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FUEL TANK EXPLOSION PROTECTION

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

Bureau of Mines
ERC Report No. 4073

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March 1969

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

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NOTICES

FOREWORD

This report was prepared by the Explosives Research Center of the U. S. Bureau of Mines under USAF Contract No. F33(615)-66-5005. The contract was initiated under Project No. 3048, Task 304807 "Aerospace Vehicle Hazard Protection." It was administered under the direction of the Air Force Aero Propulsion Laboratory, with Mr. Benito P. Botteri (APFH) acting as project engineer.

This report is a summary of the work recently completed under Amendment No. 4(68-1492) of this contract during the period 1 March 1968 to 30 November 1968.

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

This report was submitted by the authors January 17, 1969.

This technical report has been reviewed and is approved.

Charles R. Hudson

CHARLES R. HUDSON, Chief
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Hazards Division

ABSTRACT

Small-scale and large-scale experiments were conducted to determine the flame arrestor effectiveness of three types of hollow, perforated polyethylene spheres proposed for fuel tank fire and explosion protection. In small-scale experiments, the flame quenching effectiveness of the spheres decreased with an increase in initial pressure and flame run-up distance (ignition void length) and with a decrease in sphere size and packing density. Randomly-packed beds of sphere types A (1-inch diameter, 0.1-inch perforations) and B (1-inch diameter, 0.05-inch perforations) were effective in preventing flame propagation at pressures up to 5 and 0 psig, respectively, whereas sphere type C (3/4-inch diameter, 0.10-inch perforations) failed at 0 psig; with uniformly-packed beds, none of the spheres failed at 0 psig. All three types were noticeably less effective than 10 pore/inch reticulated polyurethane foam. Results from most of the large-scale gun firing experiments with randomly-packed spheres revealed that the spheres were not effective in preventing flame propagation at 0 psig in a 74-gallon modified fuel tank. Other data that were obtained in pressure drop experiments at various air velocities indicated that the flow resistance is slightly greater for sphere type C than for A or B. Empirical relationships are presented for predicting the pressure drop gradients across dry and wet beds of the spheres at air velocities from 5 to 25 ft/sec.

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INTRODUCTION

This report summarizes the results of an investigation conducted to determine the flame arrestor effectiveness of hollow, perforated polyethylene spheres proposed for fuel tank fire and explosion protection. The use of the perforated sphere concept represents an alternate approach that has been advanced as a possible improvement on the reticulated foam concept. Previous Bureau work demonstrated the explosion-suppression capability of 10, 20 and 40 pore/inch (ppi) polyurethane foams under various temperature and pressure conditions.[1] These foams provide protection against hydrocarbon fuel vapor-air explosions but they are not satisfactory for reducing the external fire hazard that can arise from gun firings into fuel tanks. In comparison, gun firing experiments by the Air Force Aero Propulsion Laboratory[2] have indicated that plastic spheres can significantly reduce the external fire hazard. Although the spheres are combustible and have an autoignition temperature of approximately 825°F in air,[3] they are not necessarily damaged by exposure to hydrocarbon air flames when the time of contact is of short duration. Therefore, this work was undertaken to determine if these materials are also suitable for suppressing vapor phase explosions.

The flame arrestor effectiveness of 1-inch and 3/4-inch diameter polyethylene spheres was investigated with n-butane or n-pentane-air mixtures at various temperatures and pressures. Randomly-packed beds of the spheres were used in most of the experiments and the results were compared to those previously found for the polyurethane foam.[1] The flame arrestor effectiveness of the spheres was also examined in several large-scale experiments under gun firing conditions. In addition, data are presented on the flow resistance of the spheres and foam under various air flow conditions.

EXPERIMENTAL APPARATUS AND PROCEDURE

A. Flame Arrestor Experiments

Three types of hollow, perforated polyethylene spheres having 0.02-inch thick walls and 34 equally spaced holes were evaluated; samples of each type are shown in figure 1. The spheres examined were as follows:

Type A - 1-inch diameter, 0.10-inch perforations.
Type B - 1-inch diameter, 0.05-inch perforations.
Type C - 3/4-inch diameter, 0.10-inch perforations.

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[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] Communication from Air Force personnel.

[3] Determined in 200 cc vessel by ASTM D-2155-66 Method.

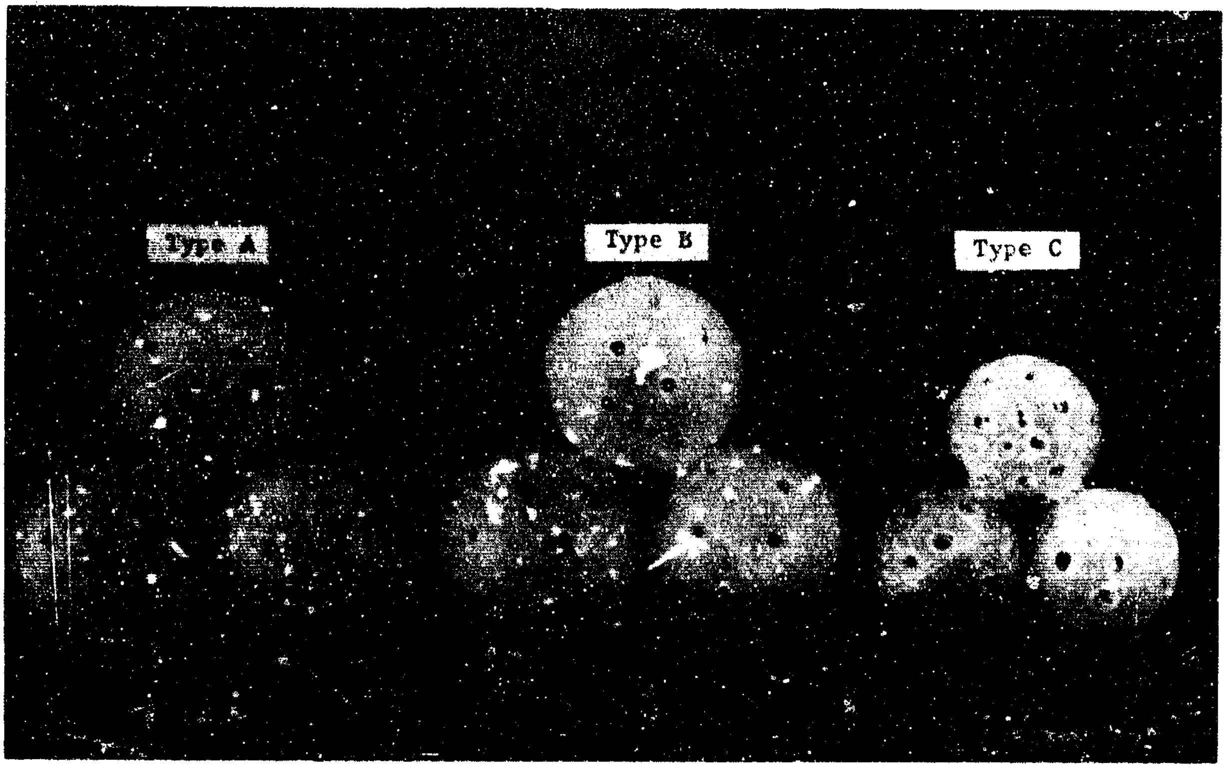

FIGURE 1. - Three types of hollow, perforated polyethylene spheres.

The flame arrestor effectiveness of the spheres was investigated in experiments with near-stoichiometric mixtures of n-pentane or n-butane and air that were ignited at temperatures of 60° to 180°F and pressures of 0 to 10 psig. In small-scale experiments, 6- and 12-inch diameter cylindrical vessels were used under fully- and partially-packed vessel conditions; under the partially-packed condition, the arrestor bed length was less than that of the vessel. Most of the large-scale experiments were run in a modified 74-gallon aircraft fuel tank, fully packed, using incendiary ammunition as the ignition source. The packing densities given in this report refer to the fraction of total bed volume occupied by the spheres.

1. Small-Scale Experiments

Most of the small-scale experiments were set up as shown in figure 2. A 12-inch diameter by 35-inch long cylindrical steel vessel, normally mounted in a horizontal position, served as the test chamber. The vessel was instrumented with 0.004-inch Chromel-Alumel thermocouples at selected positions and a strain-gage pressure transducer to monitor the gas mixture temperature and pressure during a trial; their signals were displayed on oscillographs. An electrical spark ignition source, centrally located on the upstream end of the vessel, was used to ignite the combustible mixture. The vessel was also equipped with a photodiode near its downstream end to detect any flame propagation through the spheres. For experiments at elevated temperatures, the vessel was externally heated by three separately-controlled Nichrome wire heaters.

The spheres were randomly packed in the vessel at various bed lengths. When the vessel was only partly filled, gross void spaces of various lengths were permitted between the ignition source and the bed of spheres; a gross void in the downstream end of the vessel was also used in some runs. The bed of spheres was secured between two, 2-mesh steel screens. After the spheres were packed in the vessel, the vessel was evacuated and filled with the combustible mixture to the desired pressure. The mixture was then ignited and the extent of flame propagation was determined from temperature and pressure measurements. All experiments were conducted with approximately 2.5 percent n-pentane-air mixtures at a temperature of 70° ± 10°F, unless otherwise noted. At the end of each run, the spheres were removed and visually examined to determine the extent of damage.

Small-scale experiments were also conducted in 6- and 12-inch diameter Pyrex vessels to observe photographically the mode of flame propagation through closely packed beds of the plastic spheres; the vessels were 48 and 60 inches long, respectively, and were equipped with spark ignition sources and strain-gage pressure transducers. Figure 3 shows a uniformly-packed bed of 1-inch diameter polyethylene spheres (type A) in a 12-inch diameter vessel. The spheres were arranged in the vessel layer-by-layer

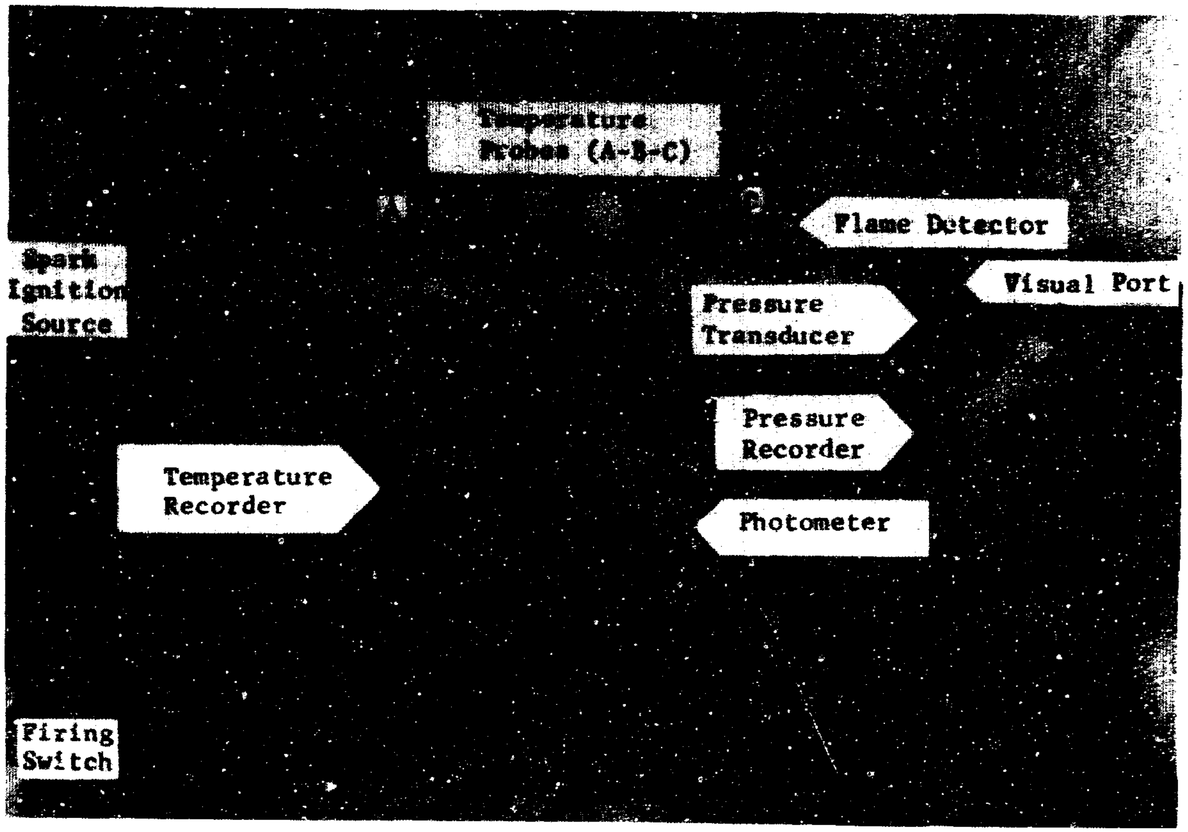

FIGURE 2. - Experimental setup for flame arrestor experiments in a 1 ft^3 cylindrical steel vessel (6-inch diameter by 60 inches long).

FIGURE 3. - Uniformly-packed bed of 1-inch diameter polyethylene spheres (type A) in a Pyrex vessel (12-inch diameter by 60 inches long).

so that the packing density was near maximum. Flame propagation was photographed with a high-speed Fastax camera at framing rates between 1300 to 2200 pictures per second. Here, near-stoichiometric mixtures of n-butane and air were employed as in the large-scale flame arrestor experiments.

2. Large-Scale Experiments

Large-scale experiments were conducted with randomly-packed polyethylene spheres in a modified fuel tank section. Because of the limited quantity of spheres, only the mid-section of a 450-gallon aircraft fuel tank (figure 4) was used; the modified tank had a 74-gallon capacity, 27 inches diameter by 30 inches long. A pressure transducer was mounted at each end and 0.004-inch Chromel-Alumel thermocouples were located at various stations to obtain temperature and pressure rise data. In some runs, the tank was completely packed with the spheres, whereas in others, 20 ppi polyurethane foam sections were packed at either or both ends of the bed of spheres to fill the tank. One run was also made in a partially-packed fuel tank that measured 27 inches in diameter and 97.5 inches long.

The flame arrestor performance of the spheres was examined in approximate stoichiometric mixtures of n-butane and air that were ignited with 30-caliber incendiary ammunition at atmospheric pressure. The incendiary ammunition was fired through the middle of the bed with an M-1 military rifle at about 150 feet; projectile velocity was approximately 2800 ft/sec. In addition to temperature and pressure rise measurements, a Fastax camera was used to photograph tank rupture when arrestor failure occurred.

B. Pressure Drop Experiments

Pressure drop experiments were performed with the polyethylene spheres and polyurethane foam at various air flow conditions in an 8-inch diameter by 60-inch long cylindrical steel pipe mounted in a vertical position. The vessel was equipped with seven manometer ports for measuring the pressure drop at fixed intervals over a 24-inch length of the vessel. Air flow rates were adjusted by means of a portable manometer located above the exit surface of the arrestor beds. The exact air velocities were calculated from manometer readings across a calibrated orifice plate and refer to the velocities at the inlet (bottom) of the arrestor beds; the air velocities were between 4 and 60 ft/sec. The pressure drop measurements were made with beds of spheres and sections of foam ranging from 6 to 24 inches; the spheres were randomly packed in the vessel and secured in place with 2-mesh steel screens. Experiments were conducted using both wet and dry arrestor materials. The measurements with wet arrestor beds were made under two different wetting conditions; in one, the bed was saturated by a spray of water prior to passage of air through it, and in the second, an approximately equal quantity of water was passed through the bed in the opposite direction to the air flow.

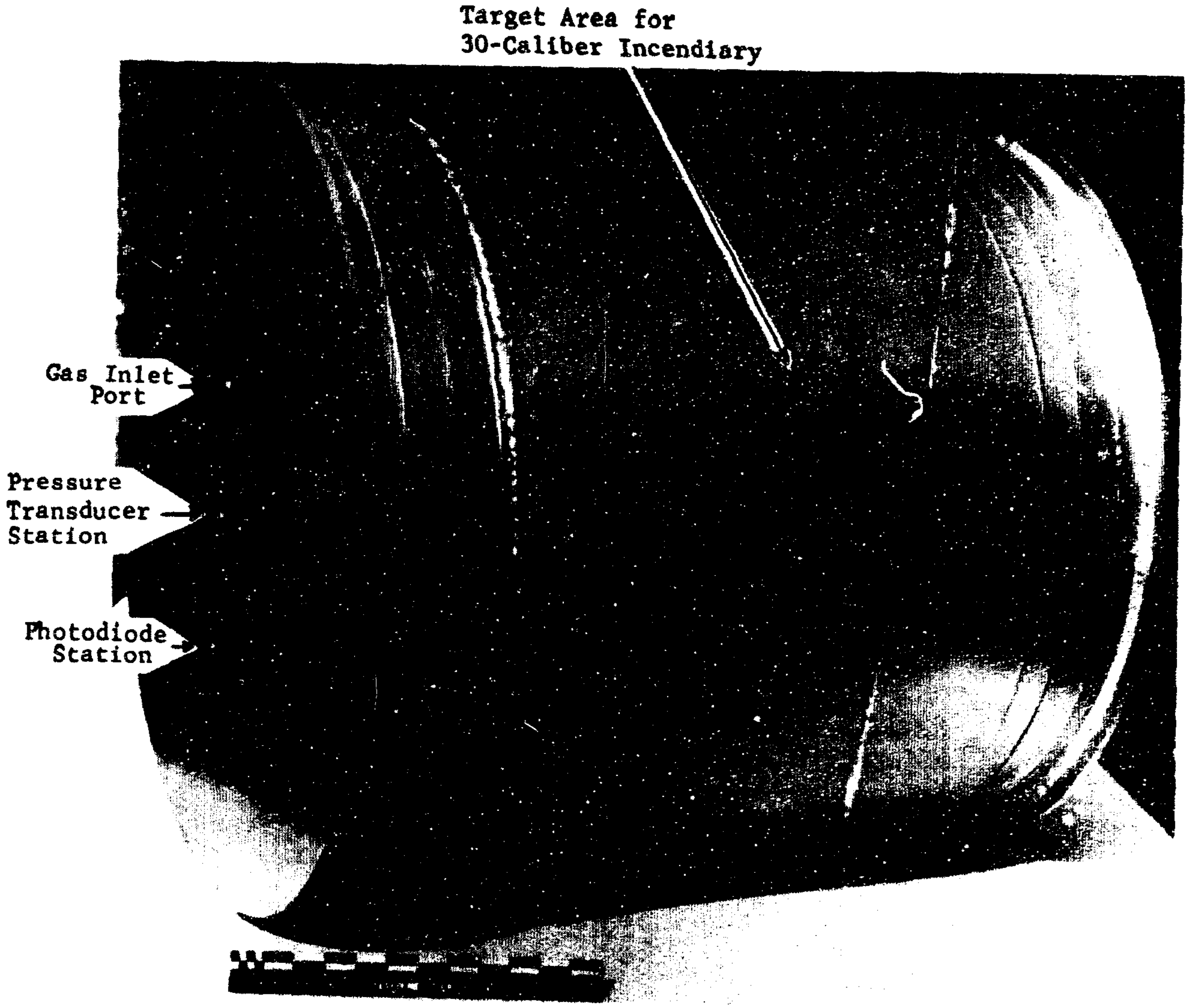

FIGURE 4. - 74-gallon modified fuel tank (27-inch diameter by 30 inches long).

RESULTS AND DISCUSSION

A. Small-Scale Flame Arrestor Experiments

The experiments in the 12-inch diameter cylindrical steel vessel revealed that the flame arrestor effectiveness of the perforated polyethylene spheres varies with initial gas mixture pressure, ratio of arrestor length to ignition void length (ℓ_2/ℓ_1), and sphere size or type. Packing density of the spheres is also important although it was not varied greatly in the present work since loose arrestor beds would not be effective. Such factors as the initial temperature, direction of flame propagation, and sphere condition (wet or dry) had little influence on the effectiveness of the spheres except where the experimental conditions were near critical for arrestor failure.

1. Fully-Packed Vessels

Figure 5 shows the pressure rise data obtained from runs at 0 psig mixture pressure with randomly-packed spheres of type A (1-inch diameter, 0.1-inch perforations) at various packing densities. For comparison, similar data are also shown in figure 5 for runs made in a 12-inch diameter by 60-inch long Pyrex vessel at a uniform packing density of 70.4 percent, approximately the maximum possible for these spheres. At a packing density of 70.4 percent, the spheres were effective in quenching flame propagation in each trial; the maximum pressure rise was less than 5 psi and flame travel was less than 12 inches. Similar results were obtained in most of the experiments with the randomly-packed spheres at packing densities of 66, 67, and 68.5 percent. However, the spheres also failed to prevent flame propagation in a few experiments at these lower packing densities. In such cases, the pressure rises were greater than 35 psi and flame was detected at the downstream end of the vessel; nonuniform packing can account for these few spurious results.

The effect of gas mixture pressure on arrestor effectiveness of the spheres was investigated in experiments at initial pressures from 0 to 10 psig; the packing density of the arrestor beds varied from approximately 65 to 69 percent. Table 1 and figure 6 compare the pressure rise data from these experiments with those previously reported[4] for the 10 ppi polyurethane foam in a fully-packed steel vessel, 6-inch diameter by 60 inches long. As shown in figure 6, the effectiveness of each arrestor material decreases with increasing mixture pressure. However, none of the polyethylene spheres were as effective as the 10 ppi polyurethane foam. The pressure rises with the 10 ppi foam varied from approximately 2 to 40 psi over the range of pressures investigated (0 to 20 psig) and flame propagation was quenched within 30 inches from the ignition source. The results obtained for the polyethylene spheres indicate that sphere type A is a more effective flame arrestor than either type B or C. Type A was effective in most experiments at initial pressures up to 5 psig. When arrestor failure was not observed, the pressure

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[4] Reference in footnote 1.

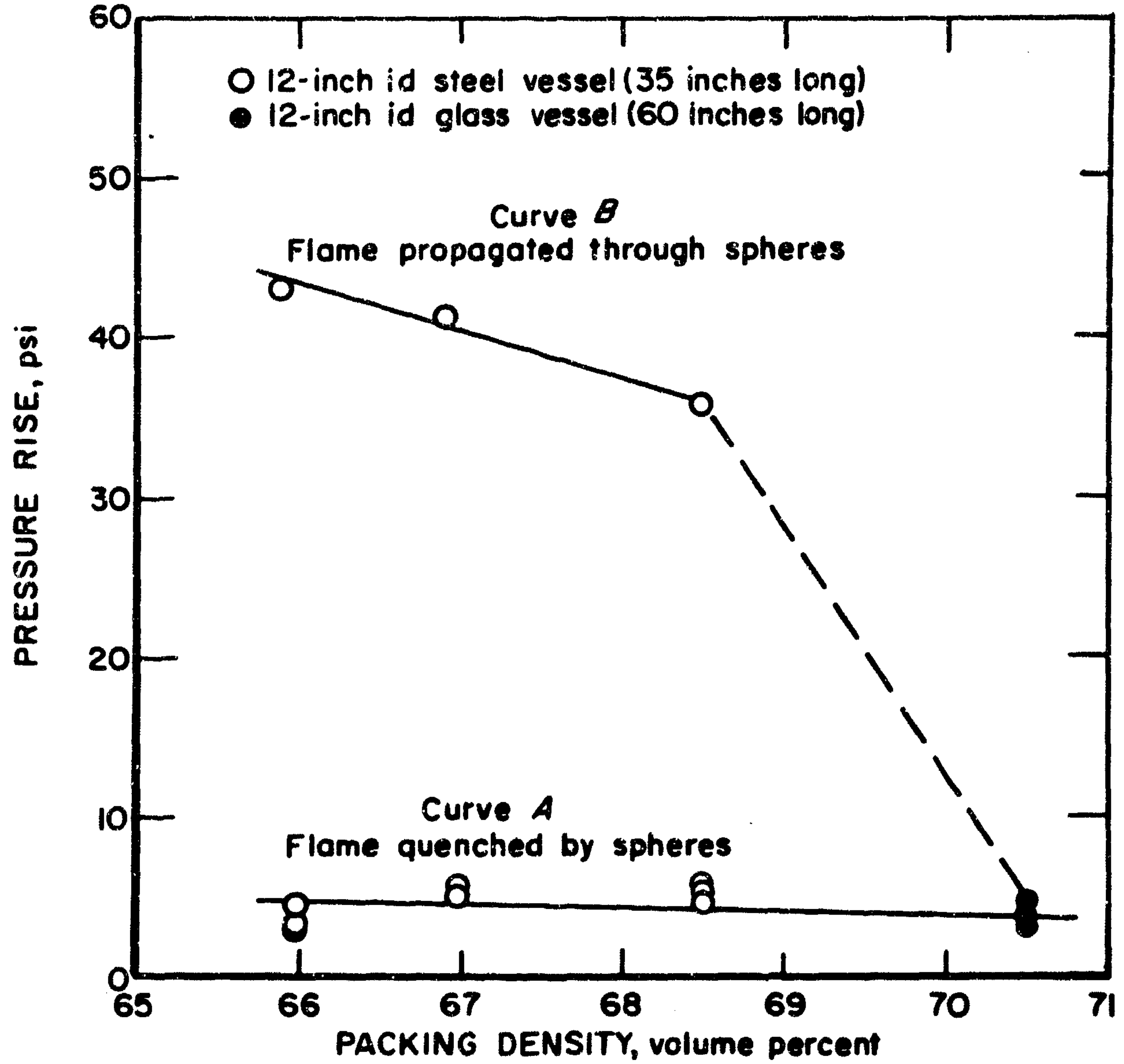

FIGURE 5. - Pressure rise vs packing density from flame arrestor experiments with 1-inch diameter perforated polyethylene spheres (type A) and ~2.5 percent n-pentane-air mixtures at 0 psig.

TABLE 1. - Flame Arrestor Data for Perforated, Polyethylene Spheres (A, B, C) and 10 pore/inch Polyurethane Foam in Fully-Packed Cylindrical Steel Vessels With 2.5 Percent n-Pentane-Air Mixtures.

Random packing of spheres - $\geq$65 percent packing density

Initial Pressure, psig	Maximum Pressure Rise, psi	Arrestor Failure Detected by Flame Sensor[2]	Depth of Flame Penetration,[3] inches
Sphere Type A (1" diam., 0.1" perforations) - 12-inch ID Vessel			
0	5.2[1]	No	<15
0	36.9	Yes	35
0	43.2	Yes	35
0	46.8	Yes	35
5	9.0	No	<15
5	14.4	No	<15
5	22.5	Yes	35
10	59.4	Yes	35
Sphere Type B (1" diam., 0.05" perforations) - 12-inch ID Vessel			
0	7.2	No	26
5	34.2	Yes	35
5	43.2	Yes	35
Sphere Type C (3/4" diam., 0.1" perforations) - 12-inch ID Vessel			
0	13.5	Yes	35
0	16.5	Yes	35
0	32.0	Yes	35
0	36.0	Yes	35
10 ppi Polyurethane Foam - 6-inch ID Vessel			
0	~1.8	No	<18
10	9.0	No	<18
15	17.5	No	<30
20	39.6	No	<30

1/ Value represents an average of twelve trials where flame was quenched by the arrestor models.

2/ Flame sensors (photodiode) located 2 to 6 inches from downstream end of vessel.

3/ 35 inches represents length of 12-inch ID vessel.
60 inches represents length of 6-inch ID vessel.

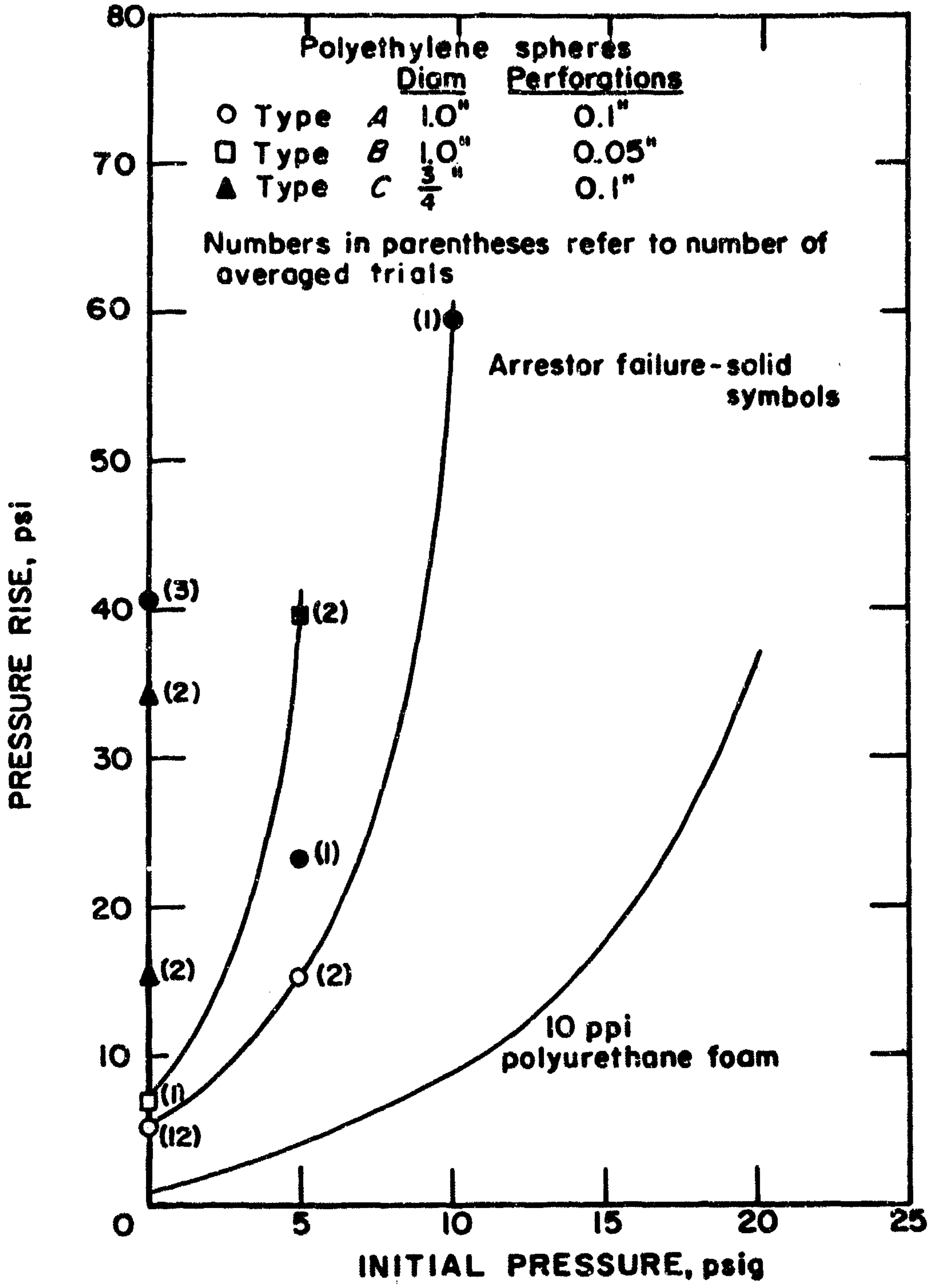

FIGURE 6. - Pressure rise vs initial pressure from flame arrestor experiments in fully-packed vessels with randomly-packed polyethylene spheres (~65-68 percent packing density) and 10 ppi polyurethane foam (~2.5 percent n-pentane-air mixtures).

rise was 11.5 ± 3 psi at 5 psig (2 trials) and 5.2 ± 1.8 psi at 0 psig (12 trials). Ordinarily, the spheres failed if flame propagation was not quenched within about 15 inches from the ignition source. In comparison, sphere type B which has the smallest perforations (0.05 inch) appeared to be effective at 0 psig but failed to prevent flame propagation at 5 psig; type C, which has the smallest diameter (3/4 inch), was least effective and failed at 0 psig in the four runs that were made (table 1). When arrestor failure occurred, the spheres showed evidence of thermal degradation and generally were deformed; figure 7 shows the deformation that was observed in an experiment with sphere type A at 10 psig.

Pressure-time traces obtained in some of these experiments are shown in figure 8. As noted, the polyethylene spheres gave sharp pressure rises following ignitions at 0 and 5 psig and the peak pressures were reached in less than 0.05 second; the greater arrestor effectiveness of sphere type A is also evident when comparing these data. In contrast, the pressure rises with the 10 ppi foam were noticeably less abrupt even at higher initial mixture pressures (10 and 15 psig). At the latter conditions, the peak pressures were not recorded until 0.2 to 0.4 second after ignition; the low level of pressure decay following the peak pressure development is partly attributed to some arrestor burning which tends to occur more readily in the elevated pressure runs.

The effect of increased gas mixture temperature on flame arrestor effectiveness was less noticeable than that of increased pressure, as noted in figure 9. With sphere type A, the maximum pressure rise increased only approximately 6 psi when the initial mixture temperature was varied from 60° to 180°F at 0 psig initial pressure. At 5 psig, the temperature effect was greater and arrestor failure occurred when the temperature was increased to 85°F or higher; this result is not surprising since even at 60°F the pressure rise was approximately 14 psi and near critical for arrestor failure.

Since the arrestor effectiveness of both wet and dry spheres is of interest, a few experiments were also made with spheres previously soaked in kerosine. JP-4 jet fuel was not used since nonflammable vapor-air mixtures could then form if the liquid fuel temperature was approximately 70°F. Sphere type A was examined in ignitions at 65° ± 5°F and initial gas mixture pressures of 0, 5, and 10 psig. Little difference was found between the effectiveness of wet and dry spheres except that the times to maximum pressure were about an order of magnitude longer with the wet spheres.

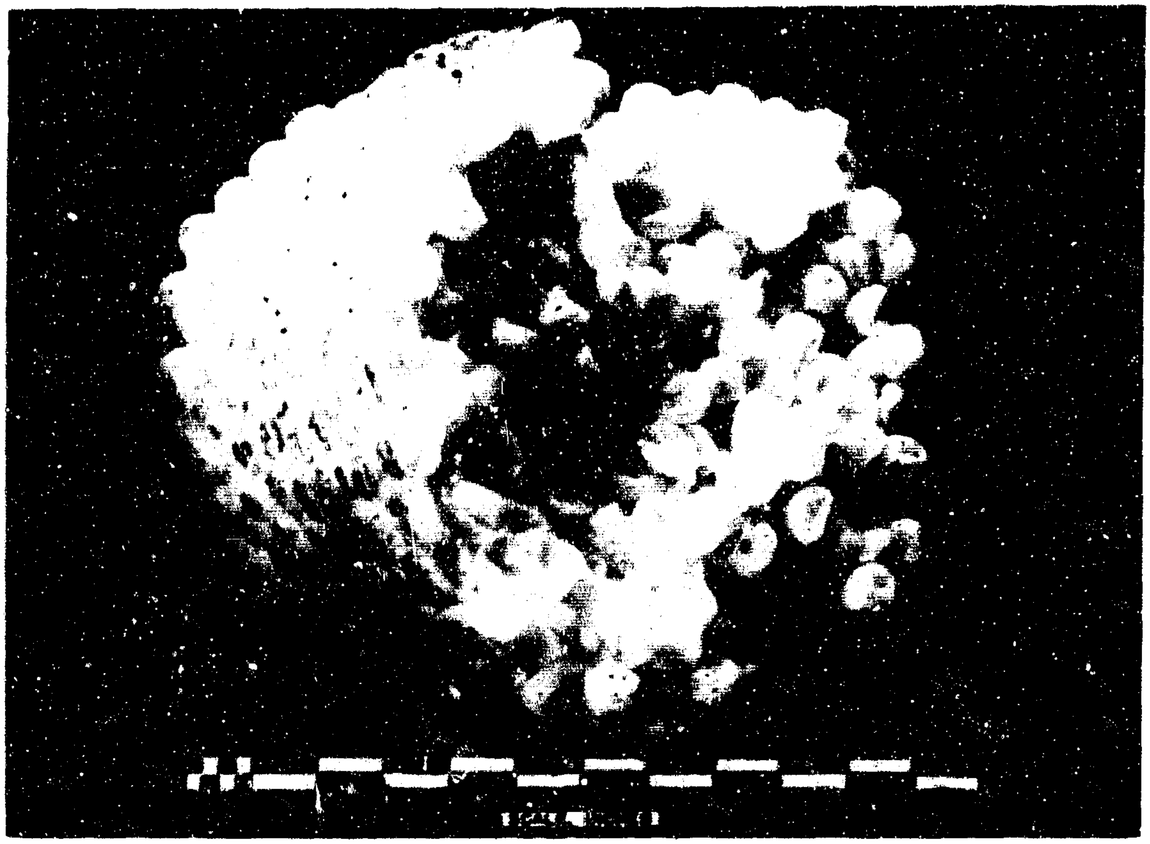

FIGURE 7. - Deformation of polyethylene spheres (type A) in flame arrestor experiment with 2.5 percent n-pentane-air mixture at 10 psig (12-inch diameter steel vessel).

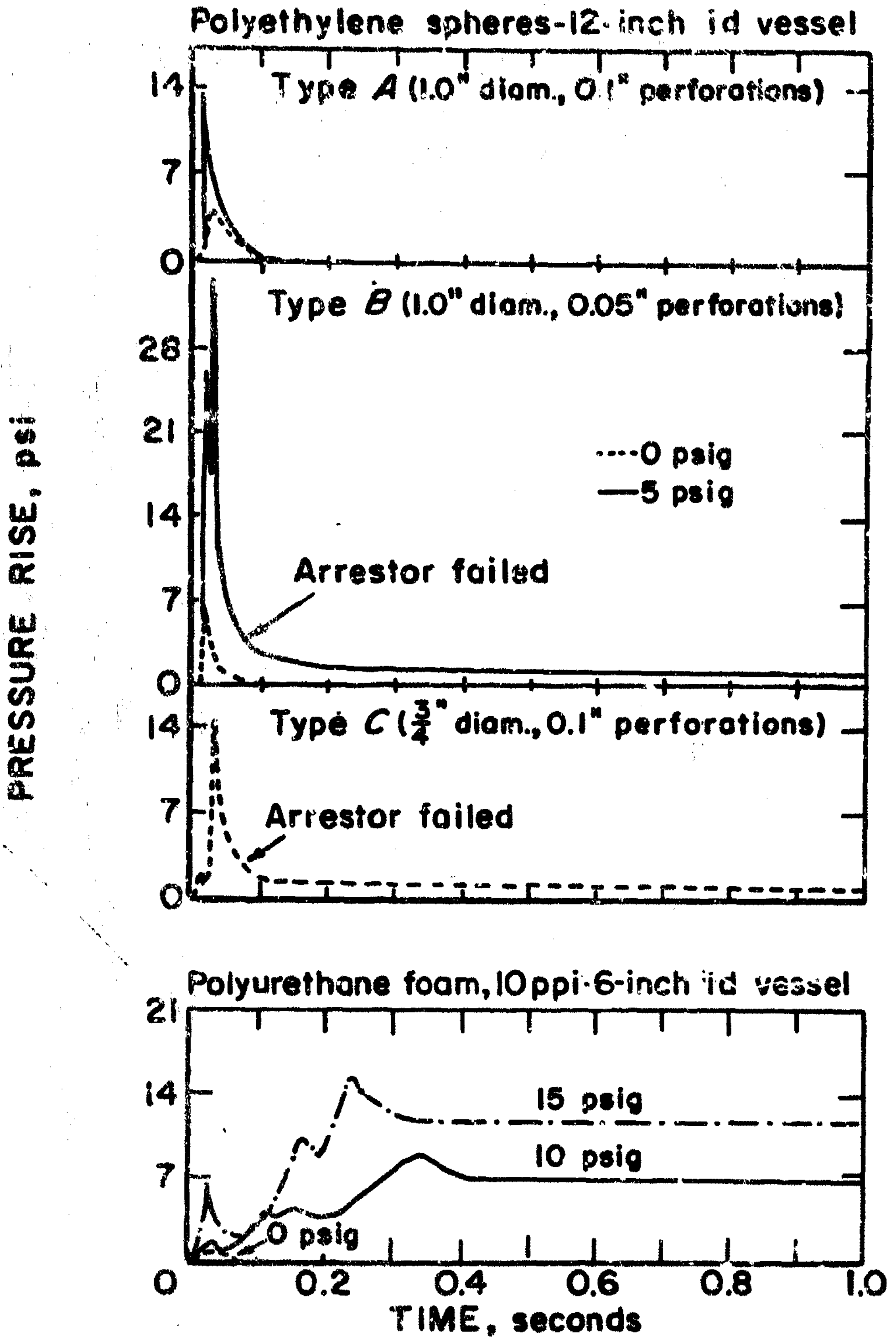

FIGURE 8. - Pressure-time traces from flame arrestor experiments in fully-packed vessels with randomly-packed polyethylene spheres and 10 ppi polyurethane foam at various initial pressures (~2.5 percent n-pentane-air mixtures).

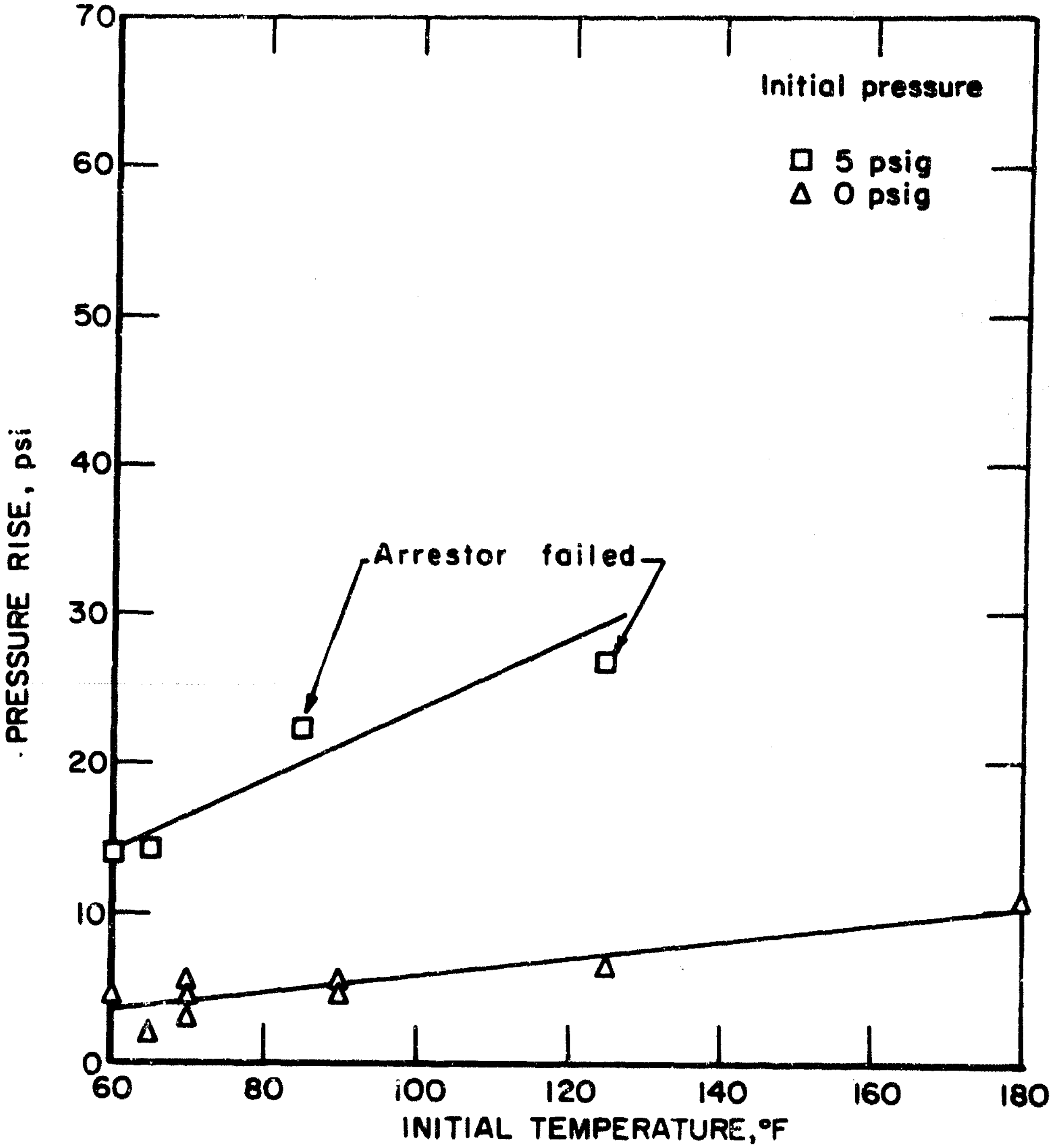

FIGURE 9. - Pressure rise vs initial temperature from flame arrestor experiments with 1-inch diameter randomly-packed polyethylene spheres (type A) and ~2.5 percent n-pentane-air mixtures at 0 and 5 psig (12-inch diameter steel vessel).

2. Partially-Packed Vessels

Ordinarily, the effectiveness of a flame arrestor decreases with an increase in the flame run-up distance because of the greater heat release and increased flame speed. In the experiments with the fully-packed vessels, ignition was initiated in the small voids between the spheres and the initial flame speeds were approximately equal to the standard burning velocity of the hydrocarbon vapor-air mixture, e.g., 1 to 2 ft/sec at 1 atm.[5] With partially-packed vessels, the flame speeds can be much higher depending upon the ignition void length and such factors as the vessel diameter, initial pressure, and gas mixture composition.

Table 2 summarizes data obtained in flame arrestor experiments with randomly-packed spheres at an ignition void length (ℓ_1) or flame run-up of 5 and 10 inches in the 12-inch diameter by 35-inch long steel vessel; approximately 2.5 volume percent n-pentane-air mixtures at 0 psig were used. According to flame speed measurements that were made using thermocouples, the flame speeds were approximately 10 ft/sec at a 5-inch run-up and 16 ft/sec at a 10-inch run-up (figure 10); the zero run-up in figure 10 corresponds to the fully packed condition. As noted, sphere type A did not fail at either flame run-up distance, while type B failed when the run-up was increased to 10 inches. At higher run-up distances, type A would be expected to fail since, even at the 10-inch run-up, the pressure rise was relatively high (15.3 psi) and flame had propagated about 18 inches according to the T_3 thermocouple (table 2). Figure 10 also shows that the 10 ppi polyurethane foam is effective at higher flame speeds than the plastic spheres, although the result for the foam was obtained in a smaller diameter vessel.

With uniform packing of the spheres, none of the spheres failed in experiments at 0 psig with a fully packed vessel or with an ignition void length up to 3 inches, the maximum used. The experiments with types A and B were conducted in a 12-inch diameter by 60-inch long Pyrex vessel at a packing density of 70 to 71 percent and those with type C in a 6-inch diameter by 48-inch long vessel at a packing density of approximately 63 percent; the smaller vessel was used in the latter runs because of the limited supply of the spheres. The maximum pressure rises were equal to or less than 5 psi, that is, they were less than those found with the randomly-packed spheres (table 1). The use of a smaller diameter vessel also probably contributed to the improved performance of the smaller spheres (type C). According to motion picture records, the spheres quenched flame propagation at a distance of 12 inches or less from the ignition source. Generally, the flame front was not uniform and consisted of flamelets moving predominantly through the voids between the spheres. Few, if any, perforations appeared to be illuminated, which

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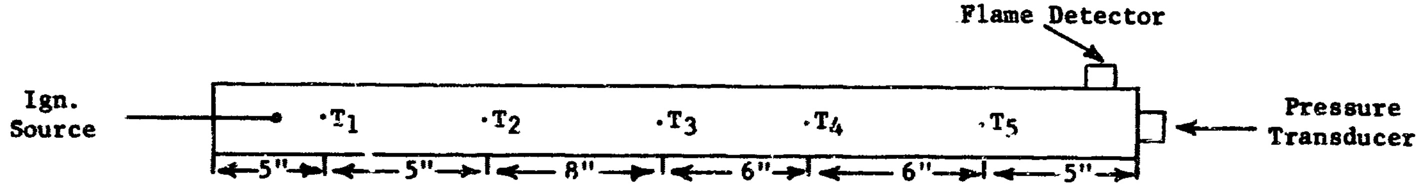
[5] Simon, G. M., Flame Propagation. Ind. and Eng. Chem., Vol. 43, No. 12, December 1951, p. 2718.

TABLE 2. - Pressure, Gas Temperature, and Light Emission Data From Flame Arrestor Experiments in 12-inch Diameter Steel Vessel With Perforated Plastic Spheres at 0 psig.

Combustible Mixture - ~2.5 Volume Percent n-Pentane-Air Mixture



	Sphere Type A[1]		Sphere Type B[2]	
	Experimental Conditions			
Initial temperature, °F	85	90	85	80
Arrestor bed length (ℓ_2), inches	25	20	25	20
Ignition void length (ℓ_1), inches	5	10	5	10
Total gross void, vol. percent	~29	~43	~29	~43
	Pressure Rise Data			
$\Delta P_{initial}$, psi	10.8	15.3	9.0	45.8
ΔP_{max}, psi	"	"	"	"
Time to $\Delta P_{initial}$, sec.	0.05	0.07	0.05	0.08
Time to ΔP_{max}, sec.	"	"	"	"
	Temperature Rise Data[3]			
ΔT_1, °F	1120(0.04)	--	540(0.04)	--
ΔT_2, °F	760(0.04)	300(0.05)	500(0.04)	440(0.05)
ΔT_3, °F	0(5.0)	100(0.06)	0(5.0)	1790(0.07)
ΔT_4, °F	"	0(5.0)	"	300(0.07)
ΔT_5, °F	"	"	"	600(0.07)
	Flame Detection by Photodiode at T_5 Station			
Flame	No	No	No	Yes
Time interval, sec.	--	--	--	0.06 to 0.35

1/ One-inch diameter with thirty-four 0.1-inch perforations.
2/ " " " " " " 0.05-inch " .
3/ Values in parentheses indicate the time in seconds to initial temperature rise.

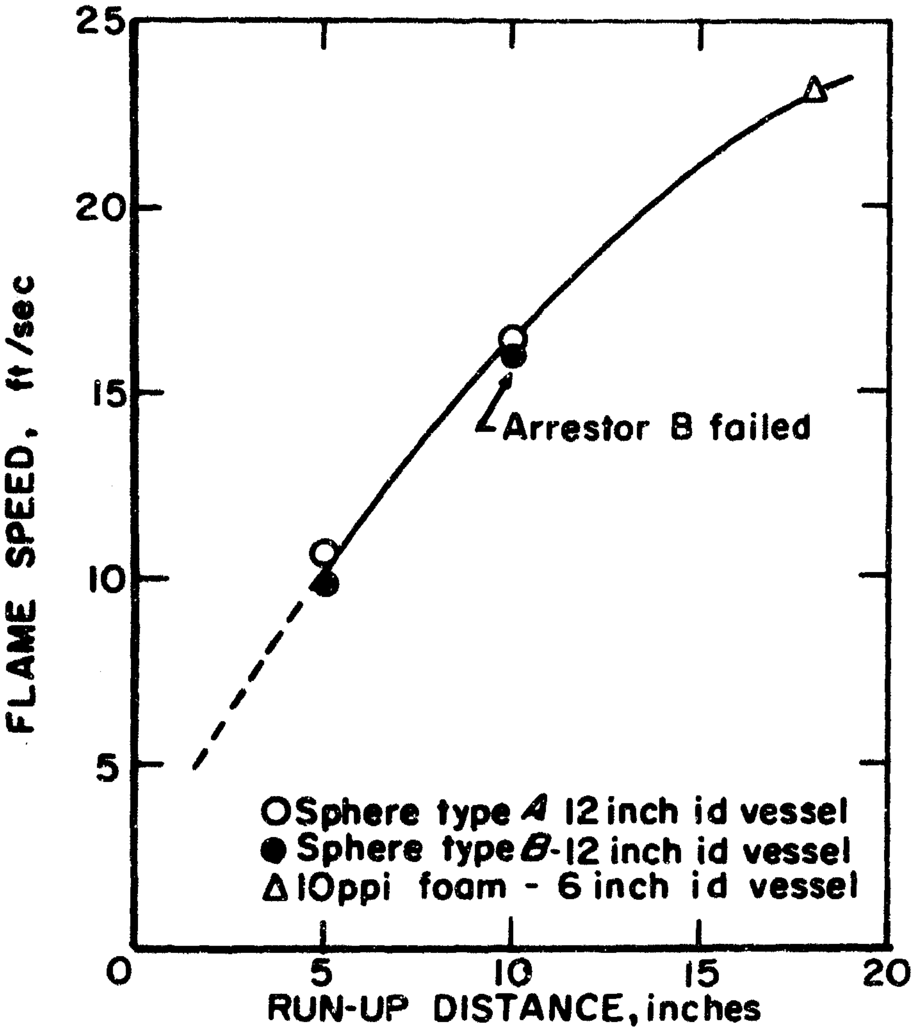


FIGURE 10. - Flame speed vs run-up distance from flame arrestor experiments with randomly-packed polyethylene spheres and 10 ppi polyurethane foam at 10 psig (~2.5 percent n-pentane-air mixtures).

indicated that little burning occurred inside the spheres. However, the photographs also revealed that some deformation and movement of the spheres occurs after ignition under these conditions. Accordingly, arrestor failure could occur if the interconnecting voids or passages between the spheres are widened sufficiently by such action. This is more likely to occur with randomly-packed spheres than for uniformly-packed spheres and with beds that are not adequately secured.

B. Large-Scale Flame Arrestor Experiments Under Gun Firing Conditions

In most of the large-scale experiments, randomly-packed beds of the polyethylene spheres (A, B, and C) failed to prevent flame propagation at 0 psig with 30-caliber incendiary ammunition as the ignition source. Table 3 summarizes the pressure measurements from experiments in a fully-packed 74-gallon tank (27-inch diameter by 30-inch length) at sphere packing densities of 61 to 65 percent. For comparison, pressure rise data are also shown in table 3 for experiments conducted with the 10 ppi reticulated polyurethane foam. In the first series of runs (Nos. 1-6), the maximum pressure rises with each sphere type were equal to or greater than 18 psi except in one run where the tank failed prematurely at a pressure rise of only 6 psi. In the above runs, at least one end plate of the tank failed when the maximum pressure rise occurred; the end plates were secured to the tank by locking clamps. Other runs were also made with the end plates welded to the tank to minimize possible arrestor failure as a result of tank expansion and displacement of the spheres following ignition. Under this tank condition, sphere type A quenched flame propagation in one run but failed in another, whereas the 10 ppi foam was effective in quenching flame in two similar runs. The peak pressures and the rates of pressure rise were lower in the runs with the foam; also, as noted in figure 11, the foam displayed little evidence of any burning. The failure of the 3/4-inch diameter spheres (C) is consistent with the results obtained with randomly-packed spheres of this size in the 12-inch diameter steel vessel. Similarly, the results for the 1-inch diameter spheres (A and B) are not surprising since sphere type A failed at 0 psig in some of the small-scale experiments (table 1).

In another large-scale experiment, the flame arrestor performance of sphere type A was borderline under a partially-packed condition in a modified fuel tank, 27 inches diameter by 97.5 inches long. As shown in figure 12, a 37-inch long bed of spheres was randomly-packed ($\sim$65%) in the bulkhead section (ℓ_4) and secured in place with steel screens; also, two cylindrical segments of the 20 pore/inch foam were placed at the upstream and downstream ends to give gross void spaces 12 and 14.5 inches long. The maximum pressure rise obtained in this trial was only 12.5 psi and this occurred within 0.3 second after ignition; also, the tank did not rupture. However, the temperature and light emission measurements revealed that flame had propagated through the bed into adjacent gross voids (ℓ_3, ℓ_5). Apparently, the spheres reduced flame propagation sufficiently to permit contamination of the unburned gas mixture in the gross voids and,

FIGURE 11. - 10 ppi reticulated polyurethane foam sections after ignition of 3.1 percent n-butane-air mixture at 0 psig with 30 caliber incendiary ammunition (74-gallon fuel tank).

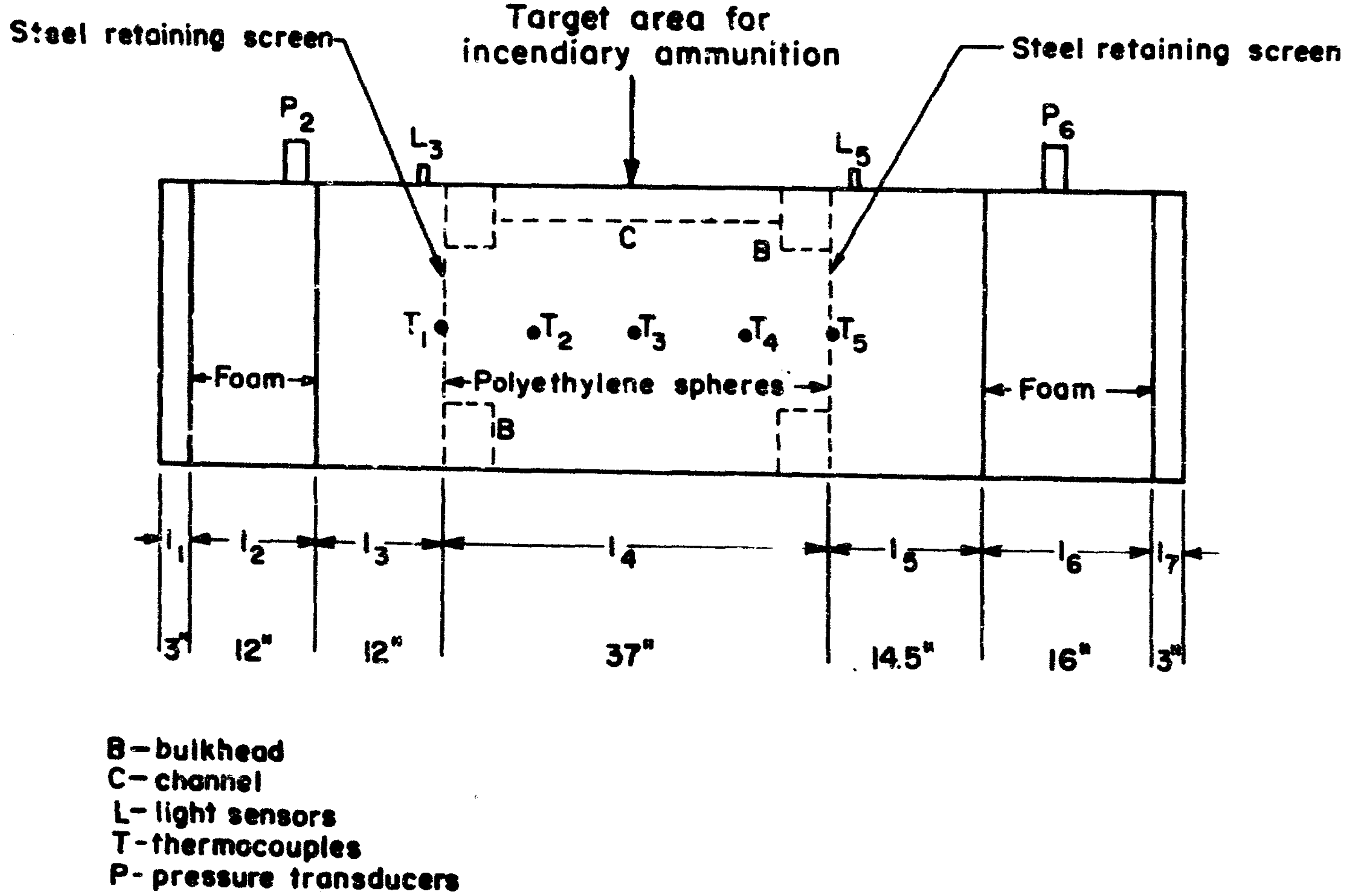


FIGURE 12. - Arrangement for large-scale flame arrestor experiment with randomly-packed 1-inch diameter polyethylene spheres (type A) in a 27-inch diameter by 97.5-inch long fuel tank.

Gas mixture - ~3.0 percent n-butane and air (1 atm).
Ignition source - 30-caliber incendiary.

thereby, prevented complete combustion of the gas mixture. The bulkheads and steel screens, which were not present in the 74-gallon tank, also were a factor since they provided additional surface for flame quenching. Nevertheless, it appears that higher packing densities, such as those possible with uniform packing, are necessary for the spheres to provide an acceptable level of explosion suppression.

TABLE 3. - Pressure Data From Large-Scale Gun Firing Experiments With Randomly-Packed Polyethylene Spheres (A, B, C) and 10 ppi Polyurethane Foam in a 74-Gallon Fuel Tank at 0 psig.
~3.0 Vol. percent n-Butane-Air Mixtures
30-Caliber Incendiary Ammunition

Run No.	Sphere Type[1]	Bed Length, inches	Packing Density, vol.%	Peak Pressure		Init. Rate of Pressure Rise, psi/sec	Flame Quenched
				P, psig	t, sec		
			A. Polyethylene Spheres (Tank end plates secured by locking clamps)				
1	A	22	65	18.0	0.01	250	No
2	A	27	63	25.2	.01	505	No
3	A	30	63	30.6	.01	900	No
4	B	22	65	21.6	.02	450	No
5	C	22.5	61	6.0[2]	.02	265	No
6	C	30	63	19.8	.02	450	No
			B. Polyethylene Spheres (Tank end plates secured by welding)				
7	A	30	65	10.6	.01	215	Yes
8	A	30	65	22.8	.02	295	No
			C. 10 ppi Polyurethane Foam (Tank end plates secured by welding)				
1	-	30	--	9.1	.21	24.4	Yes
2	-	30	--	5.7	.19	22.6	Yes

[1] Sphere type A (1-inch diameter, 0.1-inch perforations), B (1-inch diameter, 0.05-inch perforations), C (3/4-inch diameter, 0.1-inch perforations).

[2] Tank end plate failed prematurely.

C. Pressure Drop Experiments

Pressure drop data were obtained for the perforated polyethylene spheres under various air flow conditions to determine their resistance to fluid flow. To simulate certain flow conditions encountered in practice, the measurements were made at air flow rates up to about 60 ft/sec for both wet and dry randomly-packed beds of spheres. For comparison, similar measurements were also made with the 10 and 20 ppi polyurethane foam materials.

Table 4 summarizes the pressure drop data obtained for 1-inch diameter polyethylene spheres (A) and the foam materials at various air velocities and positions in 8-inch diameter by 24-inch long beds; all materials were dry. The total differential pressure across a 24-inch bed of the spheres was less than 2.0 psi at air velocities below 20 ft/sec and over 8.5 psi at 49 ft/sec. The corresponding results for the polyurethane foams, particularly the 10 ppi, were lower than those for the spheres. Furthermore, at the higher air velocities, the pressure drop data indicated that the compressive forces caused severe deformation of the foam. For example, at 36.6 ft/sec, approximately 97 percent of the total pressure drop occurred across the last 6 inches of a 20 ppi foam bed; the 10 ppi foam displayed comparable behavior at about 45 ft/sec. Figure 13 shows the amount of reduction in the bed length that can result with the 10 and 20 ppi foams at air velocities between 5 and 60 ft/sec. It is evident from these data that the reduction in bed length is noticeable when the air velocity is equal to or greater than approximately 25 ft/sec. Therefore, the pressure drop data for these foams are meaningful only below 25 ft/sec.

The pressure drop per unit length of bed ($\Delta P/\ell$) increased with an increase in air velocity and did not vary significantly over most of the length of the bed. Figure 14 shows a plot of $\Delta P/\ell$ versus air velocity for pressure drop data taken from table 4 at a bed length or ℓ of 24 inches. As noted, there is little difference between the air flow resistance of the 20 ppi foam and sphere type A; as expected, the 10 ppi foam offered less resistance ($\sim 1/2$) than the 20 ppi foam. Approximately the same results were found by plotting the data in table 4 for the reference bed positions of 18, 12, 9, and 6 inches; the data for the 2-inch reference position gave slightly higher pressure gradients. Although bed length was also varied (6 to 24 inches), the results did not differ significantly.

The pressure drop gradients across wet beds of the hollow perforated spheres were somewhat greater than those across dry beds at air velocities between 5 and 25 ft/sec (table 5). Also, the method of wetting the spheres did not appear to affect the results except at 5 ft/sec where the pressure gradient was noticeably greater when the water was sprayed in the opposite direction to the air flow. Table 5 also compares the results obtained for the foam materials. The differences between the pressure drop gradients for the wet and dry beds are greater for the foams than for the plastic spheres at air velocities equal to or greater than about 10 ft/sec; differences in surface areas and liquid adsorption or retention properties of the materials can account for the variations in these results.

TABLE 4. - Pressure Drop, ΔP, as a Function of Air Velocity and Longitudinal Position in a 24-inch Long Randomly-Packed Bed of Arrestor Material Confined by an 8-inch ID Steel Pipe.

Longitudinal position, in.	A. Perforated, hollow polyethylene spheres, 1-inch diameter, 0.1-inch perforations				
	ΔP, psi				
	Air velocity, ft/sec				
	5.0	9.6	19.1	22.7	49.1
2	0.015	0.038	0.128	0.177	0.246
6	.034	.102	.336	.481	1.145
9	.046	.148	.518	.685	1.976
12	.061	.195	.692	.931	2.962
18	.091	.301	1.088	1.492	5.708
24	.128	.411	1.473	2.004	8.627
	B. 10 ppi Polyurethane foam				
	ΔP, psi				
	Air velocity, ft/sec				
	4.7	8.9	23.0	44.3	56.8
2	0.010	0.020	0.064	0.049	0.049
6	.034	.059	.201	.098	.000
9	.035	.074	.335	.246	.084
12	.038	.091	.477	.633	.142
18	.054	.141	.761	1.426	.568
24	.069	.182	1.068	3.650	5.131
	C. 20 ppi Polyurethane foam				
	ΔP, psi				
	Air velocity, ft/sec				
	4.7	8.2	19.0	27.0	36.6
2	0.008	0.025	0.092	0.010	0.005
6	.040	.112	.459	.010	.015
9	.059	.151	.648	-0.015	-0.038
12	.069	.192	.831	-0.006	-0.067
18	.094	.265	1.143	.468	.301
24	.115	.318	1.380	2.390	3.820

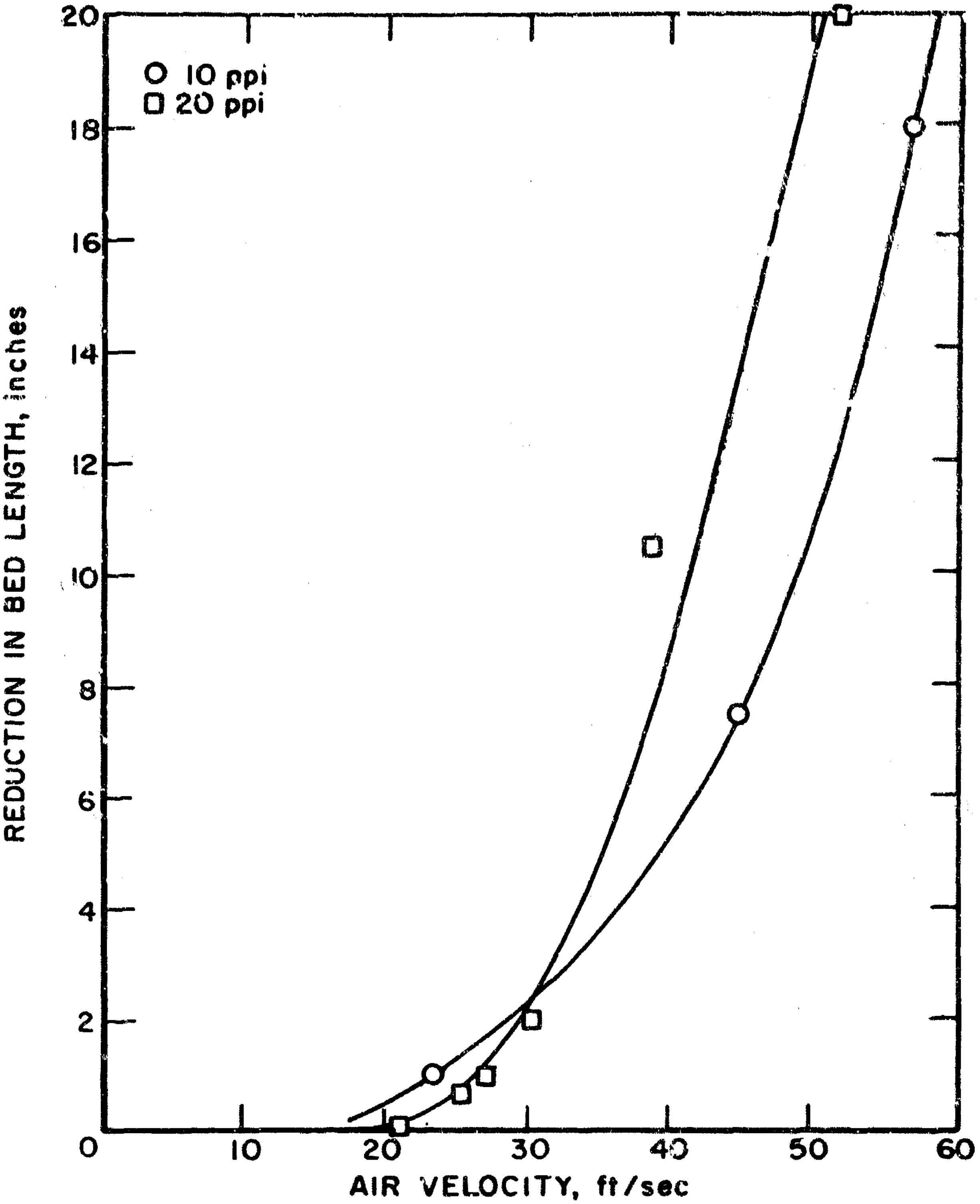


FIGURE 13. - Reduction in bed length vs air velocity for 24-inch long beds of reticulated polyurethane foam in 8-inch diameter steel pipe.

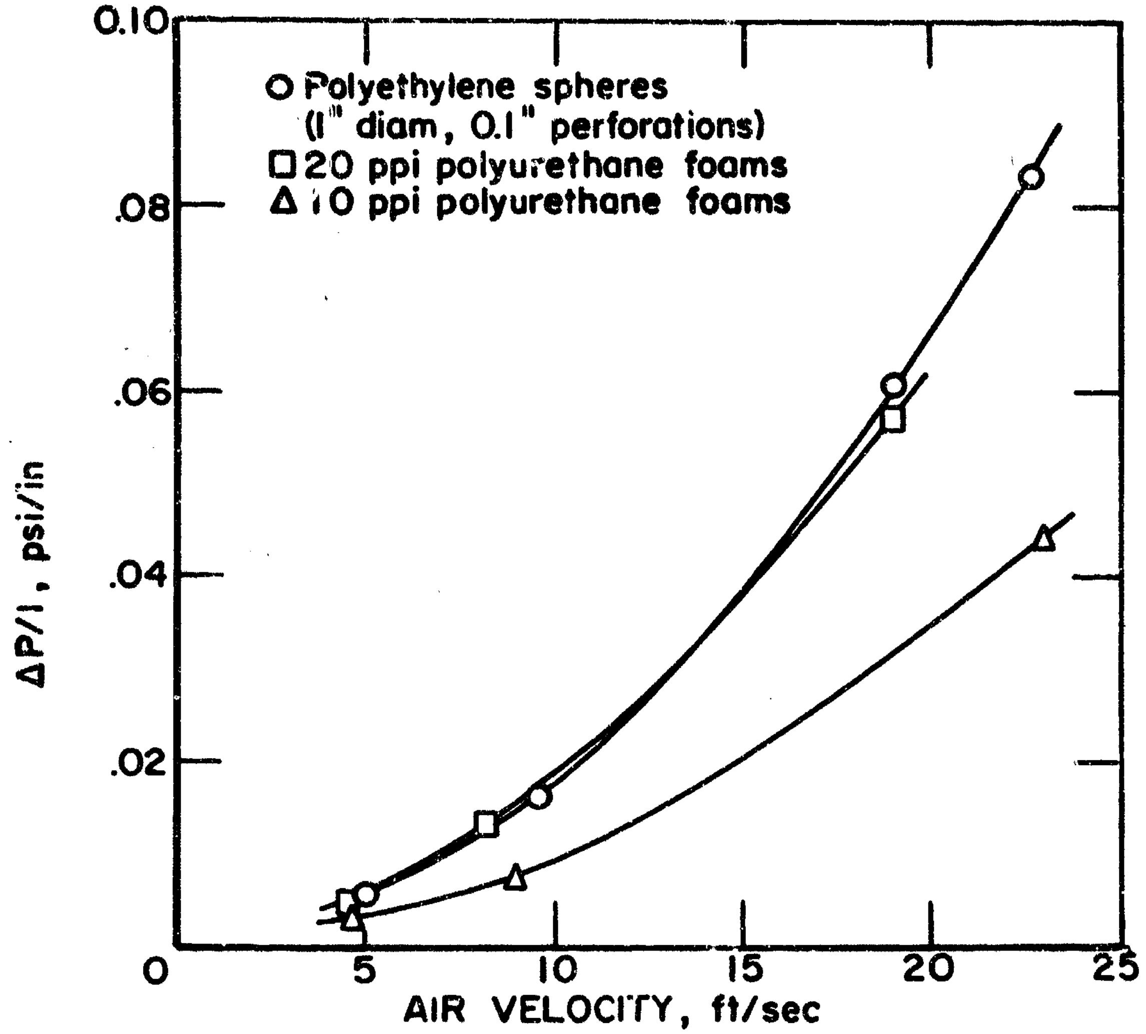


FIGURE 14. - Pressure differential per unit length ($\Delta P/\ell$) vs air velocity for 24-inch long packed beds of 1-inch diameter polyethylene spheres (type A) and 10 and 20 ppi polyurethane foam in 8-inch diameter steel pipe.

TABLE 5. - Pressure Drop, ΔP, at Various Air Velocities in 8-inch Diameter Beds of Flame Arrestor Material, 24 inches long.

A. 1-inch diameter hollow polyethylene spheres.
Perforations = 0.05-inch diameter

ΔP, psi
Air Velocity, ft/sec

	5.0	10.0	20.6	23.2	25.1
Dry	0.122	0.443	1.643	2.068	2.427
Wet	(0.272	0.565	1.710	2.116	2.419
	(.390*	.568*	1.641*	2.114*	2.403*

B. 1-inch diameter hollow polyethylene spheres.
Perforations = 0.10-inch diameter

ΔP, psi
Air Velocity, ft/sec

	5.0	9.6	19.2	22.8
Dry	0.185	0.515	1.548	2.085
Wet	(0.211	0.565	1.717	2.261
	(.371*	.590*	1.646*	2.142*

C. 3/4-inch diameter hollow polyethylene spheres.
Perforations = 0.10-inch diameter

ΔP, psi
Air Velocity, ft/sec

	5.0	10.1	18.0	21.0
Dry	0.192	0.624	1.728	2.256
Wet	0.264	.840	1.896	2.448

D. 10 ppi reticulated polyurethane foam

ΔP, psi
Air Velocity, ft/sec

	5.0	10.0	20.4	23.0	24.4
Dry	0.065	0.229	0.858	1.059	1.194
Wet	(0.090	0.334	1.215	1.015	
	(.088*	.692*	1.963*		

E. 20 ppi reticulated polyurethane foam

ΔP, psi
Air Velocity, ft/sec

	5.0	10.0	20.7	23.2	25.0
Dry	0.120	0.409	1.482	1.851	2.122
Wet	(0.121	.486	2.171	3.032	
	(.130*	.502*	2.089*	2.914*	

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* H_2O mass flow equal and opposite to air flow.

Figure 15 shows a correlation of pressure drop information that was obtained for dry and wet polyethylene spheres at various air velocities from about 5 to 25 ft/sec; $\Delta P/\ell$ is plotted against the air velocity on logarithmic axes. Since straight line plots were obtained for each sphere configuration, the following empirical equation can be used for predicting the pressure gradients:

$$\Delta P/L = kV^n \qquad (1)$$

where ΔP is the pressure drop in psi, L is the bed length of the spheres in inches, V is the air flow velocity in ft/sec, k is a proportionality constant dependent upon sphere configuration, and n is the order of flow dependency. Table 6 gives the values of the two constants (k and n) and the range of air velocities over which equation 1 is applicable. Equation 1 should be applicable for beds of spheres from 2 to 24 inches long because the pressure gradients ($\Delta P/\ell$) were essentially the same over this range of bed lengths. Based on these data, the resistance to air flow is greater for the 3/4-inch diameter spheres (C) than for the 1-inch diameter spheres (A and B); also, the flow resistance is slightly greater for sphere type A than for B which has the smaller perforations. The results are comparable to those for granular packed beds where the pressure drop gradients are proportional to the square of the velocity or less, depending upon the magnitude of the flow rates.[6]

TABLE 6. - Values of Constants in Equation 1 for Dry and Wet Polyethylene Spheres.

Sphere Type	Dry Spheres k	Dry Spheres n	Dry Spheres Air Velocity (V) ft/sec	Wet Spheres k	Wet Spheres n	Wet Spheres Air Velocity (V) ft/sec
A	.00049	1.65	$5 \geq V \leq 25$	.00055	1.64	$5 \geq V \leq 25$
B	.00025	1.85	$5 \geq V \leq 25$	.00056	1.60	$10 \geq V \leq 25$
C	.00049	1.73	$5 \geq V \leq 25$	.00094	1.54	$5 \geq V \leq 25$

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[6] Ergun, S., Fluid Flow Through Packed Columns. Chem. Eng. Prog., Vol. 48, February 1952, pp. 89, 227.

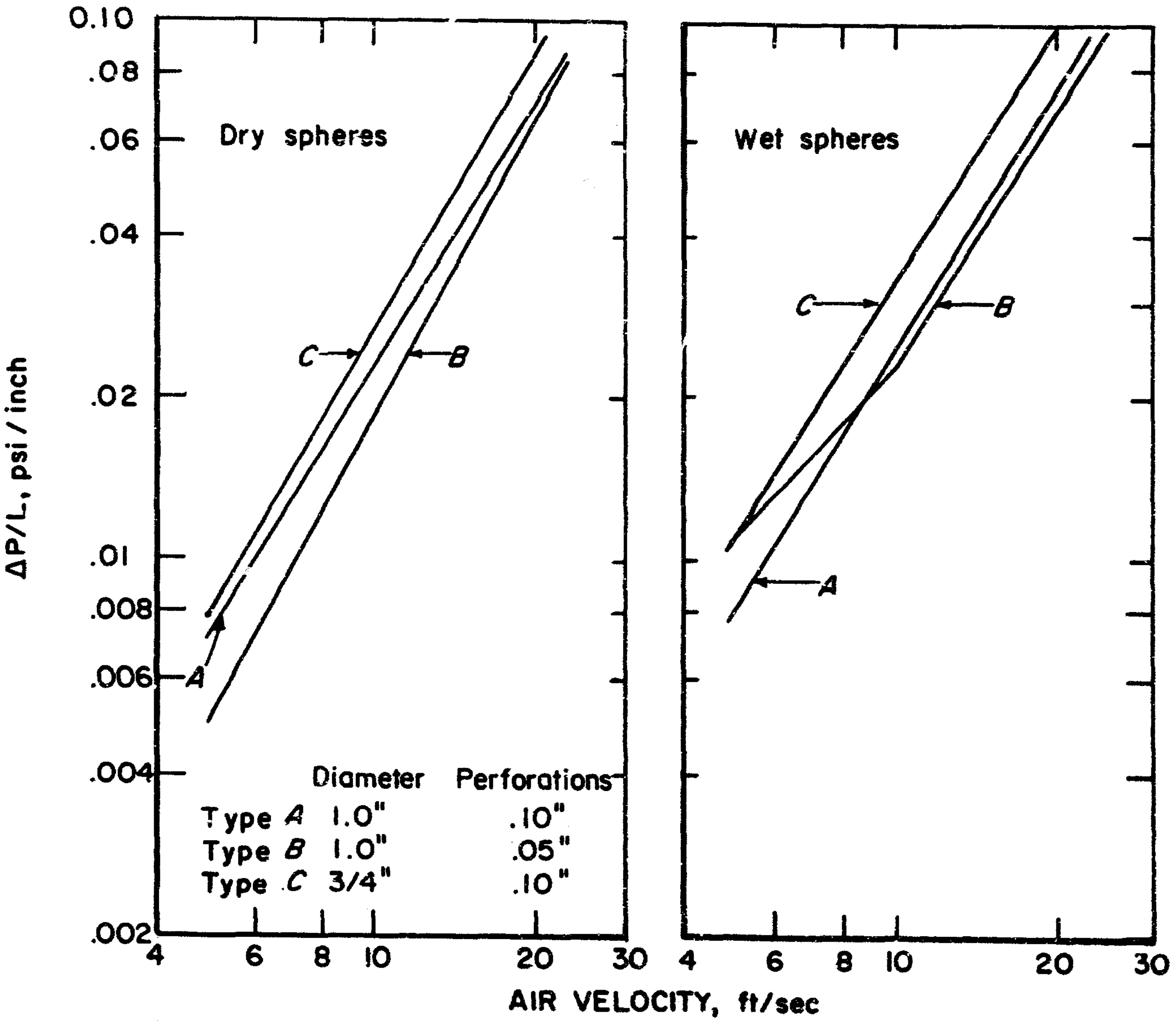

FIGURE 15. - Pressure differential per unit length ($\Delta P/\ell$) vs air velocity for 24-inch long packed beds of 1-inch diameter and 3/4-inch diameter polyethylene spheres in 8-inch diameter steel pipe.

CONCLUSIONS AND RECOMMENDATIONS

The flame arrestor effectiveness of the hollow, perforated polyethylene spheres decreases with an increase in initial gas mixture pressure and flame run-up distance (ignition void length) and with a decrease in sphere size and packing density. Small-scale experiments revealed that randomly-packed spheres of type A (1-inch diameter, 0.1-inch perforations) are more effective in preventing flame propagation than either type B (1-inch diameter, 0.05-inch perforations) or C (3/4-inch diameter, 0.1-inch perforations). All of the spheres are much less effective than the 10 pore/inch reticulated polyurethane foam. With random packing of the spheres, type C was the least effective as a flame arrestor since it failed at 0 psig mixture pressure in a fully-packed vessel; the greater number of gross voids possible with the smaller spheres was probably the major factor responsible for their poor performance. In comparison, sphere types A and B were effective at initial pressures up to 5 and 0 psig, respectively; packing densities for these materials were generally at least about 65 percent. With uniform packing of the spheres to give near maximum packing, they were effective in quenching flame at 0 psig and the performance results were more reproducible than with random packing.

The results obtained in the large-scale gun firing experiments indicated that randomly-packed beds of the polyethylene spheres are not satisfactory for quenching flame propagation at 0 psig in a fully-packed fuel tank. Higher packing densities (>65%) than those achieved with random packing appear to be required for the spheres to be effective in the fuel tank application.

According to pressure drop experiments, the resistance to air flow is slightly greater for sphere type C than for A or B. The flow resistance of sphere type A is comparable to that of the 20 pore/inch polyurethane foam. The pressure gradients ($\Delta P/\ell$) across dry beds of the spheres varied directly with the air velocity raised to a power between 1.6 and 1.85; greater pressure gradients occurred with wet beds.

The following work is recommended on problems pertinent to the prevention and suppression of fuel tank fires or explosions:

1. Continue small-scale experiments to evaluate flame arrestor effectiveness of new candidate materials for fuel tank applications. Compare the effectiveness of promising candidates to that of the 10 pore/inch polyurethane foam at simulated flight temperatures to 600°F.

2. Conduct additional large-scale gun firing experiments with the polyethylene spheres to determine their effectiveness in the fuel-wet condition with steel mesh screens at various intervals in the fuel tank.

3. Conduct a basic study on the evaluation of flame inhibitors, including halogenated hydrocarbons, that may be used as explosion suppressants in aircraft fuel tanks or as fire suppressants in areas outside the fuel tanks. In this connection, the possible use of arrestor materials with encapsulated inhibitor or coatings of inhibitor should be investigated.

4. Determine the autoignition temperature and flammability properties of any new aircraft combustible fluids submitted for evaluation.

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