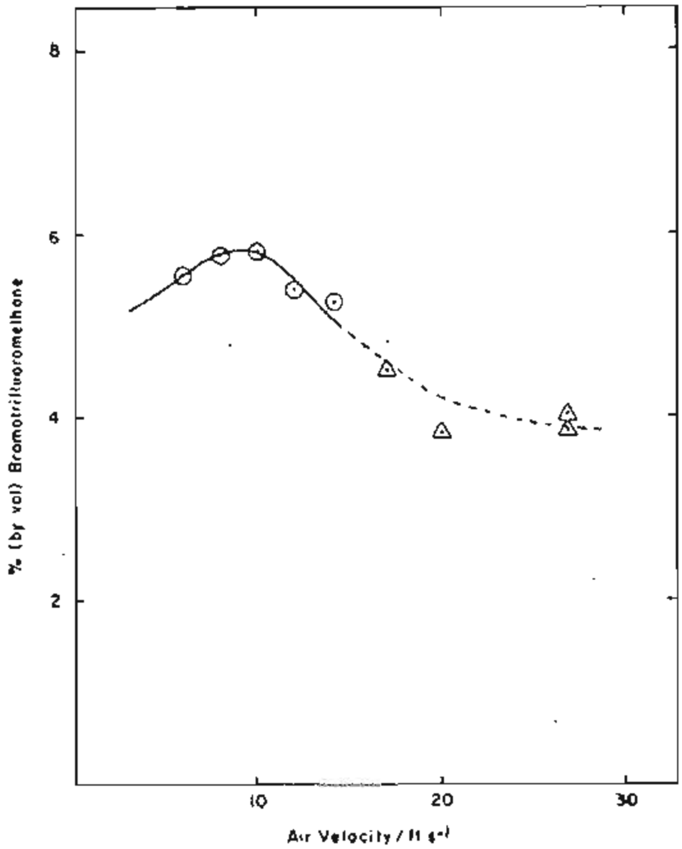

Figure 5. Variation in the concentration of BTM required to extinguish the flame with airflow. ○ concentrations obtained using detector; △ concentrations obtained by slowly increasing concentration in airflow.

there is no time restriction for the extinction of the flame as is the case with the halogenated agents. Therefore, a slightly different approach was adopted with nitrogen. This is illustrated by Figure 6, which shows not only the time to extinguish the fire as a function of injected concentration, but also the time required for the nitrogen concentration to reach 95 percent of the injected value. The intersection of the two lines gives an actual concentration at which the fire was extinguished; namely, 39.6 percent at this particular airflow. This concentration is very close to the limiting concentration below which the fire could not be extinguished. The concentration was obtained in this way rather than from the limiting value, because the latter was not well defined at the very low air velocities, in that the curve tended to drift down rather than to reach a plateau. If anything, this approach will tend to slightly overestimate the actual limiting concentrations, but in doing so, tends toward the side of safety.

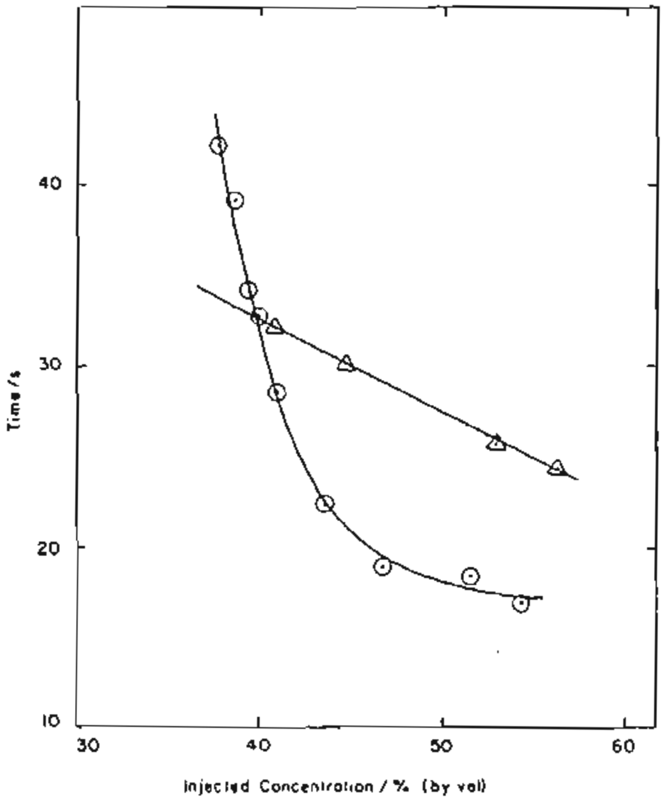

Figure 6. Variation in time to extinguish the flame ⊙ *and time for the concentration to reach 95 percent of its final value* △ *as a function of the injected concentration of nitrogen. Airflow, 1.02* $ft^3\,s^{-1}$ (0.03 $m^3\,s^{-1}$).

Figure 7 shows these concentrations as a function of the total flow velocity rather than the air velocity, since the addition of such large quantities of nitrogen produces a marked change in the total gas velocity in the fire zone. It will be seen that the nitrogen concentration passes through a maximum value of 42.5 percent. If this concentration was maintained in a fire zone, any fire would be extinguished.

DISCUSSION

The present results show that the concentrations of MB, BCF, and BTM required to extinguish any fire are 7.8 percent, 6.5 percent, and 5.8 percent, respectively. It is instructive to see how these concentrations compare with other estimates. The extinguishant required at low airflows has been examined also, in the case of MB and BCF, using a scaled down model in which kerosine was burned in an open cup with the airflow passing upwards around the cup.[7] The lag between the time the concentration of

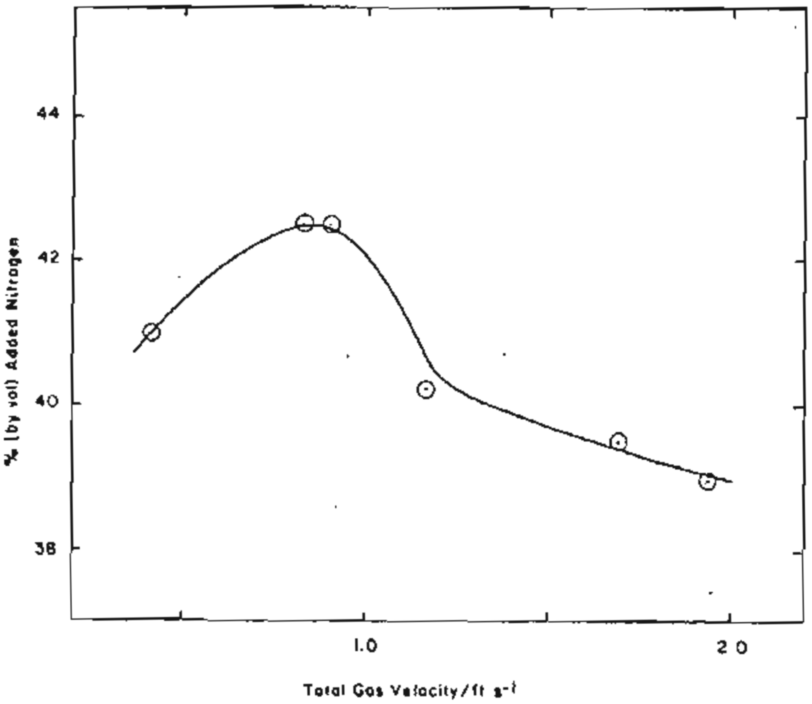

Figure 7. Variation with total gas flow of the concentration of added nitrogen required to extinguish the flame.

agent was changed and the time that change reached the burning fuel was quite small because of the relatively small volume of the apparatus. Thus, it was possible to determine directly the concentration required to ensure that the flame was extinguished at any airflow. These results showed that 7.8 percent MB or 6.1 percent BCF was required. Both values are in good agreement with those obtained in the wind tunnel work. With MB as the extinguishing agent, the maximum value occurred with the same air velocity in both determinations; namely, between 2.0 and 2.5 fps (0.61 and 0.76 m s^{-1}). In contrast, the maximum concentration of BCF from the wind tunnel work was at an air velocity of 9.0 fps (2.74 m s^{-1}); whereas, with the cup burner, the maximum was again with an airflow in the region of 2.0 to 2.5 fps (0.61 to 0.76 m s^{-1}). A comparison of the wind tunnel results for MB and BCF, however, shows that there is a marked decrease in the concentration of BCF required at the low airflows. With MB, the maximum is much flatter, and there is hardly any decrease in the concentration, even at very low air velocities. It is difficult to suggest any plausible explanation for this difference, but it may be connected with the fact that MB, itself, will burn if it is heated to a sufficiently high temperature.

TABLE 1. *Some Typical "Peak" Concentrations Reported for BCF, BTM, and MB from Limits of Flammability Measurements.*

Agent	*Fuel peak concentrations (%)*			
	Ethane[3]	*Hexane*[4]	*Heptane*[5]	*Present study*
BCF (CF_2BrCl)	5.8 (0.72)	5.2 (0.94)	9.3 (0.66)	6.5 (0.89)
BTM (CF_3Br)	4.2 (1.00)	4.9 (1.00)	6.1 (1.00)	5.8 (1.00)
MB (CH_3Br)	5.9 (0.71)	7.1 (0.70)	9.7 (0.62)	7.8 (0.74)

One of the earliest ways used to estimate the concentration of extinguishing agent required to extinguish a fire was to determine its effect on the limits of flammability of a typical fuel in air and thence obtain the "peak" concentration from the limits of flammability diagram. Table 1 lists the "peak" concentrations for the agents used in the present study, which were obtained using three different fuels, together with the concentrations obtained in the present work. The values in brackets are the relative efficiencies compared to that of BTM in each set of data. At first sight, it is surprising that there is such a large difference in the values reported for hexane and heptane as fuels, especially as it has often been suggested that the results for these fuels should also be applicable to petroleum and kerosine. An examination of the literature shows that values between 7.05 percent and 12.5 percent have been reported for the "peak" concentration of MB when hexane is the fuel.[3, 4] It seems unlikely, therefore, that the limits of flammability are much more sensitive than usual to the precise experimental conditions when an halogenated compound is present. The variation in the relative efficiencies listed in Table 1 also supports this view. Thus, it would be unwise to use such "peak" concentrations alone to decide how much agent is required to extinguish an actual fire.

So far, the present results have been considered only in terms of the extinction of a fire in an airflow where the concentration of agent can be maintained only for a short time. There are other situations, however, where this time restriction does not apply, such as in a total flooding system. The present results show that somewhat lower concentrations can be used safely in such cases. With a given agent and airflow, the plot of time to extinguish the fire against injected concentration tends to a concentration below which extinction is not possible. (See Figure 1.) Where there is no time restriction for the extinction of the fire, it is this lower limiting value that is applicable. Unfortunately, these values were not always obtained with precision, since they were only obtained coincidentally; but an examination of the results shows that 4.0 percent BCF, 4.0 percent BTM, or 5.5 percent MB are applicable to total flooding situations.

The concentration of nitrogen required to ensure extinction of a fire was found to be 42.5 percent. Though this is very much greater than the required concentrations of MB, BCF, or BTM, it is only to be expected. The latter three agents act as chemical inhibitors in the flame; whereas, nitrogen acts solely as an inert diluent.[9] A nitrogen concentration of 42.5 percent corresponds to an oxygen content of 12.0 percent, which is not unreasonable when compared with oxygen contents for the extinction of diffusion flames burning on a hemispherical burner.[10] The limiting oxygen contents obtained in the latter work were constant at 13.3 percent for the long chain paraffins, i.e. paraffins containing more than four carbon atoms. Lower values were obtained for the lower paraffins and unsaturated hydrocarbons. For example, values of 10.5 percent and 11.8 percent oxygen were obtained for ethylene and ethane, respectively. Thus, if there was any thermal decomposition of the fuel before it entered the flame, as seems likely, the minimum oxygen content should be lower than 13.1 percent. The present value of 12.0 percent is not unreasonable.

The use of the thermal conductivity detector with BCF, BTM, and nitrogen has made it possible to obtain information about the rate at which the concentration of extinguishant built up in the fire zone; whereas, in the work with MB, the limited number of analyses that could be made only allowed the concentration at the point of extinction to be measured. In this type of work, some scatter in the results is to be expected solely because it is difficult to reproduce exactly the precise conditions from experiment to experiment. An analysis of the results for BCF (in particular) suggests part of this scatter can be attributed to changes in the rate at which the concentration of extinguishant built up in the fire zone. For example, in a series of tests with an injected concentration of 5.5 percent BCF, extinction of the flame occurred between 3.8 percent and 5.0 percent BCF. In general, where major differences of this kind existed in the results, the lower concentration always corresponded to a more rapid buildup to the final equilibrium concentration.

Throughout this work, these effects were much more apparent at the lower rather than at the higher airflows. This probably arises from the change in inclination of the flame to the horizontal as the airflow decreases. At moderately high flows, the flame is almost horizontal, so that radiation back on to the surface of the liquid fuel ensures a steady rate of evaporation. With the lower flows, however, the flame is much more upright. This will decrease the rate of evaporation of fuels to feed the flame. Under these conditions, any change in the rate of evaporation will affect the stability of the flame. Stability will be controlled mainly by the pocket of premixed gases that forms just behind the flame holder. As long as the linear gas velocity does not exceed the burning velocity of this mixture, a stable flame will be obtained. If the inhibitor is introduced into the flame slowly, the flame has time to adjust to each small change in concentration as it is made, so that the maximum concentration to extinguish the flame is reached. On the other hand, if the extinguishant is introduced very rapidly, the resultant changes in burning velocity can produce surges in the flame, which in turn affect the vaporization of the fuel, so that the flame is extinguished prematurely. Such effects can obviously be important in the practical extinction of a fire in an engine nacelle, but it would be wiser to ensure that the concentration of agent is sufficient to extinguish the fire, even under the most demanding conditions. These other features can then be used to give an improved margin of safety.

CONCLUSIONS

It is concluded that 7.8 percent MB, 5.8 percent BTM, 6.5 percent BCF, or 42.5 percent nitrogen are required to extinguish a liquid surface diffusion flame burning behind a flame holder. These concentrations will ensure that even the most stable flame is extinguished. Thus, they represent the lowest concentration of each extinguishing agent that should be used in a fire protection system for an aircraft engine. A higher concentration should be used for design purposes, however, to allow for factors such as uneven distribution of the agent.

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