ON THE APPLICABILITY OF RETICULATED FOAMS FOR THE SUPPRESSION OF FUEL TANK EXPLOSIONS

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SUMMARY

It is known, that reticulated foams can inhibit flames, which develop inside fuel tanks. The application of such foams in aircraft tanks neccessitates a compromise to be made between best flame suppression properties and lowest additional weight of the foam structure. Also technological questions, like mechanical behaviour during refuelling, have to be considered.

Investigations have been carried out at DFVLR, Porz-Wahn, in which the flame suppression properties of polyurethane foams with varying cell size have been studied by means of a flame tube and an explosion vessel. Results on the thickness of the foam layer necessary for flame quenching will be given, depending on pore size, fuel-air ratio and on pressure. The behaviour of reticulated foam during explosion in a closed vessel will be discussed, as well as its mechanical behaviour. Conclusions with respect to the application of foam structures in tanks will be drawn.

INTRODUCTION

FOR MILITARY AIRCRAFT it is highly desirable to have technical systems which can prevent the explosion of aircraft fuel tanks when subjected to enemy actions. There are several systems which can fulfill this duty, for example nitrogen inerting systems, fast-response fire-fighting systems or the application of reticulated plastic foams, which are fitted to the interior of fuel tanks. Whereas the physical working-principles of the first two mentioned systems are rather well understood, only little information is available on the fire-suppressing properties of reticulated foams. Therefore an investigation concerning these and some other interesting mechanical properties has been started under a contract of the Min.of Def., F.R.G.

There are several important points which have to be clarified before optimum use of reticulated foam in aircraft fuel tanks can be made. Tests carried out under the guidance of military authorities of several NATO-countries have shown that it is possible to avoid explosions of fuel tanks after being hit by projectiles, if the tank volume is filled with reticulated foam. However, the volume of the solid structure of the foam, on one hand detracts from the usable storage capacity of the tank; on the other hand it withholds, by means of adhesive forces, a certain amount of fuel. This means that the fuel stored in the tank cannot be fully used for propulsion purposes. Hence, a reduction of the range of the aircraft is inevitable. A further penalty results from the additional weight of the foam structure which decreases the payload. Therefore, a need for optimisation of the foam structure with respect to the mentioned losses exists.

There are several ways to achieve this. One is to decrease the specific mass of the foam structure by increasing the cell size and reducing the dimensions of the cross-pieces, without changing the flame suppression qualities. Another possibility is to divide the available tank space into small volumes by using layers of reticulated foams of a certain thickness and a cell-size which is sufficient to prevent a flame from spreading from a cavity to the neighbouring ones. For this case it is also of interest to know how large the size of the cavities left free from foam can be.

From these objectives a number of questions can be deduced which have to be answered before an optimum design of flame-suppressing foam structures can be made. The first part concerns the foam layer thickness necessary for flame suppression as a function of cell size, mixture ratio, fuel quality, pressure and temperature. The second part concerns the tolerable cavity sizes formed by the crosswise foam layers inside the tank, and a third area is given by mechanical and chemical problems, like flow resistance, fuel retainment by the foam structure, suppression of fuel sloshing, aging of the foam, and so on. The experiments reported in the following were intended to get better informations on some of these areas. They are by no means complete and have to be carried on.

EXPERIMENTS ON THE FLAME SUPPRESSION PROPERTIES OF RETICULATED FOAMS

In general, an explosion inside a fuel tank is ignited within a limited area, e.g. the surface or the wake of a hot projectile [1]. The flame which develops will then spread with increasing speed throughout the whole tank volume. This flame spreading is to be suppressed by the action of the reticulated foam structure. A suitable means for the simulation of this process is resembled by a flame tube. However the spreading of a flame in such a flame tube is a quasi-one-dimensional process, whereas the flame spreading through a combustible mixture from a projectile or its wake is at least quasi-two-dimensional. This difference however, is no disadvantage, because if a flame tube is used, the studies are carried out under more severe conditions. Generally, one can assume that the flame speeds in the tube are larger than those of flames developping from projectiles in tanks. Therefore a flame-tube was chosen for most of the experiments. The experimental set-up is shown in Fig.1. The flame tube has a diameter of 60 mm, and a length of 2 m. At some distance from the ignition end of the tube, a cylindrical foam specimen was placed between two flanges. This distance was chosen so that certain fixed values of the flame speed were obtained in the region immediately upstream of the foam specimen.

The measurement of the flame travelling speed was performed optically, by using fototransisters, which observed the passing-by of the luminous flame front. Three of these detectors were installed upstream of the specimen with a distance of 100 mm between two of them.

Ignition of the combustible mixture was achieved by a spark or by a hot wire. The combustible mixture was formed from fuel and air flows measured by rotameters. In order to vary the mixture temperature, the two gas flows were heated or cooled by means of heat exchangers, downstream of the rotameters. For avoiding heat losses from the tube after filling with the heated or cooled mixture, the tube could be thermostatizised. The pressure inside the tube was registered with quarz transducers. The homogeneity of the mixture was ensured by mixing fuel and air far upstream of the tube. Ignition was performed immediately after filling the tube. The resulting flame then travelled the distance up to the foam specimen; here it was either arrested or passed through the foam, in the latter case igniting the combustible gas volume downstream of the obstacle. The appearance or non-appearance of this downstream ignition was again registered optically by a fototransistor.

The tests were carried out in such a way that for given conditions (fuel mixture-ratio, pressure, temperature, cell size of the foam) the thickness of the foam specimen in the direction of flame propagation was varied from test to test until no ignition of the combustible mixture downstream of the specimen was observed. Each test point was repeated 10 times.

For the tests 7 foam qualities with different cell sizes were available, each of which was characterized by the number of cells per unit length (cm). In order to count the number of cells a very simple procedure was applied; the specimen was immerged into a opaque liquid, the color of which has to give enough contrast to the color of the foam. If the surface of the liquid and of the foam specimen are located in the same plane, it is possible to count the number of cells without interference from the adjacent cell layers. The cell sizes of the foams investigated ranged between 3 and 24 cells per centimeter.

TEST RESULTS

Fig.2 shows the results on the necessary specimen thickness depending on the number of cells for stoichiometric, fuel-rich and fuel-lean propane air-mixtures at a pressure of 1 bar and a temperature of 293 K. Two different values of the flame speed, 1,2 m/s and 8 m/s have been chosen. For the lower velocity the flame was ignited at the open end of the tube; the higher velocity could only be obtained with ignition at the closed end. As expected in this case the flame speed showed some fluctuations [2]. The distance between the ignition point and the specimen was chosen so that the prescribed value of the flame velocity could be reproduced with a scatter of approx. 10 - 15 %.

For all mixtures investigated the specimen thickness necessary for the suppression of the flame has a tendency to decrease with increasing cell numbers. This tendency is most pronounced for stoichiometric mixtures. For fule-lean and fuel-rich mixtures the thickness of the specimen is only slightly dependent on the number of cells. This seems to indicate that the total surface of the foam material exposed to the flame, at which radicals can be deactivated and which can absorb heat, is a controlling factor. Furthermore, for mixtures close to stoichometric ratios the necessary specimen thickness increases with the speed of the travelling flame. From this it can be concluded that the time intervall which the flame is in contact with the foam structure, is another controlling factor. However, this effect is not observed with fuel-rich mixtures.

It must be mentioned that with mixture ratios containing excess oxygen inspection of the foam specimen after a successful test always showed that the foam structure was partly burned at the upstream surface. This means that chemical reactions between the foam material and the oxygen can be induced by thermal effects.

Fig.3 shows the influence of different fuels and of pressure on the necessary specimen thickness; the results are valid for stoichiometric mixtures. The change in pressure showed no significant influence on the flame speed; however the scatter of the measured speeds at different pressures increased. Whereas the flame velocities for C_3H_8 resp. CH_4 were in the order of 8 to 9 m/s, for ethylene due to its higher reaction rate a value in the order of 20 m/s was found. In order to compare the results of all three fuels on the same base the foam thicknesses for ethylene have been corrected to the same velocity level as measured for propane and methane; assuming a linear relationship between foam thickness and flame speed, approximately.

The foam thickness h necessary for the suppression of the flame increases with pressure for all three fuels; the dependency can be described approximately by a power law

$$h = h_1 \cdot (P/P_1)^n,$$

where h_1 is the foam thickness at P_1 = 1 bar. The exponent n is nearly the same for all three fuels and has a value of 1.66. A first explanation is possible, if one assumes that a purely thermal process was responsible for the flame suppression. The solid surface of the foam structure necessary for the absorption of heat is proportional to the heat produced and inversely proportional to the heat absorbed by unit area of the surface. Assuming a constant temperature difference between the burnt gas and the surface, the heat produced increases with P^n, where n is the reaction order. The heat absorbed is proportional to the heat transfer coefficient which should be $\sim P^{0.38}$ in the prevailing range of very small Reynolds numbers. Keeping in mind that for a constant cross-section of the foam plug, the active surface A of the structure increases with the thickness h of the plug, we have approximately

$$A \sim h \sim P^{n-0.38},$$

which for a reaction of approx. 2 leads to

$$h \sim P^{1.6}.$$

This compares very well with the observed experimental value of 1.66.

If one crossplots against the laminar burning velocity the measured thickness h for the three fuels at 1 bar, one finds that h increases like

$$h \sim S_L^{1.73}.$$

This could be explained similarly if one assumes that for constant heat transfer properties the necessary length h is approx. proportional to the heat Q produced in the flame. A simplified consideration of the propagation of a wrinkled laminar flame front shows, that Q should vary with S_L^2, which is not very far from experimental observation. One should however bear in mind that the above treatment is a strong simplification of the real physical process of flame suppression and can therefore yield only qualitative results. Especially, radical recombination on the finely distributed solid surface in the way of the flame should play a major role.

A number of experiments has been carried in order to study the influence of the gas temperature before ignition on the necessary foam thickness. The first results have shown that there is some inconsistency which is rather difficult to explain without more insight into the process. Measurements have been carried out at gas temperatures of 353 K, 293 K, and 233 K. They show a distinct minimum of the foam plug thickness h around 293 K, and an increase of the necessary foam thickness both with decreasing and increasing gas temperature. The increase of h with gas temperature can be understood from an increase of the heat release rate for nearly constant heat transfer conditions. However, the reason for the increase of h at lower temperatures is not clear, presently. Some influence has to be expected surely from the change of the wave propagation patterns which occurs with varying temperature. Further experiments have to be carried out before firm conclusions can be drawn.

TEST IN AN EXPLOSION VESSEL

The experiments described in the previous section were intended to get basic information on the behaviour of flame-suppression foams under simplified conditions, which allow a comparison of different foam structures. The physical conditions in a flame propagating through the gas-filled space of a fuel tank differ however to some extent from those prevailing in a flame tube. Therefore, some experiments have been carried out on the extinction of flames propagating through an explosion vessel (Fig.4). Its diameter was 300 mm, its length 1 m. The purpose of the investigation was to find out how the results of the small diameter flame tube can be carried over to larger dimensions and what flame-suppressing qualities could be expected from different geometrical arrangements of foam layers. The filling of the vessel with combustible mixture took place in the same way as described in the previous chapter. For all tests stoichiometric propane-air mixtures were employed. The pressure at the wall of the vessel was measured half way between both end flanges. The extinction of the flame could be observed through a window.

Two kinds of tests have been performed, the first using the explosion vessel like a short flame tube of large diameter. The combustible mixture was ignited at one end flange, and foam plugs of 300 mm dia. and length of 100 to 900 mm were placed in the vessel at different distances from the ignition point. Foams with 4, 6 and 7 cells per cm have been used. Foams with 4 cells per cm or less cannot prevent flame propagation through the vessel at all, even if the vessel is completely filled with foam. However, the propagation process was considerably slowed down; also the pressure measured after combustion was completed is lower than in a vessel without foam inserts. It decreases from 12 bar in the latter case to 2 bar, if the whole vessel is filled with foam. For foams with 6 and 7 cells/cm the flame could not be prevented from passing through a foam layer of 100 mm thickness if the distance of the foam from the ignition source was larger than 400 mm. For smaller distances a passage of the flame through the foam cannot be excluded with certainty; the reason for this is not yet understood. From the fact that the foam shows severe destructions on the surface opposite to the ignition source and that the vessel is filled with dense white acid smoke after the test one can suppose that some reactions between the foam material and the hot gases take place, which were not observed in the flame tube.

The second kind of tests in the explosion vessel dealt with the size of cavities inside the foam structure necessary for flame suppression. These tests are not yet complete at the time of writing. Up to now only two cavity sizes have been investigated, one with 200 mm dia, 200 mm length, surrounded by foam walls of 100 mm thickness, the other with 80 cm dia, 80 mm length and foam walls of 80 mm thickness. The number of cells/cm were 6 in the first and 6 and 7 in the second case.

The respective specific gravities of the foams were 40.1 and 15.0 kg/m^3. Ignition was performed by sparks in the center of the cavity. When using foam with 6 cells/cm, passage of the flame through the foam was observed in every case. This holds also for the foam with 7 cells/cm and the smaller 80 dia cavity. In this case the already mentioned destruction together with the appearance of with smoke was observed. A possible reason for this may be that the 7 cell/cm-foam with its very small specific mass of 15 kg/m^3 has been heated more intensely than the heavier 6 cell/cm-foam. It is planned to continue these tests down to smaller cavity sizes.

SOME PHYSICAL PROPERTIES OF THE FOAM

Fitting of the fuel tank with foam rises some questions concerning fuelling and emptying the tank. Furthermore the fuel retainment of the foam is of great interest. The use of foam also leads to a decrease in sloshing of the fuel.

FLOW RESISTANCE OF THE FOAM

The measurements were carried out in a tube, with a foam plug of 500 mm length in order to ensure uniform flow conditions in the foam. It is obvious that the wall friction is much smaller than the flow resistance of the foam structure, hence the flow velocity inside the foam structure should be uniform over a large part of the tube cross-section. The wall friction losses have been subtracted from the measured total pressure drop across the foam plug. The measurements have been carried out using two tube diameters, 18 and 59 mm, thus Reynolds numbers in the laminar and in the turbulent flow range were obtained. As can be seen the flow resistance coefficient increases with increasing number of cells/cm, and decreases slightly with increasing Reynolds number (Fig.5). After these tests the fuel velocity was increased until the foam plug showed noticeable signs of compression. This limiting velocity was nearly the same for all foams investigated and amounted to approx. 0.5 m/s. If this velocity is exceeded the flow resistance increases sharply and the foam acts as a stopper.

FUEL RETAINMENT

The foam structure holds back fuel in its network. That means, that the fuel tank cannot be emptied fully. For the measurement of the fuel loss two tank configurations were used. The volume of the tanks was equal, but they differed in the hight (1 : 3) and hence in base area. From this followed, that the bottom areas of the tanks differed. The test results are shown in Fig.6. As can be seen, the fuel retained in the tank increases with decreasing cell numbers. The tank geometry has an influence too. The fuel retainment in a flat tank, e.g. with the larger bottom area is larger than in the tank with the smaller bottom area. The foam layer immediately adjacent to the horizontal bottom wall withholds a fuel layer, which cannot be drained without further measures. It seems, however, possible to reduce the quantity of fuel retained to a large extent by suitable design of the tank bottom including the geoemtrical arrangement of the foam.

REDUCTION OF SLOSHING OF THE FUEL IN THE TANK

This question is mostly important for tank lorries. Under acceleration and deceleration forces, the fuel or liquid in the tank sloshes. The uncontrolled movement of the liquid mass can lead to dangerous situations during braking or changes in the course. This sloshing can be suppressed to a large extend by the foam. For example under certain circumstances the maximum amplitude of the sloshing fuel inside the tank under the action of a deceleration force of 0.4 g was reduced to 10 % by the foam. This did change only slightly for different cell sizes.

DISCUSSION

The first part of the work has verified, that reticulated foam is basically able to act as a flame-arresting device. The length of a foam plug, necessary for extinction of the flame depends on the number of cells per cm, as well as on pressure and fuel type. Taking into account some simplifying assumptions, the quenching properties of the reticulated foam can be explained, at least qualitatively, by an energy balance on a purely thermal base. This assumes that the heat produced by the chemical reaction in the combustion volume must be, to a certain degree, absorbed by the solid surface of the foam structure.

In view of an optimization of the flame-suppressing properties of a foam it must be kept in mind, that there is not much freedom for changes in the geometry of the foam structure. First of all, only few different types of foams are available on the market; second, the geometrical shape of the foam network (number of cells/cm, uniformity) depends on the manufacturing process and mostly varies from one type of foam to the other. This of course makes an interpretation of the results difficult.

For the flame suppression in aircraft fuel tanks not only the dimensions of such a foam plug but also its weight is of interest, because this quantity influences the decrease in payload involved. For a given cross-section and a given specific mass of the foam the weight of the foam necessary for extinction is proportional to the length of the flame-suppressing plug. The results of Fig.2 (replotted in Fig.7 mass against cell/cm) therefore suggest to choose foams with large cell numbers per cm, surely above 10. However, this means that the quantity of fuel retained in the foam structure increases, too. Hence, the use of a foam with a smaller specific mass and smaller numbers of cells per cm is advisable. The following table compares results for two foams with a ratio of specific masses of 2 : 1:

ρ_{sp} (kg/m^3)	cell number (1/cm)	plug length (cm)	mass of plug (kg)	fuel retainment (%)
30	17	5	15	10 - 11.5
15	7	10	15	6.7 - 8.5

It can be seen that the reduction of the specific mass by a factor 0.5 together with a nearly twofold increase increase in cell number/cm results in the same mass of foam necessary for extinction combined with a lower fuel retainment.

Furthermore, as could be expected the flame-suppressing qualities increase with decreasing pressure. This would mean that the tank protection in low level flight is the critical condition. From a fire-protection point of view the pressure inside a fuel tank should therefore always be kept as low as possible, e.g. by connecting the exists of the venting tubes to areas on the aircraft surface where low pressures prevail during flight. The influence of temperature is not quite clear, presently; deserves further study.

Although the experimental results obtained with a flame-tube have clearly demonstrated the flame-suppressing properties of reticulated foams, it is difficult to apply them to different geometric boundary conditions, as is shown by the experiments in the explosion vessel. It seems that further influences have to be considered. This limits the validity of the above mentioned results to some extent. Especially, if one introduces void cavities in the foam structure one finds that free convection flows can be generated which lead to local destruction of the foam. Such an effect was not observed in the flame tube experiments; therefore, presently, the scaling of the flame tube results to larger dimensions is rather difficult. One possible way to solve these problems is to decrease the hollow spaces in the foam; this however, needs further investigations.

If one uses foams with small cell numbers/cm (< 4), flame propagation through the foam cannot be suppressed in the explosion vessel. This is in contrast to the flame-tube results; however the reasons for this observation are not understood, presently. The pressure rise in the vessel during such a test is rather slow, indicating that during the time interval of flame-spreading a large quantity of heat is transferred to the walls. Applied to aircraft fuel tanks, this would mean that as long as the burst pressure of the tank is not exceeded, the damage to the tank should remain limited. From a practical point of view this already is one of the effects which was sought for. Furthermore, if one considers a tank penetrated by a hot shell, the pressure arising from a slow combustion in the tank could be relieved more easily by the bullet holes. However, it has still to be checked whether this effect also occurs to the same extent if the walls of the vessel are made from plastics or have a plastic coating.

From the above discussion it follows that further investigations have to be carried out in order to get a clear picture on the flame-suppressing qualities of reticulated foams and its application to fuel tanks.

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[2] AGARDograph No. 75: Nonsteady Flame Propagation. Pergamon Press 1964.

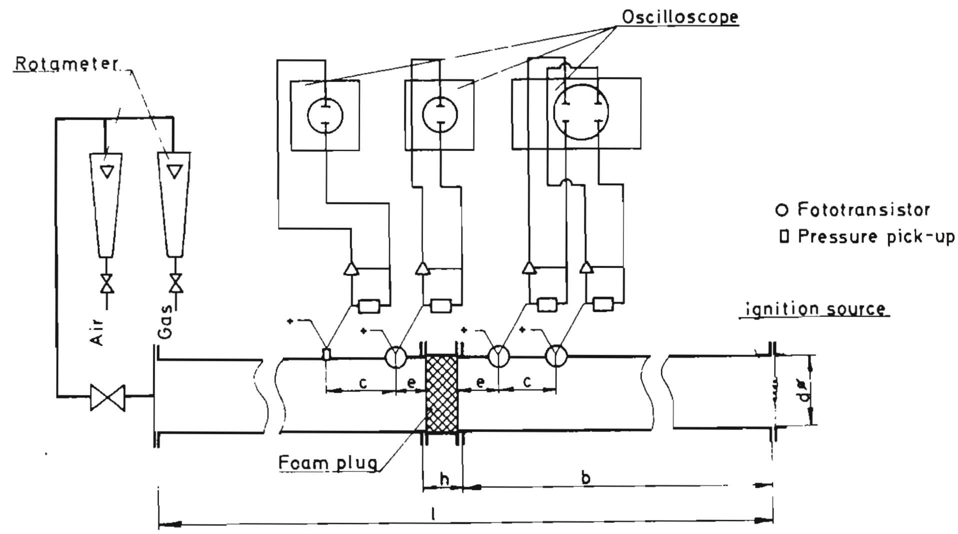

Fig. 1 Schematic of the test-apparatus

l = 2000 mm; b = 500 mm resp. 1100 mm; e = 50 mm;
d = 60 mm; h = foam thickness c = 100 mm;

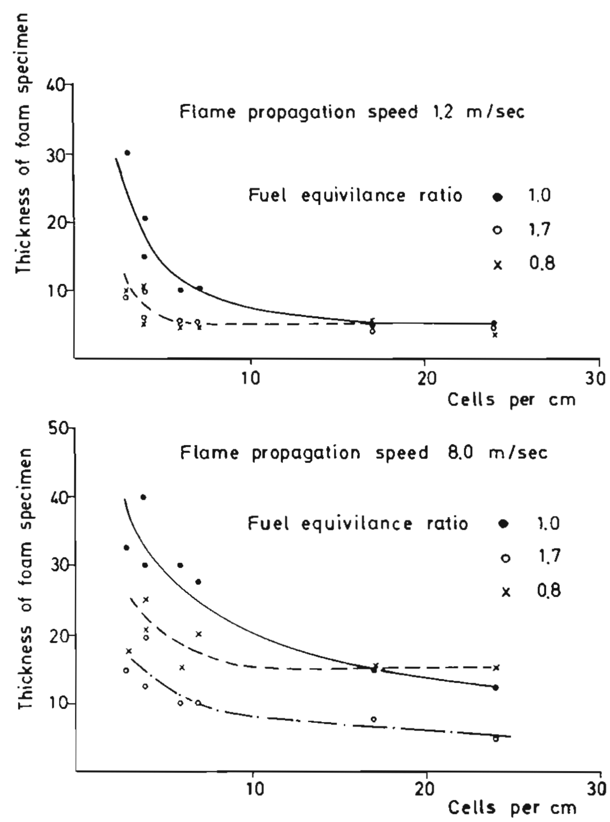

Fig. 2 Thickness of foam specimen necessary for flame suppression, depending on the number of cells/cm, for two flame propagation speeds Propane - air mixture.

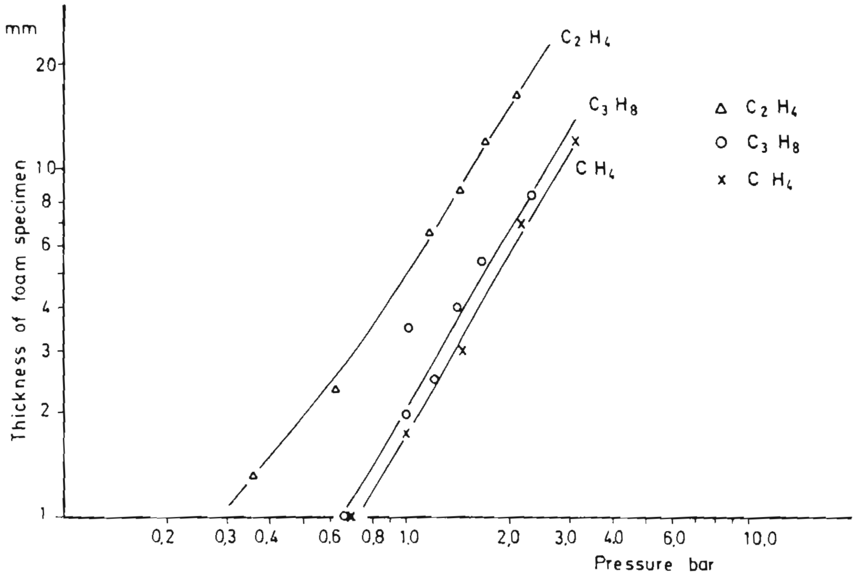

Fig. 3 Influence of pressure on the thickness of foam for stoichiometric methane - ethylene - and propane - air mixtures. Foam : specific mass 15 kg/m^3, 7 cells/cm. Flame speed : 8 m/sec

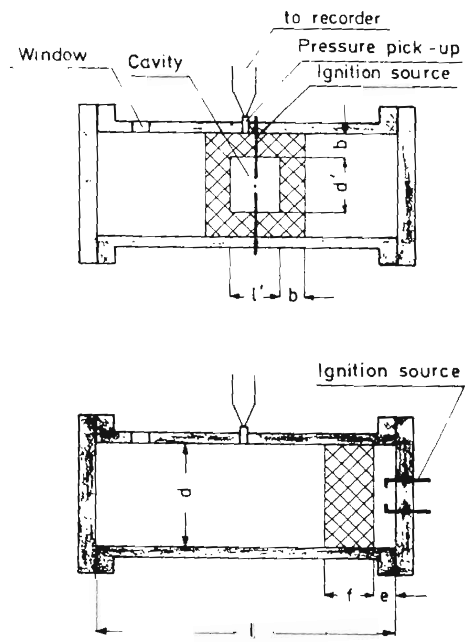

Fig. 4 Schematic of explosion vessel showing foam arrangement

d = 300 mm
l = 1000 mm
f = Thickness of foam plug
e = Distance of foam plug from wall

d' = Diameter of cavity
l' = length of cavity
b = Thickness of foam layer

Foam manufacturer	Cells/cm	Spec. gravity kg/m³	Fuel retainment [high tank] %	Fuel retainment [flat tank] %	Volume l/m³
A	3	43.4	6.2	7.1	49.5
A	4	47.5	8.5	8.7	48.0
B	4	30.0	4.8	6.3	39.5
A	6	40.1	6.5	7.8	49.5
B	7	15.0	6.7	8.6	33.0
A	17	37.8	10.1	11.5	90.0
A	24	35.4	15.0	18.1	115.0

Fig. 6 Fuel retainment of reticulated foam for two tank configurations

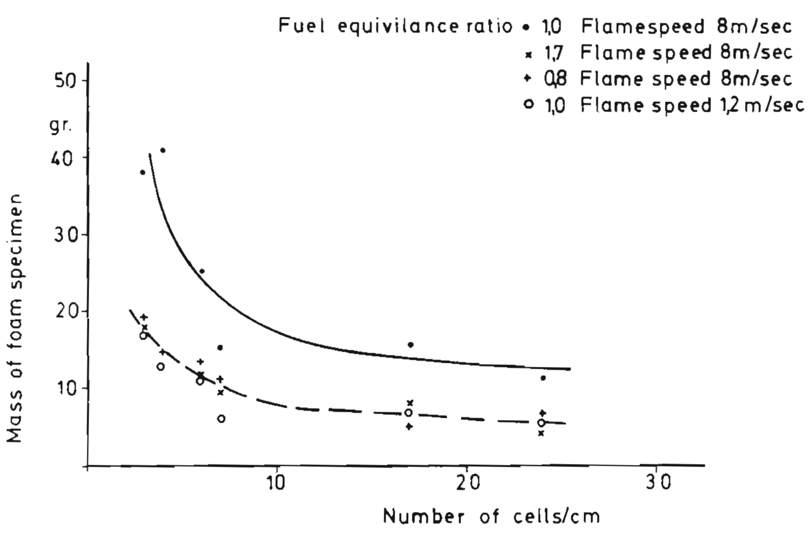

Fig. 7 Mass of foam specimen necessary for flame suppression, depending on the number of cells/cm, for two flame propagation speeds.
Propane-air-mixture

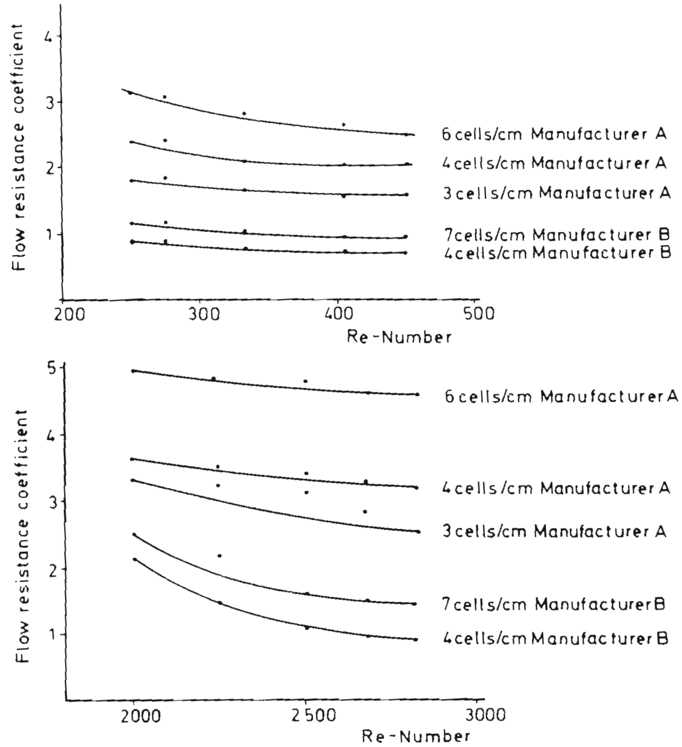

Fig.5 Flow resistance coefficient for reticulated foam

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Mr Pinkel: Regarding the use of reticulated polyurethane foam, some years ago we were working with metallic flame arrestors which are similar in action. We found that if the vessel on the protected side was closed as compared to open, the effectiveness was enhanced when the flame arrestor was wet with fuel. I wonder if on your flame tube tests you left an opening on the protected side, the results would be more comparable with the results in your vessels where the large volume gives you the effect of openness.

Mr Winterfeld: We are quite aware that pressure wave effects should occur in the flame tube and should influence the results to some extent. We did not try this case that you mentioned because in the tank you always have a solid surface bounding the space volume in which the flame can travel.

Mr Glassman: Could you clarify the exact manner in which the foam is used in the tank?

Mr Winterfeld: Yes, we use a system of small cavities in the body of foam which fills the whole tank. This gives us a weight saving and reduces retention. There are actually a series of compartments.

Mr Botteri: The US uses both solid fill and compartmented gross voided approaches. The key to the latter approach is the sizing of the compartments to keep the resulting overpressure in the overall cell in cases of ignition from exceeding structural limitations.

AGARD-CP-166

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AGARD Conference Proceedings No.166

AIRCRAFT FIRE SAFETY

Papers and discussions presented at the 45th Meeting of the AGARD Propulsion and Energetics Panel held at the Palazzo Aeronautica, Roma, Italy, 7–11 April 1975