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FLAME ARRESTOR MATERIALS FOR FUEL TANK EXPLOSION PROTECTION

Joseph M. Kuchta
Ralph J. Cato
Whittner H. Gilbert

Bureau of Mines
SRC Report No. S4138

TECHNICAL REPORT AFAPL-TR-70-40

July 1970

Air Force Aero Propulsion Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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FLAME ARRESTOR MATERIALS FOR FUEL TANK EXPLOSION PROTECTION

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FOREWORD

This report was prepared by the Safety Research Center of the U. S. Bureau of Mines under USAF Contract No. F33615-69-M-5002. The contract was initiated under Project No. 3048 "Fire and Explosion Hazards Assessment, Prevention and Suppression Techniques for Aerospace Vehicles." It was administered under the direction of the Air Force Aero Propulsion Laboratory, with J. R. Manheim (APFL) acting as project engineer.

This report is a summary of the work recently completed as part of this current contract during the period 1 January to 31 December 1969. This report was submitted by the authors February 13, 1970.

Dr. Robert W. Van Dolah was the administrator for the U. S. Bureau of Mines and Messrs. Joseph M. Kuchta, Ralph J. Cato and Whittner H. Gilbert participated in this work at the U. S. Bureau of Mines Safety Research Center, Bruceton, Pa.

This technical report has been reviewed and is approved.

Benito P. Botteri

BENITO P. BOTTERI, Chief
Hazards Branch
Fuels, Lubrications, and
Hazards Division

ABSTRACT

An investigation was conducted to extend the data on the flame arrestor effectiveness of reticulated polyurethane foams proposed for explosion protection of aircraft fuel tanks. Foams of 10, 15, 20, and 25-pore/inch were evaluated in small- or large-scale experiments using various arrestor packing configurations. Results from small-scale experiments indicated that the ability of the foams to suppress n-pentane-air explosions does not vary noticeably when the foam bulk density is reduced from 1.86 lb/ft^3 to 1.35 lb/ft^3. Other light-weight arrestors that were evaluated included crimped or honeycomb aluminum and Nomex materials which proved to be more effective than 10 ppi polyurethane foam; samples of reticulated aluminum foam were also investigated. Large-scale gun-firing experiments made in a 74-gallon fuel tank showed that a cored arrestor model of the dry 20-pore/inch polyurethane foam, having 2-inch diameter cores, can be a suitable design configuration for integral fuel tank applications at pressures up to 5 psig; however, some arrestor burning can be expected. Data are also given from other large-scale experiments in which the fuel tank was fully packed with the foam (dry or wet) and the effects of tank ullage and addition of air after ignition were investigated.

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INTRODUCTION

This report summarizes the results of an investigation conducted during the past year by the Bureau of Mines to determine the flame arrestor effectiveness of reticulated polyurethane foams and other candidate materials proposed for fuel tank explosion protection. The work was pursued as part of the current Air Force program, "Fire and Explosion Hazard Assessment, Prevention and Suppression Techniques for Aerospace Vehicles." In previous work,[1,2] the explosion suppression effectiveness of 10 and 20 pore/inch (ppi) polyurethane foams was compared to that of 1-inch and 3/4-inch diameter hollow, perforated polyethylene spheres under various temperature and pressure conditions. Results from large-scale experiments revealed that the 20 ppi foam is more effective than the 10 ppi foam or polyethylene spheres in reducing the explosion hazard from gun firings into fuel tanks containing aircraft fuel vapor-air mixtures. The present investigation was made to extend the flame arrestor data on the 20 ppi foam under various fuel tank ignition conditions and to determine a suitable design configuration for integral fuel tank applications. Cored and fully-packed arrestor models of the 20 ppi foam (density ~ 1.9 lb/ft^3) were examined in a 74-gallon fuel tank containing hydrocarbon vapor-air mixtures that were ignited with incendiary ammunition; the variables of study included initial pressure, foam condition (dry or wet), and tank ullage under a static or flow condition. In addition, laboratory scale evaluations were performed to compare the effectiveness of low and high bulk density foams and of various aluminum or Nomex arrestor materials.

EXPERIMENTAL APPARATUS AND PROCEDURE

1. Small-Scale Experiments

The experimental setup used in the small-scale experiments is shown in figure 1. A cylindrical steel vessel, 6-inch diameter by 60 inches long, was mounted horizontally and was equipped at one end with an electrical spark ignition source. The vessel was instrumented with 0.004-inch Chromel-Alumel thermocouples at various positions and a strain-gage pressure transducer to monitor the gas mixture temperature and pressure during a trial; their signals were displayed on oscillographs. Photodiodes were also positioned at various stations along the vessel to obtain flame speed measurements and verify the extent of flame propagation.

1/ Kuchta, J. M., R. J. Cato, I. Spolan, and W. H. Gilbert, Evaluation of Flame Arrestor Materials for Aircraft Fuel Tanks. Air Force Aero Propulsion Laboratory AFAPL-TR-67-148, February 1968.

2/ Kuchta, J. M., R. J. Cato, W. H. Gilbert, and I. Spolan, Fuel Tank Explosion Protection. Air Force Aero Propulsion Laboratory AFAPL-TR-69-11, March 1969.

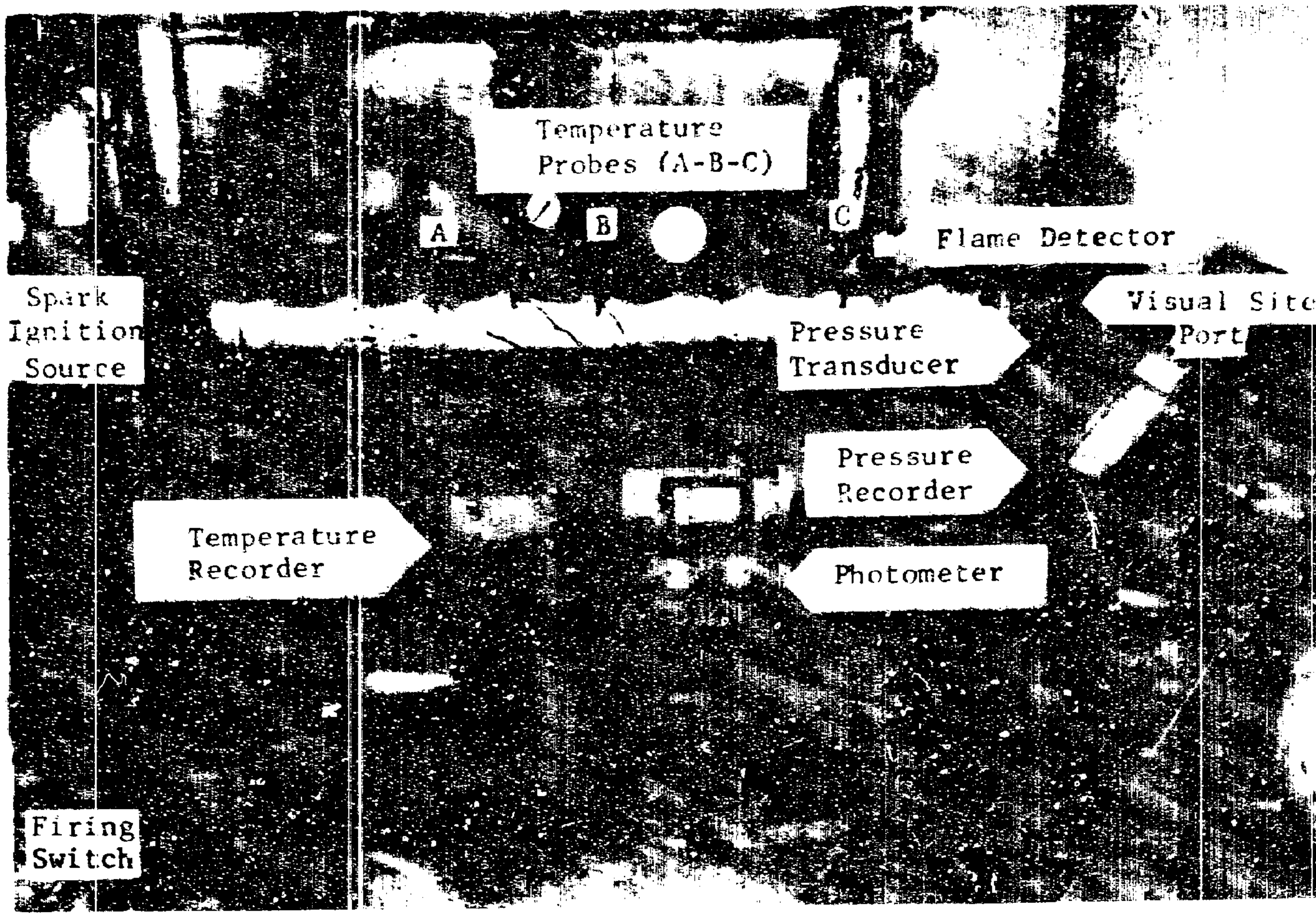


FIGURE 1. - Experimental setup for flame arrestor experiments in a 1 ft^3 cylindrical steel vessel (6-inch diameter by 60 inches long).

During an experiment, a cylindrical segment of the arrestor material was fitted into the vessel at a selected distance from the ignition source. The vessel was evacuated and filled with the combustible mixture to the desired pressure and then ignited by the electrical spark source; the energy was supplied by a high voltage (15 kv) transformer that produced a total power dissipation of about 60 watts across the spark gap. The extent of flame propagation was determined from temperature and pressure rise measurements. All experiments were conducted with approximately 2.5 percent n-pentane-air mixtures at ambient temperature, 70° ± 10° F. The arrestor length, ignition void length (flame run-up), and initial pressure were varied in these experiments.

2. Large-Scale Experiments

Large-scale experiments were made with cored and fully-packed arrestor models of the 20 ppi polyurethane foam in the mid-section of a 450-gallon aircraft fuel tank. The modified tank, shown in figure 2, was 27 inches in diameter by 30 inches long and had a 74-gallon capacity. It was instrumented with a photodiode at one end, a pressure transducer at each end, and four 0.004-inch diameter Chromel-Alumel thermocouples at stations along its longitudinal axis. In these experiments, the effectiveness of the arrestor models was examined with near-stoichiometric compositions of n-butane and air that were ignited with 30-caliber incendiary ammunition; a spark ignition source was also used in a few runs.

Experiments were performed with two cored arrestor models having gross voids of 36.6 and 16.3 percent of the total volume. One model (36.6 percent gross void) had three 8-inch long cored sections which were separated by 2-inch or 3-inch long plain sections. The cored sections were uniformly aligned in the tank and contained thirty-seven evenly spaced (1-inch apart) voids, 3 inches in diameter by 8 inches long. The other model (16.3 percent gross void) had a corresponding number of cored sections and voids; however, the voids in each cored section were 2 inches in diameter by 8 inches long and were spaced 2 inches apart. The flame arrestor effectiveness of the cored models was examined at pressures from 0 to 5 psig. When the electrical spark source was used, the combustible mixture was ignited at one end of the tank. Except where noted, the incendiary ammunition was fired at an incident angle of about 15 degrees into a 1/8-inch thick steel striker plate that was positioned in the middle of the tank. The incendiary firings were made with an M-1 military rifle at about 150 feet; projectile velocity was approximately 2800 ft/sec.

Similar large-scale experiments were made to determine the flame quenching effectiveness of dry and wet 20 ppi foam under the fully-packed tank condition. The wet foam was prepared by soaking the dry foam in kerosene. Some of these runs were made with air flowing through the fuel tank after the incendiary ignition (< 2 seconds) to simulate a post-firing condition that may be encountered in flight operations; the air flow rate was 25.4 CFM

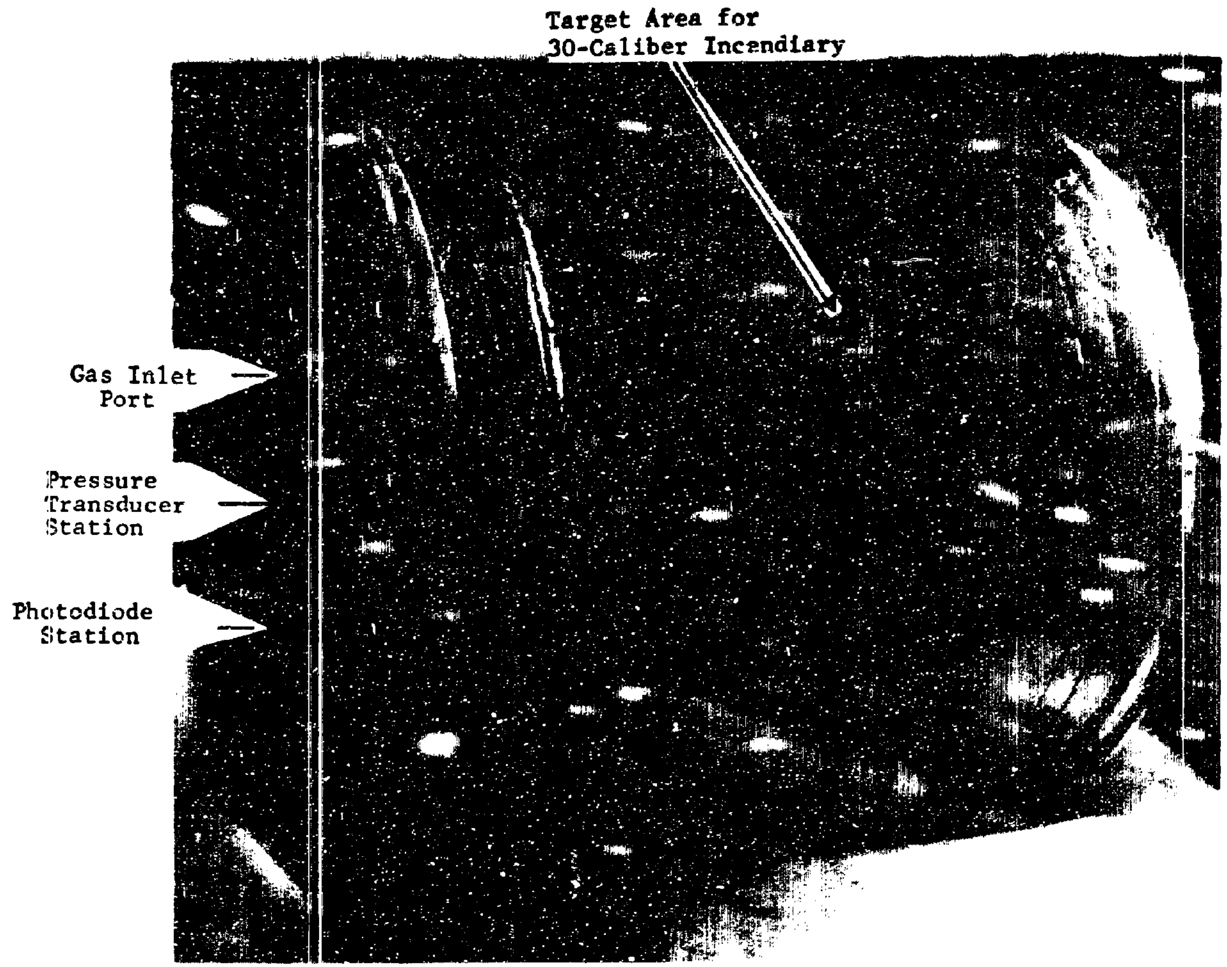


FIGURE 2. - 74-gallon modified fuel tank (27-inch diameter by 30 inches long).

at 5 psig and 80° F. In addition, the effect of reduced tank ullage was investigated in the latter runs by firing into the tank packed with foam and partially filled with 35 gallons of kerosene. Movies of these runs were taken with a Fastair camera to record an external fire that developed.

RESULTS AND DISCUSSION

1. Small-Scale Flame Arrestor Experiments

Data obtained in the 6-inch diameter vessel revealed that the flame quenching effectiveness of the reticulated polyurethane foam does not vary greatly when the bulk density is reduced from 1.86 lb/ft^3 to 1.35 lb/ft^3. Figure 3 compares the pressure rise data from flame arrestor experiments with 9-inch long segments of 15 and 25 ppi foams (1.35 lb/ft^3) and 10 and 20 ppi foams of higher bulk density at various ignition void lengths and atmospheric pressure; the data shown for the 20 ppi foam were obtained in a previous investigation.[2] In these runs, the maximum pressure rises increased with increasing ignition void length for each of the materials used; also, all of the materials failed to prevent flame propagation when the ignition void length was increased above some critical value. The 10 ppi foam was the least effective material since it failed when the ignition void length was increased beyond 18 inches. As noted, the pressure rise was small (2 to 8 psi) when the ignition void length was varied from 6 to 18 inches but increased abruptly to 29 psi at a void of 21 inches. In comparison, the corresponding critical ignition void lengths for the 15 and 25 ppi foams of lower bulk density were 33 and 40 inches, respectively. It is also interesting to note that for comparable ignition void lengths, the pressure rise data for the 15 and 25 ppi foams do not differ greatly from those for the 20 ppi higher bulk density foam. The maximum pressure rises in all of the runs were much lower than would be expected with no arrestor material present; for example, a pressure rise of at least 85 psi was observed at 0 psig with a 2.5 percent n-pentane-air mixture.

The greater arrestor effectiveness of the finer pore size foams was also observed with the 10, 15 and 25 ppi foams at various initial pressures; 9-inch long cylindrical segments were employed in these runs at a fixed ignition void length of 18 inches. Figure 4 shows the effect of initial pressure on the pressure rise developed in these flame propagations. Again the 10 ppi foam (1.86 lb/ft^3) is the least effective material; the maximum pressure rise increased abruptly (7.7 psi to 36.6 psi) when the initial pressure was increased from 0 to 1 psig. With the 15 and 25 ppi lighter weight foams, the pressure rises were all less than 10 psi until the initial pressure was increased above 2 and 4 psig, respectively; the pressure rises were in excess of 25 psi when arrestor failure was observed. According to these data, it is evident that the effectiveness of the polyurethane foam depends more upon pore size than upon bulk density.

Other light-weight flame arrestors such as crimped and honeycomb aluminum and a honeycomb Nomex fabric were found to be superior to the

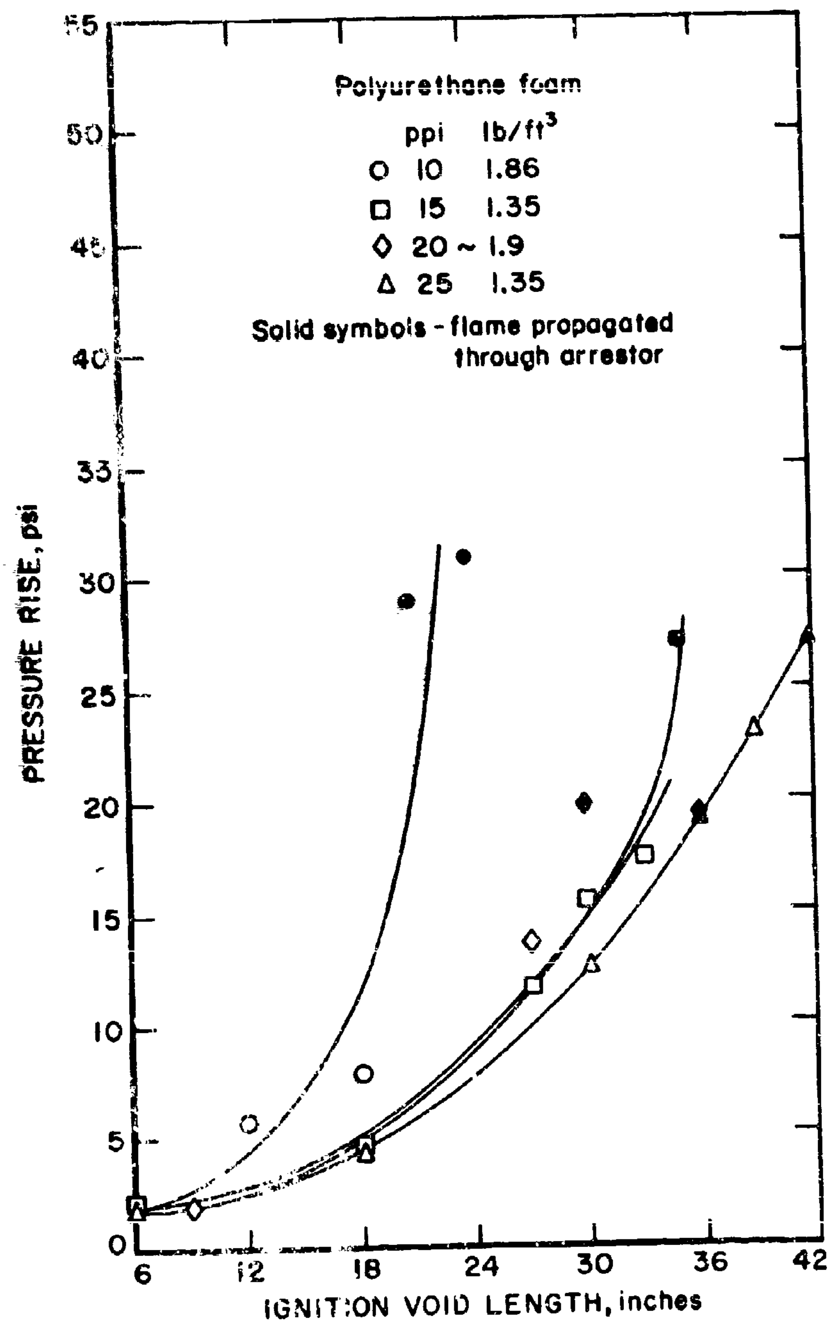


FIGURE 3. - Effect of ignition void length on pressure rise in experiments with 9-inch long segments of 10, 15, 20 and 25 ppi polyurethane foam and 2.5 percent n-pentane-air mixtures at atmospheric pressure (6-inch diameter vessel).

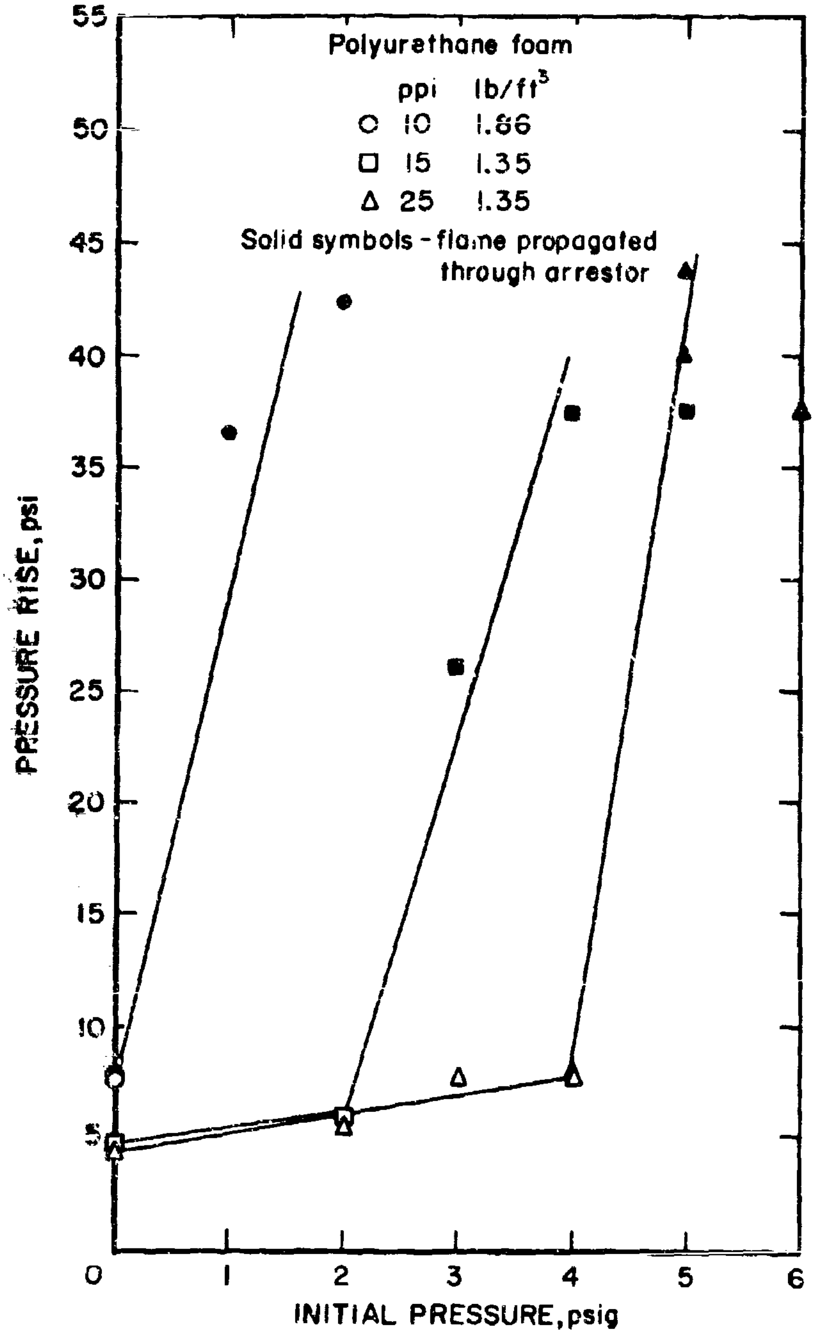


FIGURE 4. - Effect of initial pressure on pressure rise in experiments with 9-inch long segments of the 10, 15 and 25 ppi polyurethane foam and 2.5 percent n-pentane-air mixtures (6-inch diameter vessel). Arrestor length/ignition void length = 9"/18".

10 ppi foam in preventing flame propagation. A photograph of the Nomex and aluminum arrestors is shown in figure 5; the cell size and approximate bulk density of each material is also given in this figure. Table I summarizes the pressure rise data that were obtained in runs with these materials at various initial pressures (0 to 20 psig); all runs were made in a 6-inch diameter vessel at a fixed ignition void length of 18 inches. The crimped aluminum with 1/8-inch by 1/16-inch longitudinal cells was the most effective flame arrestor since it prevented flame propagation at initial pressures up to 10 psig. At initial pressures from 0 to 10 psig, the maximum pressure rises with the crimped aluminum were all less than 12 psi and no arrestor burning occurred; at 15 and 20 psig, the pressure rises were greater than 80 psi. The crimped aluminum that had alternate layers of 1/8-inch by 1/8-inch longitudinal and transversal cells failed when the initial pressure was increased from 5 to 7 psig, whereas, both the honeycomb aluminum and Nomex with 1/8-inch by 1/8-inch longitudinal cells failed at 2.5 psig. In comparison, the 10 ppi foam failed to prevent flame propagation even at 0 psig with the same flame run-up and arrestor length. Figure 6 shows the extent of arrestor burning that occurred on the downstream ends of the aluminum and Nomex materials after ignitions at the pressures where such materials failed. Based on the data shown for arrestors of comparable cell dimensions, arrestor configuration appears to have more influence than the type of material on flame arrestor performance. The crimped aluminum arrestors were more effective than the polyurethane foam because of greater mass and greater flow restriction between cells.

Flame arrestor performance of a 10 ppi reticulated aluminum foam was compared to that of the 10 and 20 ppi reticulated polyurethane foams. Two shipments of the aluminum foam were used; these differed in physical appearance and are designated as reticulated aluminum foam Sample A and B. Table II and figure 7 show pressure rise data that were obtained in runs at 0 psig with 2-inch long cylindrical segments of these materials at arrestor length/ignition void length ratios (ℓ_2/ℓ_1) between 0.33 and 0.13. According to these data, the variation of maximum pressure rise with ignition void length is essentially the same for the 10 ppi samples of the aluminum foam (Sample A) and polyurethane foam. The maximum pressure rises obtained with these materials were less than 6 psi when the ignition void length was equal to or less than 12 inches; above 12 inches, the maximum pressure rises were between 45 and 65 psi. By comparison, the 20 ppi polyurethane foam was more effective in quenching flame propagation than either of the above 10 ppi materials, since it did not fail until the ignition void length was increased beyond 15 inches.

Other experiments with the 10 ppi aluminum foam (Sample B) produced less favorable results than those with the 10 ppi polyurethane foam. The effect of pressure on the effectiveness of the two foams was examined in the 6-inch diameter vessel using an 8-inch long segment at a fixed ignition void length of 3 inches (ℓ_2/ℓ_1 = 2.67). The results are compared in table III and figure 8. Here, it is seen that the critical pressure for arrestor

Honeycomb Nomex	Honeycomb Aluminum	Crimped Aluminum	Crimped Aluminum
(1/8"x1/8" cells)	(1/8"x1/8" cells)	(1/8"x1/16" cells)	(1/8"x1/8" cells)
2.1 lb/ft^3	3.2 lb/ft^3	8.9 lb/ft^3	5.9 lb/ft^3

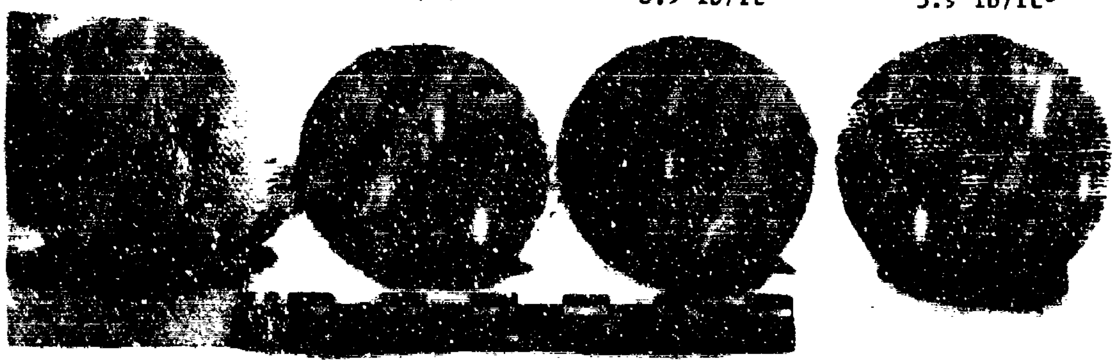
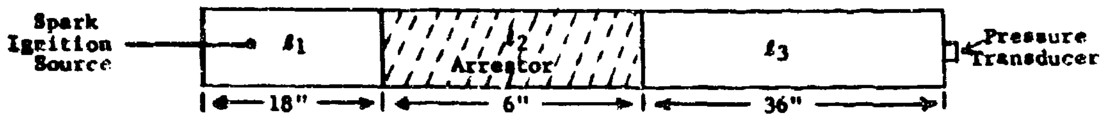


FIGURE 5. - Nomex and aluminum flame arrestors prior to ignition.

TABLE I. - Flame Arrestor Data for Aluminum, Nomex and Polyurethane Foam Materials in a 6-inch Diameter Steel Vessel With 2.5 Percent n-Pentane-Air Mixtures at Various Pressures.



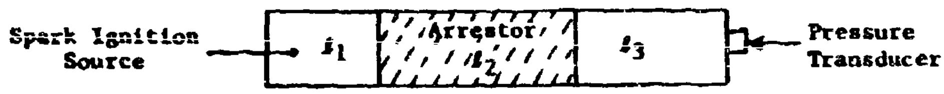
Initial Pressure, psig	Pressure Rise $\Delta P_{initial}$[1] psi	Δt sec	ΔP_{max} psi	Δt sec	Appearance[2] of Flame in ℓ_3 Void	Arrestor Burning
			Crimped Aluminum (1/8" x 1/16" cells)			
0	--	--	6.7	0.06	No	None
2.5	--	--	7.7	0.08	No	"
5.0	--	--	8.6	0.11	No	"
7.5	--	--	10.5	0.08	No	"
10.0	--	--	11.4	0.08	No	"
15.0	14.0	0.05	84.0	5.0	Yes	Downstream end - 1/2 inch
20.0	18.0	0.08	120.0	1.2	Yes	" " "
			Crimped Aluminum (1/8" x 1/8" cells)			
0	--	--	6.0	0.08	No	None
5	--	--	10.0	0.07	No	"
7	--	--	66.0	0.25	Yes	Downstream end - 1/2 inch
10	--	--	78.0	0.30	Yes	" " "
			Honeycomb Aluminum (1/8" x 1/8" cells)			
0	--	--	7.7	0.07	No	None
0	--	--	7.7	0.07	No	"
2.5	8.6	0.07	50.0	0.96	Yes	Downstream end - 3/4 inch
2.5	9.6	0.07	53.9	0.83	Yes	" " "
			Honeycomb Nomex (1/8" x 1/8" cells)			
0	--	--	7.5	0.06	No	Upstream end - < 1/8 inch
0	--	--	7.5	0.08	No	" " "
2.5	--	--	55.0	0.36	Yes	Downstream end - 1 inch
5.0	--	--	65.0	0.61	Yes	" " "
			Polyurethane Foam (10 ppi)			
0	--	--	42.8	0.57	Yes	Downstream end - 2-1/2 inch
0	--	--	43.7	0.34	Yes	" " - 1-1/2 inch

1/ Pressure rise before the main explosion event.
2/ Observation made by flame sensor (thermocouple or photodiode).

	Honeycomb Nomex (1/8"x1/8" cells)	Honeycomb Aluminum (1/8"x1/8" cells)	Crimped Aluminum (1/8"x1/16" cells)	Crimped Aluminum (1/8"x1/8" cells)
Init. Press., psig	2.5	2.5	15	7

FIGURE 6. - Downstream end view of Nomex and aluminum flame arrestor materials after ignition of 2.5 percent n-pentane-air mixtures at initial pressures that resulted in arrestor failure (6-inch diameter vessel).

TABLE II. - Flame Arrestor Data for Reticulated Aluminum (Sample A) and Polyurethane Foam Materials in a 6-inch Diameter Steel Vessel With 2.5 Percent n-Pentane-Air Mixtures at Atmospheric Pressure.



ℓ_2 = 2 inches

Ignition Void Length, ℓ_1 inches	ℓ_2/ℓ_1	Maximum Pressure Rise, psi	Appearance[1/] of Flame in ℓ_3 Void	Arrestor Burning
	~10 pore/inch Reticulated Aluminum Foam			
6	0.33	2.7	No	None
6	.33	2.3	"	"
9	.22	3.6	"	"
12	.17	4.8	"	"
12	.17	5.4	"	"
14	.14	44.1	Yes	2/
15	.13	46.8	"	2/
15	.13	56.7	"	2/
	10 pore/inch Reticulated Polyurethane Foam			
9	.22	3.6	No	Upstream end - < 1/8-inch
12	.17	4.5	"	" " "
15	.13	61.2	Yes	Downstream end - 2 inches
	20 pore/inch Reticulated Polyurethane Foam			
2	1.0	0.2	No	Upstream end - < 1/8-inch
4	0.5	2.7	"	" " "
8	.25	3.0	"	" " "
10	.20	3.2	"	" " "
12	.17	4.8	"	" " "
15	.13	7.2	"	" " - 1/2 inch
18	.11	62.0	Yes	Downstream end - 1 inch

1/ Observations made visually and by flame sensors (thermocouple or photodiode).
2/ Arrestor material did not burn but was damaged slightly on downstream end.

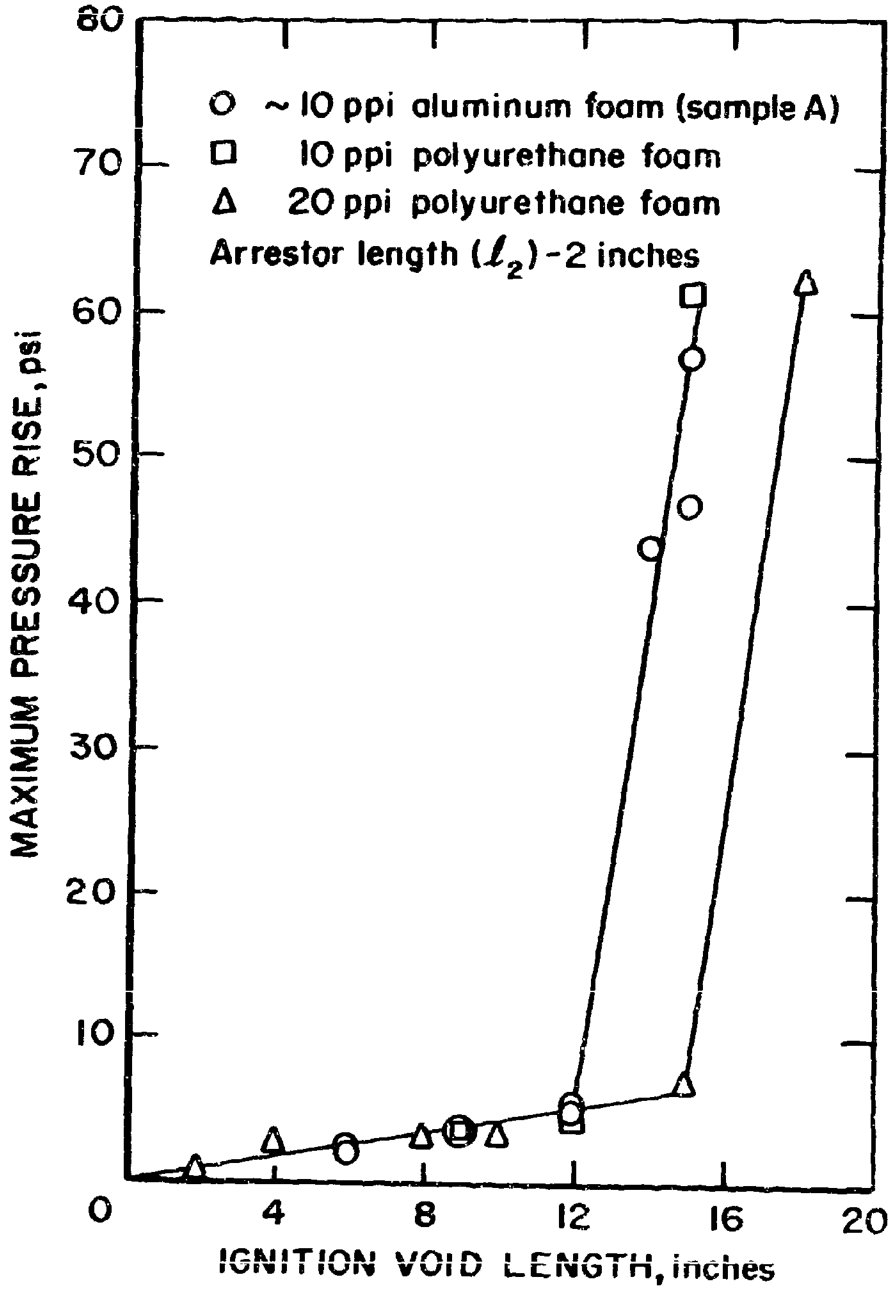
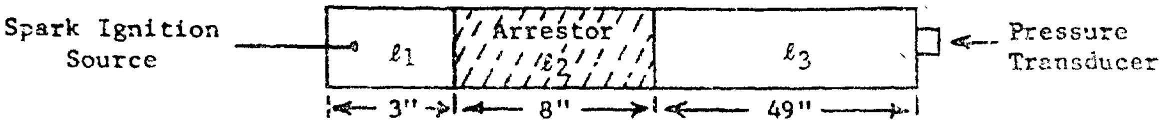


FIGURE 7. - Effect of ignition void length on pressure rise in flame arrestor experiments with reticulated aluminum and polyurethane foams and 2.5 percent n-pentane-air mixtures at atmospheric pressure (6-inch diameter vessel).

TABLE III.- Flame Arrestor Data for Reticulated Aluminum (Sample B) and Polyurethane Foam Materials in a 6-inch Diameter Vessel With 2.5 Percent n-Pentane-Air Mixtures at Various Initial Pressures.



$\ell_2/\ell_1 = 2.67$

Initial Pressure, psig	Maximum Pressure Rise, psi	Appearance[1/] of Flame in ℓ_3 Void	Arrestor Burning
	~10 pore/inch Reticulated Aluminum Foam		
0	0.9	No	None
1	1.8	No	None
2	51.3	Yes	2/
2.5	48.6	Yes	2/
	10 pore/inch Reticulated Polyurethane Foam		
0	0.9	No	Upstream end - 1/4 inch
2	1.8	No	" " - 3/4 inch
4	1.8	No	" " - 1/2 inch
5	75.6	Yes	Downstream end - 2-1/2 inches

1/ Observations made visually and by flame sensors (thermocouple or photodiode).

2/ Arrestor material did not burn but was damaged slightly on downstream end.

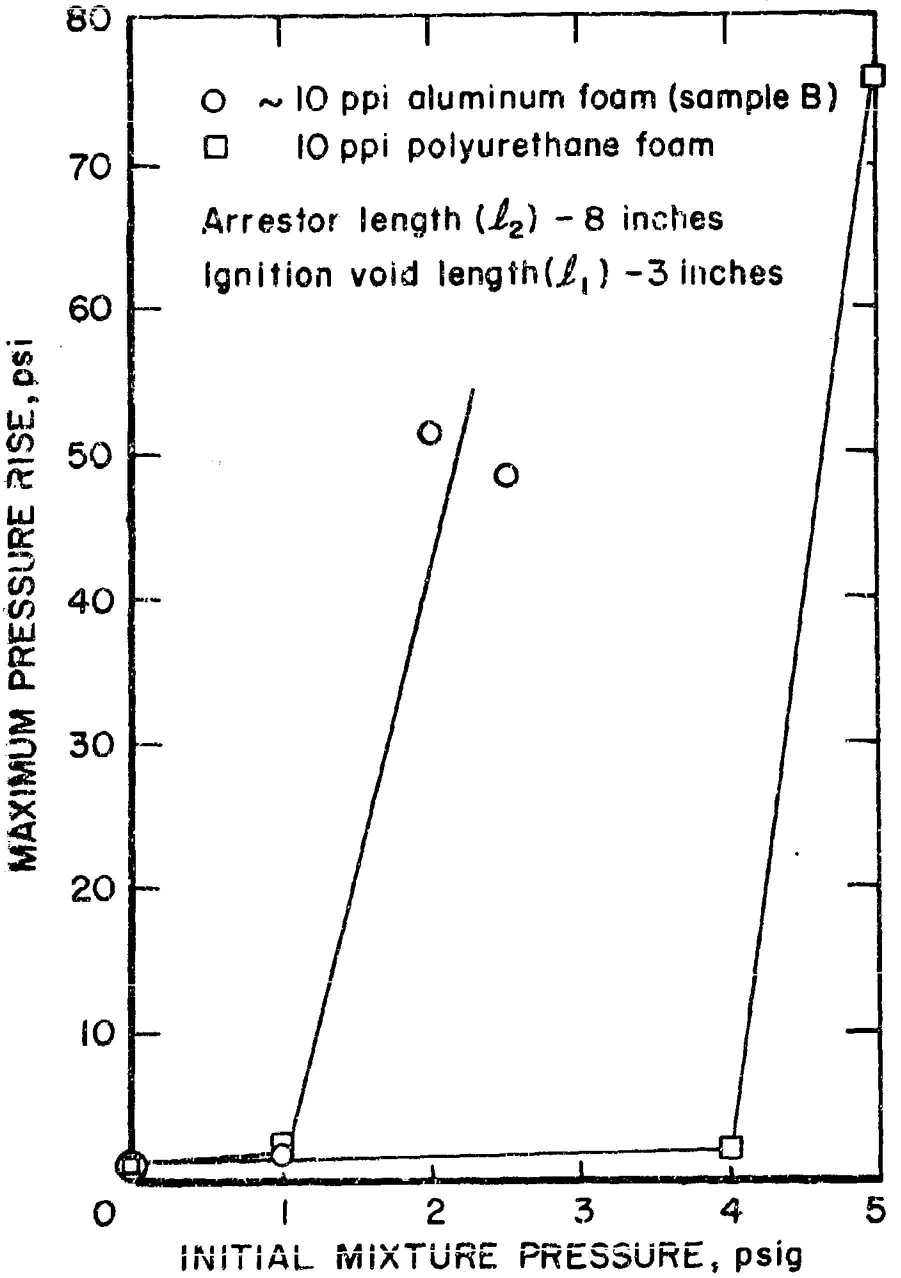


FIGURE 8. - Effect of initial mixture pressure on pressure rises in flame arrestor experiments with reticulated aluminum and polyurethane foams and 2.5 percent n-pentane-air mixtures (6-inch diameter vessel).

failure was 2 psig for the aluminum foam and 5 psig for the polyurethane foam. At 0 psig, both Sample A and B of the aluminum foam appeared to be as effective as the 10 ppi polyurethane foam; the performance of Sample A at elevated pressures was not determined due to the limited quantity that was available for evaluation.

2. Large-Scale Experiments in a 74-Gallon Fuel Tank With Cored Arrestor Models of the 20 ppi Polyurethane Foam.

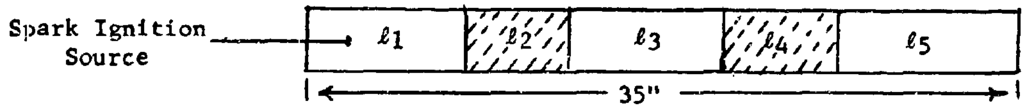
In the large-scale flame arrestor experiments, cored models of the 20 ppi polyurethane foam were evaluated to obtain a suitable design configuration for internal fuel tank applications in which the tank pressure is generally not more than 5 psi above the outside ambient pressure. The arrestor models selected were based on earlier small-scale experiments[3/] in a 12-inch diameter by 35-inch long steel vessel. Table IV summarizes the pressure rise data from some of these earlier experiments in which the gross void of the models was between 32 and 42 percent of the total vessel volume; the arrestor models were cored sections of various lengths with seven 3-inch diameter cores. According to these data, the flame arrestor effectiveness of the cored models varied with the length of the cored section, the thickness of the plain segment between the cored sections, and the initial combustible mixture pressure; the core diameter is also important. At the maximum pressure used (5 psig), flame propagation between voids could be suppressed if the length of the cored section was not over 10 inches and the thickness of the plain segment separating the cored sections was at least 2 inches.

The arrestor model used in the large-scale experiments consisted of three separate cored sections, each having thirty-seven, 3-inch diameter by 8-inch long holes that were evenly spaced 1-inch apart (figure 9); the cored sections were aligned and separated by 2-inch long, plain arrestor segments. Table V presents the pressure rise data obtained in three experiments conducted in the 74-gallon fuel tank with this cored model (36.6 percent gross void). With a spark ignition source, it was effective in quenching flame propagation at an initial pressure of 0 psig and the maximum pressure rise was less than 4 psi. Temperature rise measurements and visual observations revealed that flame propagation was mainly in the axial direction and was confined to three or four gross voids in the first two cored sections of the model. However, at 3 psig, the pressure rise was 14.4 psi and flame propagated through at least 60 percent of the arrestor model.

Other large-scale experiments with cored arrestor models were made using 30-caliber incendiary ammunition to ignite the combustible gas mixture. The models used in these experiments also contained three cored sections, each of which had thirty-seven evenly spaced holes that measured 2 or 3 inches in diameter by 8 inches long; here, the cored sections were separated

3/ Unreported data from previous work in 1968.

TABLE IV. - Data From Flame Arrestor Experiments in a 12-inch Diameter Steel Vessel With Cored Arrestor Models of the 20 ppi Polyurethane Foam and 2.5 Percent n-Pentane-Air Mixtures at 0 and 5 psig.



Cored arrestor sections (ℓ_1, ℓ_3, ℓ_5)
Plain arrestor sections (ℓ_2, ℓ_4)

Arrestor Configuration	Ignition Void Space (ℓ_1) Length x Dia. inches	Cored Sections No.	Cored Sections Length, inches	Plain Arrestor Sections No.	Plain Arrestor Sections Length, inches	Total Gross Void, Vol.%	Pressure Rise: Initial Ignition ΔP_1 psi	Initial Ignition Δt_1 sec	Secondary Ignition and Arrestor Burning ΔP_2 psi	Secondary Ignition and Arrestor Burning Δt_2 sec
					0 psig					
7 - 3" voids	10 x 3	(3	10	3	0.5	40.0	< 0.9	--	3.6	12
		(1	3-1/2							
7 - 3" voids	10 x 3	(2	10	2	1	39.4	--	--	1.8	94
		(1	13							
7 - 3" voids	10 x 3	(2	10	2	2	37.1	< 0.9	--	1.8	136
		(1	11							
7 - 3" voids	10 x 3	(2	10	2	4	32.2	< 0.9	.22	1.8	371
		(1	7							
					5 psig					
7 - 3" voids	6 x 3	(4	6							
		(1	3	4	2	32.2	< 0.9	--	4.1	149
7 - 3" voids	10 x 3	(2	10							
		(1	11	2	2	37.1	1.8	--	3.6	130
7 - 3" voids	16 x 3	(1	16							
		(1	17	1	2	39.4	0.9	.24	7.4	27
7 - 3" voids	35 x 3	1	35	None	--	41.9	9.0	0.46	None	--

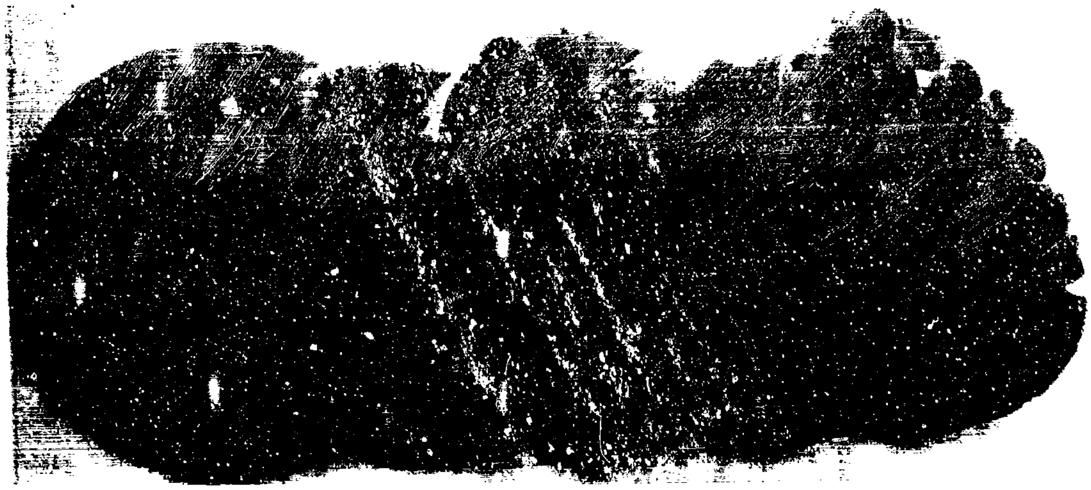


FIGURE 9. - Arrestor model of 20 ppi polyurethane foam with thirty-seven 3-inch diameter by 8-inch long voids (spaced 1 inch apart) per cored section: 36.6 percent gross void.

TABLE V. - Data From Large-Scale Flame Arrestor Experiments With a Cored Arrestor Model of the 20 ppi Polyurethane Foam and 3 Percent n-Butane-Air Mixtures at 0 and 3 psig.

Fuel tank: 27-inch diam. by 30-inch long (74 gals)
Ignition source: Electrical spark
Arrestor model: 37 holes (3-inch diameter x 8-inch long) per 8-inch cored section; 2-inch thick, plain arrestor sections.

Run No.	Initial Pressure, psig	Initial Temperature, °F	$\Delta P_{init.}$ psi	t sec	ΔP_{max} psi	t sec	Initial Rate of Pressure Rise psi/sec
1	0	50	1.0	0.5	2.3	70.0	10
2	0	59	0.8	3.3	3.8	13.2	6
3	3	70	3.8	0.1	14.4	0.2	61

by either 2 or 3-inch long plain arrestor segments. With the 3-inch segments, the total gross void of the model with 2-inch diameter cores was 16.3 percent, as compared to 36.6 percent for that with 3-inch diameter cores.

A summary of the pressure rise data obtained in the gun-firing ignitions with each of the cored arrestor models is given in table VI. The maximum pressure rises were noticeably higher for runs made with the model that contained the larger diameter cores (3 inches). At the same time, the results appeared to depend partly upon the action of the incendiary. In tests (No. 2 and 4) where th incendiary was fired into a 1/8-inch thick steel striker plate on the tank, the maximum pressure rises (12.2 and 12.9 psi) at 0 psig and 3 psig were noticeably higher than those from comparable tests (No. 1 and 3) without the plate. Under the latter firing condition, the maximum pressure rises were not over 1.5 psi, apparently because of poor incendiary action. Figure 10 shows the extent of arrestor burning that occurred in the tests (No. 2 and 4) where 2-inch long arrestor segments were used to separate the cored sections. Other experiments (No. 5 and 6) made with this model revealed that its effectiveness was not improved by increasing the thickness of the plain arrestor segment from 2 to 3 inches.

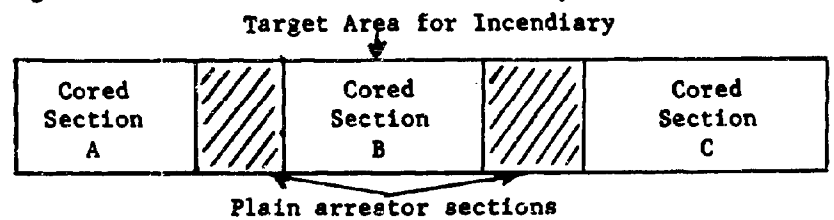
In comparison, the cored arrestor model with 2-inch diameter by 8-inch long cores was more effective than the one with 3-inch diameter cores since the maximum pressure rises were 0.8 psi or less at the various pressures (0, 3 and 5 psig) investigated. Temperature rise measurements and visual observation after firing revealed that arrestor burning was confined largely to the middle arrestor section when the incendiary was fired into the center of the tank, or extended into each of the three cored sections when the incendiary was fired at an angle to penetrate all of these sections (Test No. 8). Figure 11 shows the extent of arrestor burning that occurred at 0, 3 and 5 psig mixture pressures with incendiary firings into the middle of the fuel tank. Based on these results, this model appears to be effective for suppressing vapor phase explosions within fuel tanks at initial mixture pressures up to 5 psig, although some arrestor burning can be expected.

3. Large-Scale Experiments in a 74-Gallon Fuel Tank Fully-Packed With the 20 ppi Polyurethane Foam.

In previous work,[2] arrestor models of the 20 ppi polyurethane foam were effective in suppressing fuel vapor-air explosions in a 450-gallon aircraft fuel tank partially packed with foam. The present experiments were conducted with dry and wet foam in the modified 74-gallon fuel tank under the fully-packed condition. Since an aircraft fuel tank may be purged with air as a normal operation or as a result of gunfire, air was added after the combustible mixture was ignited; the tank ullage was also varied. The combustible mixture was a near-stoichiometric composition (3.0 percent) of n-butane and air and was ignited with 30-caliber incendiary ammunition.

TABLE VI. - Data From Large-Scale Flame Arrestor Experiments With Cored Arrestor Models of the 20 ppi Polyurethane Foam and 3 Percent n-Butane-Air Mixtures at 0, 3, and 5 psig.

Fuel tank: 27-inch diameter by 30-inch long (74 gals)
Ignition source: 30-caliber incendiary ammunition



Test No.	Plain Arrestor Sections Thickness, inches	Initial Pressure, psig	Initial Temperature, °F	Maximum Pressure Rise ΔP_{max} psi	t sec	$\frac{dP}{dt}$	Arrestor Burning
		37 holes (3-inch diam. by 8-inch long) per 8-inch cored section					
1	2	0 1/	45	1.5	0.2	17	Cored sections A and B
2	"	0	76	12.2	0.3	228	" " " "
3	"	3 1/	55	0.4	--	--	Cored section B
4	"	3	86	12.9	0.11	333	" " "
5	3	0	70	1.1	0.23	2.5	" " "
6	"	3	75	25.1	0.14	980	Cored sections A and B
		37 holes (2-inch diam. by 8-inch long) per 8-inch cored section					
7	3	0	77	< 0.4	--	--	Cored section B
8	"	0 2/	60	0.8	0.20	5.4	Cored sections A, B and C
9	"	3	84	0.4	0.02	--	Cored section B
10	"	5	63	< 0.4	--	--	" " "

1/ Runs made without 1/8-inch thick striker plate.
2/ Incendiary fired through all three cored sections of model.

0 psig

3 psig

FIGURE 10. - Arrestor burning that resulted in experiments (Test No. 2 and 4) with a cored arrestor model (36.6 percent gross void) of the 20 ppi foam after ignition of 3.0 percent n-butane-air mixtures at 0 and 3 psig with 30-caliber incendiary ammunition.

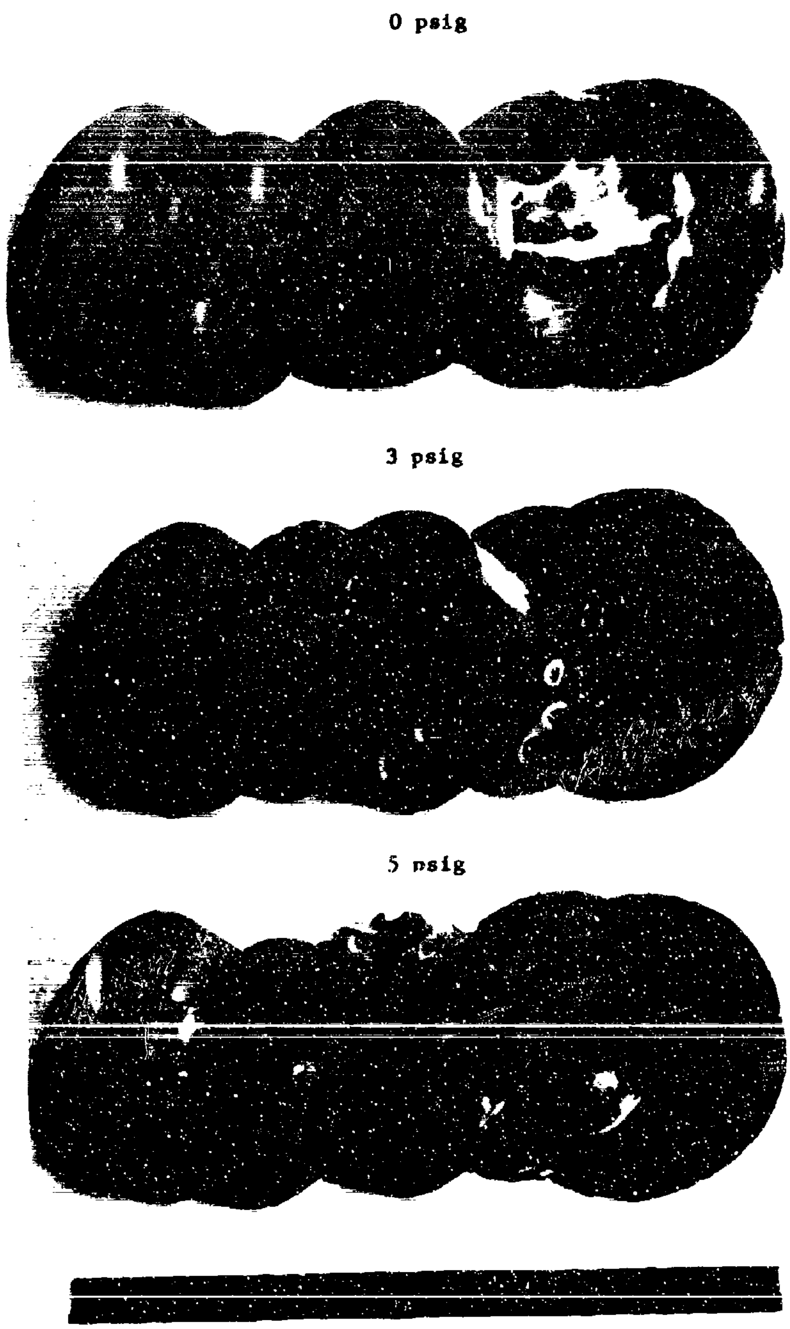


FIGURE 11. - Arrestor burning that resulted in experiments (Test No. 7, 9 and 10) with a cored arrestor model (16.3 percent gross void) of the 20 ppi foam after ignition of 3.0 percent n-butane-air mixtures at 0, 3 and 5 psig with 30-caliber incendiary ammunition.

Table VII presents the data from the large-scale arrestor experiments with 10 and 20 ppi polyurethane foam (wet and dry) fully-packed in a tank with 3 percent n-butane-air mixtures at various initial pressures. In test No. 1, at 0 psig, air was admitted into the tank through a 3/8-inch diameter port at a flow rate of 24.5 cubic feet per minute (at 5 psig and 80° F) within 2 seconds after incendiary impact; the air was discharged through holes made by the incendiary ammunition. The maximum pressure rise was only 1.1 psi, 0.03 second after ignition, and the foam was effective in suppressing the initial vapor phase explosion within the fuel tank. About 24 seconds after ignition and the addition of air, the tank pressure increased to 2.7 psig; approximately 28 percent (weight) of the material was consumed, largely as a result of the additional air supply. The 20 ppi foam was also effective in preventing flame propagation throughout the tank without air flow. In runs at 3 and 6 psig pressure, the initial pressure rises due to the explosion event were less than 0.4 psi. At 3 psig, little arrestor burning occurred after ignition. However, at 6 psig, noticeable burning was observed on one side of the arrestor model, presumably because of the higher venting rate that can occur at this pressure following ignition. In comparison, arrestor burning in runs with the 10 ppi dry foam at 0 psig was not appreciable, but the pressure rises (5.9 and 9.1 psi) were noticeably higher than those with the 20 ppi foam.

Arrestor burning does not appear to be a problem when wet foam is used. The flame quenching effectiveness of wet samples of the 20 ppi foam was determined at 0 psig with air flowing through the tank after ignition with the incendiary ammunition; the flow rate was the same as that used in test No. 1. In tests No. 4 and 5 the foam was soaked in kerosene and the tank was completely filled with the combustible gas mixture. In tests No. 6 and 7, 35 gallons of kerosene was added to the tank to provide a tank ullage of about 47 percent; here, the incendiary was fired into the ullage space in one run (Test No. 6) and through the gas mixture and liquid fuel in the other run (Test No. 7). Under each test condition, the maximum pressure rise was less than 0.4 psi and flame propagation was quenched within the fuel tank; also, no arrestor burning was noted. However, motion picture records revealed that a fireball of about 1.5-foot diameter developed outside the tank after ignition when the tank was partially filled with liquid fuel. Figure 12 shows the external fire that resulted upon ignition in test No. 7. According to the movie records, the fire persisted for at least 200 milliseconds after the main ignition event. The external fire hazard under such conditions would be expected to decrease with decreased foam pore size, since fuel leakage or spillage would be retarded more by the smaller size foams.

TABLE VII . - Data From Large-Scale Flame Arrestor Experiments With 10 and 20 ppi Polyurethane Foam (Wet and Dry) Fully-Packed in a Tank With 3 Percent n-Butane-Air Mixtures at Various Initial Pressures.

Fuel tank: 27-inch diameter x 30-inch long (74 gals)
Ignition source: 30-caliber incendiary ammunition

Test No.	Initial Pressure, psig	Tank Ullage, Vol.%	Condition of Foam	Pressure Rise ΔP_{max} psi	Pressure Rise t sec	Pressure Rise Initial Rate psi/sec	Flame Quenched	Arrestor Burning
				20 ppi Polyurethane Foam				
1	0 1/	100	Dry	1.1	0.03	--	Yes	Appreciable
2	3	100	"	< 0.4	--	--	"	Little
3	6	100	"	< 0.4	--	--	"	Appreciable
4	0 1/	100	Wet	< 0.4	--	--	"	None
5	0 1/	100	"	< 0.4	--	--	"	None
6	0 1/	47 2/	"	< 0.4	--	--	"	None
7	0 1/	47 3/	"	< 0.4	--	--	"	None
				10 ppi Polyurethane Foam				
8	0	100	Dry	9.1	0.21	24.4	Yes	Little
9	0	100	"	5.9	0.19	22.6	"	Little

1/ Within 2 seconds after ignition air was introduced at a flow rate of 25.4 CFM (at 5 psig and 80° F) through a 3/8-inch diameter inlet port of the tank.
2/ Incendiary fired into tank ullage; 35 gallons of kerosene added to tank.
3/ Incendiary fired through gas and liquid fuel in tank; 35 gallons of kerosene added to tank.

2.8 milliseconds per frame

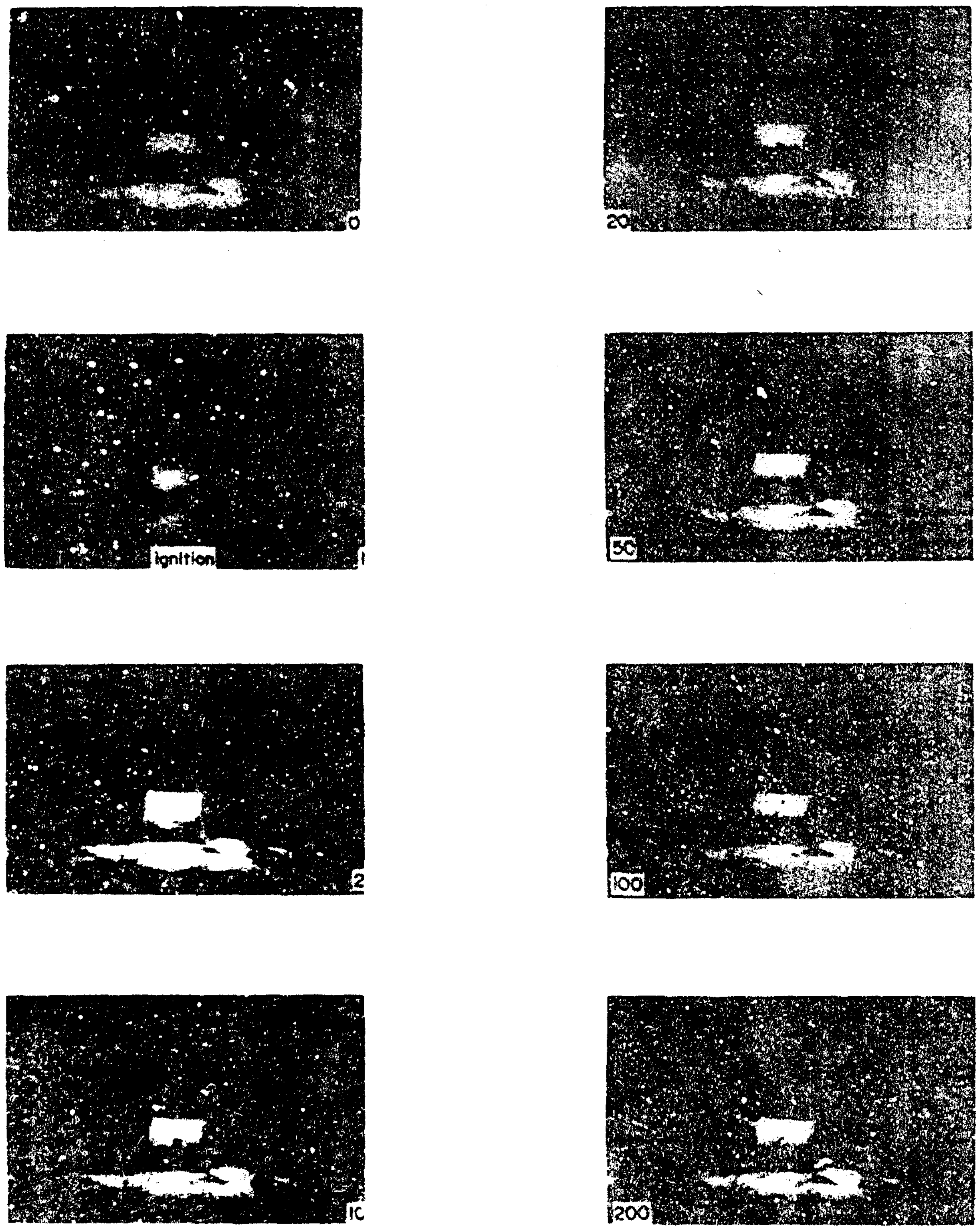


FIGURE 12. - External fire in experiment (Test No. 7) with fully-packed arrestor model (0 percent gross void) of 20 ppi foam after ignition of 3.0 percent n-butane-air mixture in ullage of 74-gallon tank with 30-caliber incendiary ammunition; 35 gallons of kerosene added to fuel tank.

CONCLUSIONS

The flame quenching effectiveness of the reticulated polyurethane foam appears to vary little when the bulk density of the foam is reduced from 1.86 lb/ft^3 to 1.35 lb/ft^3. Results from small-scale experiments revealed that the 10 ppi foam (density 1.86 lb/ft^3) is less effective in preventing flame propagation than 15 and 25 ppi foams of lower bulk density (1.35 lb/ft^3) mainly because of its larger pore size. Other light-weight arrestors such as crimped and honeycomb aluminum materials and a honeycomb Nomex fabric were more effective than the 10 ppi polyurethane foam. In addition, results obtained with a 10 ppi reticulated aluminum foam were comparable to those of the 10 ppi polyurethane foam at 0 psig, but not at elevated pressures.

The large-scale gun-firing experiments indicated that a cored arrestor model (16.3 percent gross void) of the 20 ppi dry foam having 2-inch diameter cells can be a suitable design configuration for internal fuel tank applications. In experiments conducted in the 74-gallon fuel tank, this model was effective in suppressing vapor phase explosions within the fuel tank at initial pressures up to 5 psig (maximum pressure used). Under a fully-packed tank condition, the 20 ppi dry foam can be expected to prevent flame propagation at pressures up to at least 6 psig, although some arrestor burning can occur. Although arrestor burning is enhanced by adding air after a fuel tank ignition with incendiaries, the amount of burning is greatly reduced when the foam is in a fuel-wet condition. In general, the fire and explosion hazard in a fuel tank equipped with the foam will be less with reduced tank ullage but the external fire hazard can still exist.

RECOMMENDATIONS

1. Complete the theoretical study of flame quenching mechanisms to obtain computer solutions for predicting the performance of light-weight arrestor materials. Prepare a general computer program for defining ignition and flammability requirements and generating explosion pressure-temperature data for the constant volume or constant pressure combustion of flight vehicle combustibles. This information would be useful to aircraft designers and to flight safety personnel.

2. Conduct a basic ignition study on flame inhibitors, including halogenated hydrocarbons, that may be useful as explosion suppressants in aircraft fuel tanks or as fire suppressants in areas outside the fuel tanks. Inhibitors which could provide protection against ignition by incendiary firing are particularly interesting.

3. Screen new materials including foams coated with flame inhibitors to evaluate their flame quenching effectiveness.

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13. ABSTRACT

An investigation was conducted to extend the data on the flame arrestor effectiveness of reticulated polyurethane foams proposed for explosion protection of aircraft fuel tanks. Foams of 10, 15, 20, and 25-pore/inch were evaluated in small- or or large-scale experiments using various arrestor packing configurations. Results from small-scale experiments indicated that the ability of the foams to suppress n-pentane-air explosions does not vary noticeably when the foam bulk density is reduced from 1.86 lb/ft^3 to 1.35 lb/ft^3. Other light-weight arrestors that were evaluated included crimped or honeycomb aluminum and Nomex materials which proved to be more effective than 10 ppi polyurethane foam; samples of reticulated aluminum foam were also investigated. Large-scale gun-firing experiments made in a 74-gallon fuel tank showed that a cored arrestor model of the dry 20-pore/inch polyurethane foam, having 2-inch diameter cores, can be a suitable design configuration for integral fuel tank applications at pressures up to 5 psig; however, some arrestor burning can be expected. Data are also given from other large scale experiments in which the fuel tank ullage and addition of air after ignition were investigated. In addition, a summary is given on a theoretical study that is currently being pursued to explain the flame quenching mechanisms of foam arrestors.

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