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EVALUATION OF FLAME ARRESTOR MATERIALS FOR AIRCRAFT FUEL SYSTEMS

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Irving Spolan
Whittner H. Gilbert

Bureau of Mines

TECHNICAL REPORT AFAPL-TR-67-148

February 1968

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Air Force Aero Propulsion Laboratory
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FOREWORD

This report was prepared by the Explosives Research Center of the U.S. Bureau of Mines under USAF Contract No. DO 33(615)-66-5005. The contract was initiated under Project No. 3048/6075 "Fire and Explosion Hazard Assessment and Prevention Techniques for Aircraft." It was administered under the direction of the Air Force Aero Propulsion Laboratory, Research and Technology Division, with Mr. Benito P. Botteri (APFL) acting as project engineer.

This report is a summary of the work recently completed under this contract during the period 1 January 1967 to 30 September 1967. The information in this report is unclassified in accordance with the following Air Force directive. "Downgraded to Unclassified by authority of CSAF Message AFRDDH 80391, 27 July 1967". This report was submitted by the authors October 12, 1967.

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

This technical report has been reviewed and is approved.

Arthur V. Churchill

ARTHUR V. CHURCHILL, Chief
Fuels, Lubrication and Hazards Branch
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ABSTRACT

Flame arrestor experiments were conducted with reticulated polyurethane foam materials which are currently being used for fire protection in fuel systems of military aircraft. The flame quenching effectiveness of the 20 pore/inch material was examined in both small- and large-scale flame propagation experiments under various temperature and pressure conditions. In the small-scale experiments, pressure rise measurements showed that dry samples of this foam prevent flame propagation at arrestor length/ignition void length ratios (ℓ_2/ℓ_1) as low as about 0.17 at ambient temperature and pressure. At ℓ_2/ℓ_1 ratios equal to or greater than 1.5, the material was effective at pressures up to about 15 psig and temperatures to 200°F. Improved performance was obtained when the foam was wetted with liquid fuel or when a foam of greater porosity rating was used. Full-scale experiments in a 450-gallon fuel tank indicated that the 20-pore/inch foam is effective to pressures of at least 5 psig using an arrestor packing configuration that permits a 40 percent gross void volume. However, the foam tends to be less effective when additional air is supplied following ignition. Results obtained with electrical spark ignition sources were comparable to those found with tracer or incendiary ammunition. Generally, the effectiveness of the 20 pore/inch foam was noticeably greater than that of the 10 pore/inch material that was examined earlier.

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INTRODUCTION

The present report describes the results of an investigation conducted during the past year to assess the flame arrestor effectiveness of certain cellular foam materials for possible use in aircraft fuel systems. This work was initiated by the Bureau of Mines in October 1966 and represents one phase of a current program, "Fire and Explosion Hazard Assessment and Prevention Techniques for Aircraft," sponsored by the Air Force under Contract No. DO 33(615)-66-5005. The arrestor material studied was a reticulated polyurethane foam whose use would not impose prohibitive weight and fuel load penalties on aircraft. Its fire protection capabilities have been demonstrated in earlier work by the Bureau using a material with a porosity of 10 pores per lineal inch (Ref 1). Currently, some of our military aircraft in combat environments are equipped with this flame arrestor material. The present work was conducted to evaluate the fire protection afforded by finer reticulated forms of this material for military and other applications.

Most of the data presented in this report was obtained using a 20 ± 5 pore/inch polyurethane foam; the material was a Scott Paper Company industrial "Z"-type foam of the same composition as the 10 pore/inch foam evaluated in the earlier work. Flame quenching effectiveness was determined under various temperature and pressure conditions in both small- and full-scale experiments. The data show that the flame arrestor effectiveness of the 20 pore/inch material is noticeably greater than that of the 10 pore/inch material. Its effectiveness in full-scale aircraft fuel tanks (450-gallon) was verified in gun firings using tracer and incendiary ammunition. From the data obtained in this study, optimum arrestor design configurations are suggested for the use of the foam in external fuel-tank applications. Some data are also presented for internal fuel-tank applications.

EXPERIMENTAL APPARATUS AND PROCEDURE

The flame arrestor effectiveness of the 20 pore/inch reticulated polyurethane foam was investigated in flame propagation experiments with near-stoichiometric mixtures of n-pentane or n-butane and air at initial temperatures between 70° and 200° ± 10°F and pressures between 0 and 25 psig. In small-scale experiments, cylindrical segments of the foam were examined in a 6-inch diameter test vessel at the above temperature and pressure conditions. Full-scale trials were conducted with cylindrical or conical-shaped arrestor segments in a 450-gallon (60 ft^3) aircraft fuel tank at ambient temperature and 0 or 5 psig initial pressure. Except for a few minor modifications, the apparatus and test procedures were the same as those used in the Bureau's earlier work (Ref 1). In the full-scale experiments, the performance of the arrestor material was evaluated using electrical sparks and live gun ammunition as the ignition source.

Ref. 1 - Cato, R. J., A. L. Furno, A. Bartkowiak, and J. M. Kuchta, Evaluation of Flame Arrestor Materials for Aircraft Fuel Systems (U), Air Force Aero Propulsion Laboratory, AFAPL-TR-67-36, March 1967.

1. Small-Scale Experiments With Cylindrical Arrestor Segments

Most of the small-scale experiments were conducted under static conditions in a 6-inch diameter by 60-inch long cylindrical steel vessel which was mounted in a horizontal position; figure 1 shows the experimental arrangement with this vessel. To conduct an experiment, a cylindrical segment of the foam material was fitted into the vessel at a selected distance from the ignition source which was normally mounted at one end of the vessel. For those trials where an arrestor gap was used between two arrestor segments, the ignition source was mounted near the center of the vessel. After the foam was in place, the combustible mixture was introduced to the desired pressure and ignited by an electrical spark energy source. The extent of flame propagation was determined from continuous pressure and temperature measurements that were made with a strain-gage pressure transducer and 0.004-inch Chromel-Alumel thermocouples at various stations; their signal outputs were recorded on oscillographs. Appearance of flame downstream of the arrestor was verified visually and by monitoring the light emission with a photovolt-multiplier unit.

All these determinations were made with ~2.5 percent n-pentane-air mixtures at various initial pressures and with various arrestor lengths ($\ell 2$) and flame run-up distances ($\ell 1$) in the ignition space. Except where noted, all runs were made at ambient temperature conditions (70° ± 10°F).

2. Full-Scale Experiments in a 450-Gallon Aircraft Fuel Tank

Full-scale experiments were conducted with multiple arrestor sections of the foam material in a 450-gallon aircraft fuel tank, of the F-105 external type. The tank, shown in figure 2, was 21 feet long with a 27-inch diameter by 94.5-inch cylindrical mid-section and conical-shaped nose and tail sections, both 81 inches long. It was instrumented for the experiments with two pressure transducers and five 0.004-inch Chromel-Alumel thermocouples at selected stations within; the outputs were fed to oscillographs. Photodiodes were also mounted in the tank to verify flame propagation.

For these experiments, the fuel tank was partially packed with various lengths of the arrestor material, tightly fitted to the wall in the nose, middle, and tail sections. Three or four arrestor sections, approximately 34 inches long, were packed into the tank and so arranged to allow gross void spaces at both ends of each section. Total gross void volumes corresponding to 46.5 and 40 percent of the tank volume were used. In each experiment, the tank was filled with a near-stoichiometric n-butane-air mixture and then the mixture was ignited by a spark energy source located in a given void; 30-caliber tracer and incendiary ammunition were also used as ignition sources. The effectiveness of the arrestor configuration was determined from pressure, temperature and flame luminosity measurements and by inspection of the foam material after a firing.

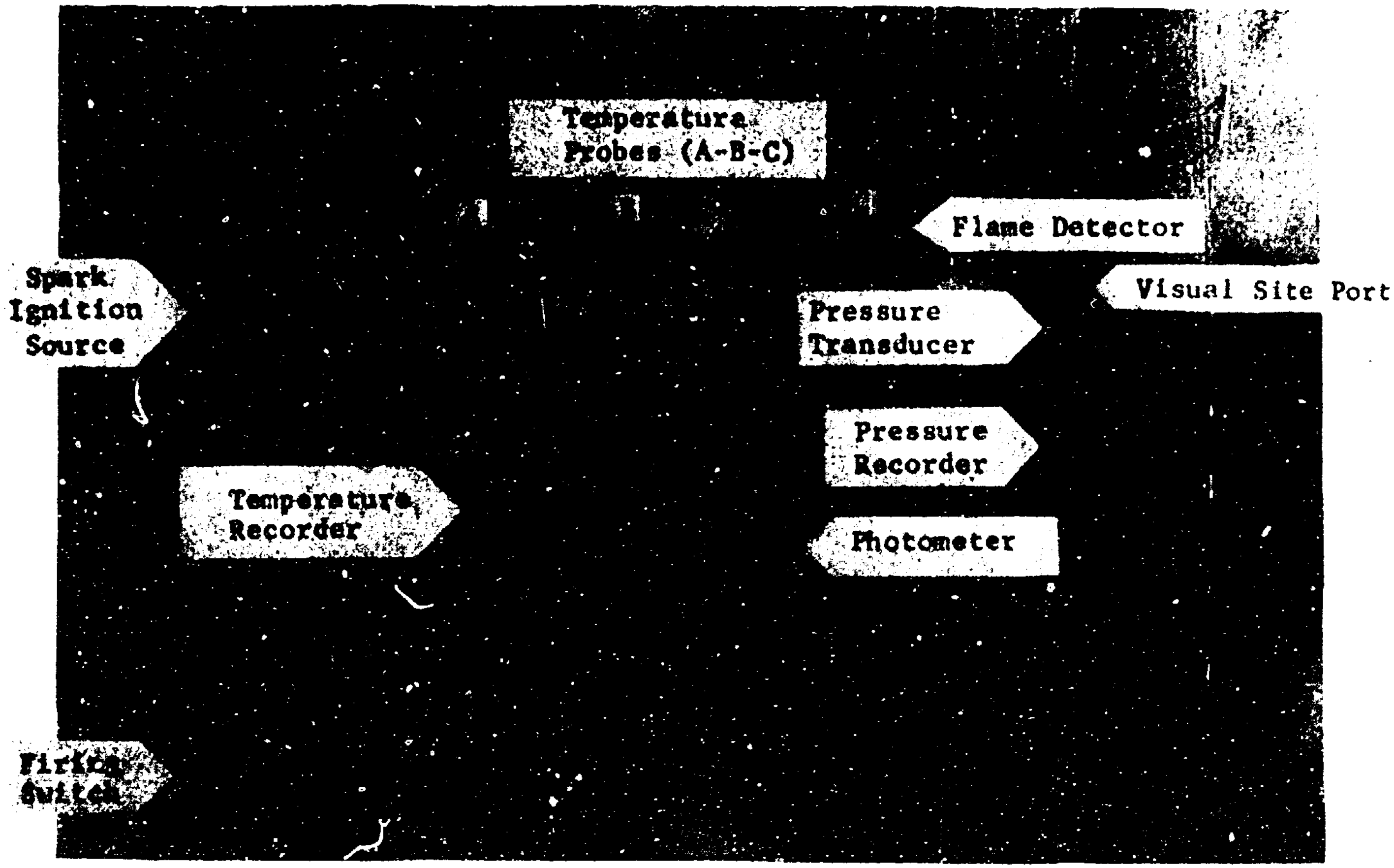


FIGURE 1. - Experimental setup for flame arrestor experiments in a 1 ft^3 cylindrical steel vessel (6" ID x 60" length).

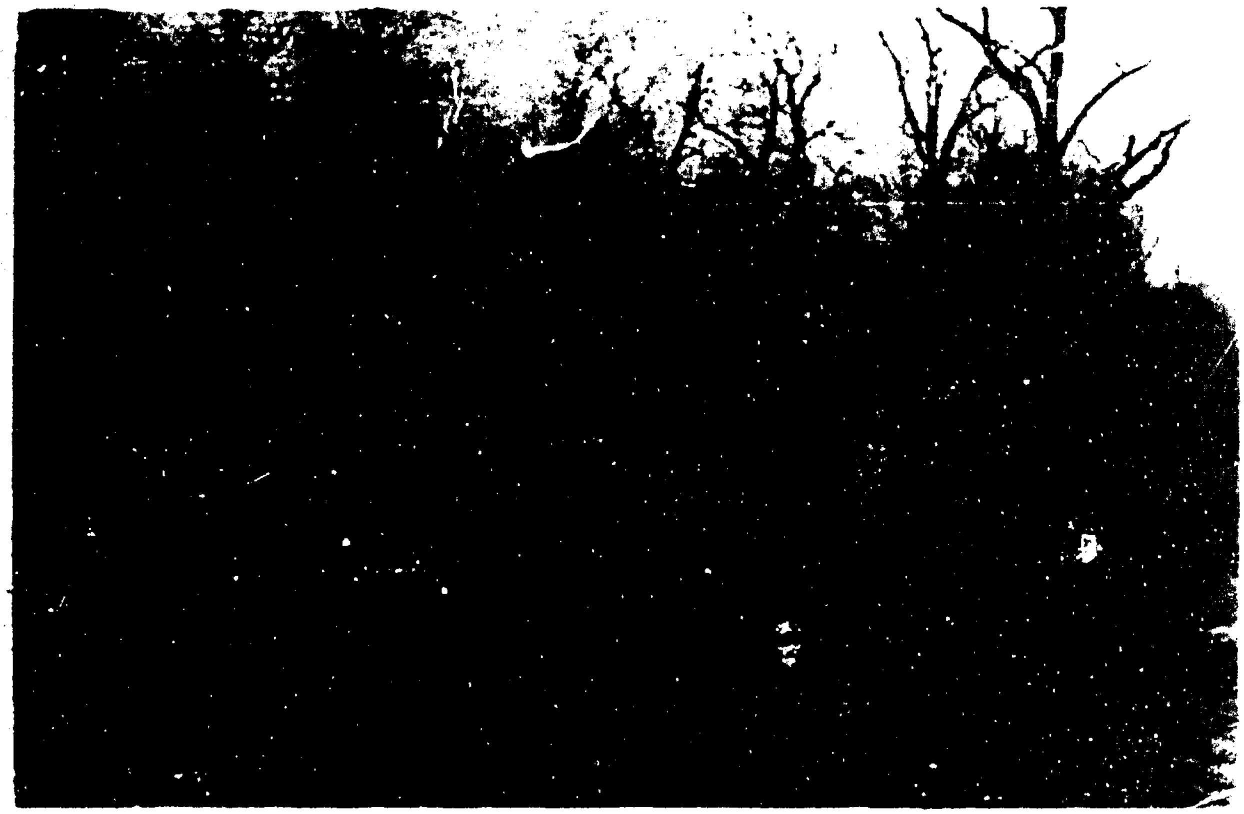


FIGURE 2. - 450 gallon aircraft fuel tank (60 ft^3 volume, 21 ft long and 27 inches maximum diameter).

RESULTS AND DISCUSSION

1. Small-Scale Experiments With Polyurethane Foam Materials in 6-inch Diameter Vessel: Spark Ignition Source

Data obtained in the 6-inch diameter cylindrical vessel showed that the flame arrestor performance of the dry reticulated foam depended on such variables as the arrestor length, flame run-up distance (ignition void length), fuel-air ratio, and the initial temperature and pressure of the combustible gas mixture. The effect of arrestor length (ℓ_2) was determined at a constant ignition void length (ℓ_1) of 18 inches with dry arrestor segments and ~ 2.5 volume percent n-pentane-air mixtures at atmospheric pressure and ambient temperature. The experimental results obtained for the 20 pore/inch foam are compared with data previously reported for the 10 pore/inch material and shown in table 1 and figure 3. As noted, the maximum pressure rises obtained in the flame propagations with the 20 pore/inch material were relatively low and varied from about 6 to 11 psi over the range of arrestor lengths investigated from ℓ_2 = 30 in. to 3 in.; maximum pressure rises of at least 85 psi were obtained without the arrestor material present. Also, any arrestor burning that resulted was confined to the upstream end of the arrestor where the gas mixture was ignited. In comparison, the 10 pore/inch material was effective only at ℓ_2 values equal to or greater than 9 inches; at lower ℓ_2 values, the maximum pressure rises were over 40 psi and flame propagated through the arrestor segments. Since the ℓ_2/ℓ_1 (30"/18") ratio of 1.67 gave the lowest pressure rises in these experiments, it was selected for most of the other determinations, except for those where the ignition void length (ℓ_1) was varied. It was also observed in similar experiments that no noticeable pressure rise or flame propagation occurs with the explosion vessel fully packed ($\ell_2/\ell_1 = \infty$) with the 20 pore/inch material; this was observed at 0 and 10 psig initial pressure.

The effect of combustible gas mixture pressure on flame arrestor effectiveness was examined with 10, 20, and 40 pore/inch dry foam at the ℓ_2/ℓ_1 ratio of 1.67 and initial pressures from 0 to 15 or more psig. The pressure rise data obtained with the different pore sizes are compared in table 2 and figure 4. Figure 4 shows that the pressure rises increased with increasing initial mixture pressure for each of the materials used. As noted, the 10 pore/inch material was least effective as a flame arrestor here and failed at initial pressures greater than 0 psig. In comparison, the 40 pore/inch material was effective at pressures up to 25 psig, the maximum that was used; the pressure rises varied from 5.4 to 22.8 psi over the range of test pressures and no flame or arrestor burning was observed on the downstream end of the arrestor (table 2). The 20 pore/inch material gave intermediate results and was effective in preventing flame propagation at initial pressures equal to or less than 15 psig. Failure of this arrestor at 20 psig was associated with secondary pressure rises after the main ignition event; these presumably resulted from ignitions in the downstream void (ℓ_3) by the hot gaseous products from the ignition void (ℓ_1). Such secondary ignitions were not always reproducible. This can be partly attributed to differences in pore size since the porosity of the 20 pore/inch material could vary ±5 pores according to the vendor's specifications.

TABLE 1. - Flame Arrestor Data for 10 and 20 pores/inch Polyurethane Foam Materials From Experiments in a 6-inch Diameter Cylindrical Steel Vessel With ~2.5 Percent n-Pentane-Air Mixtures at Atmospheric Pressure.

ℓ_1 = 18 inches

Arrestor Length, ℓ_2 inches	ℓ_2/ℓ_1	Pressure Rise, psi	Appearance of flame in ℓ_3 void	Arrestor Burning
		Material A (20 pores/inch)		
3	0.17	10.7	No	Upstream end - 1/8"
3	0.17	9.5	No	Upstream end - 2-3/4"
6	0.33	11.4	No	Upstream end - 1-1/2"
9	0.5	8.5	No	Upstream end - 3/4"
18	1.0	7.4	No	Upstream end - 3/4"
30	1.67	6.3	No	Upstream end - 3/4"
		Material A (10 pores/inch)		
3	0.17	58.9	Yes	Downstream end - 2"
4.5	0.25	46.6	Yes	Downstream end - 2-1/2"
6	0.33	42.8	Yes	Downstream end - 2-1/2"
9	0.5	7.3	No	Upstream end - 1/8"
15	0.83	7.8	No	Upstream end - 1/8"
18	1.0	7.0	No	Upstream end - 1/2"
30	1.67	5.9	No	Upstream end - 1/2"

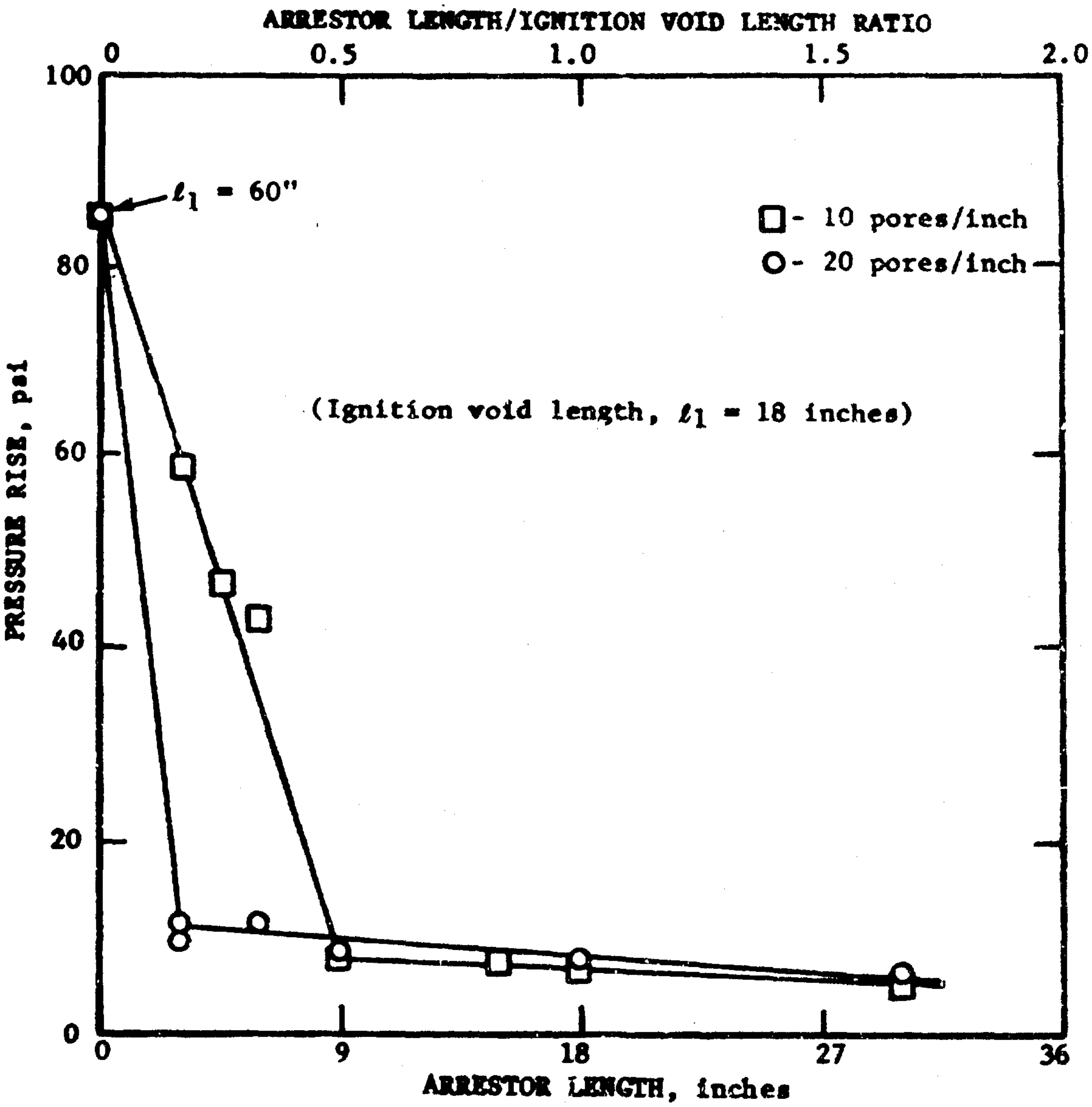
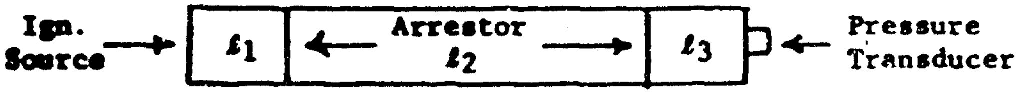


FIGURE 3. - Effect of arrestor length on pressure rise in experiments with 10 and 20 pore/inch arrestor material A and ~2.5 percent n-pentane-air mixtures at 0 psig; 1 ft^3 cylindrical steel vessel (6" diameter and 60" length).

TABLE 2. - Flame Arrestor Data for 10, 20 and 40 pores/inch Polyurethane Foam Materials From Experiments in a 6-inch Diameter Cylindrical Steel Vessel With ~2.5 Percent n-Pentane-Air Mixtures at Various Initial Pressures.



ℓ_1 = 18 inches, ℓ_2 = 30 inches, ℓ_2/ℓ_1 = 1.67

Init. Press., psig	Calc.[1/] Press.Rise, psi	Exptl. Press.Rise, psi	Appearance[2/] of Flame in ℓ_3 void	Arrestor Burning
		Material A (40 pores/inch)		
0	25.6	5.4	No	Upstream end - 1/8"
5	34.3	7.3	No	Upstream end - 1/4"
10	42.9	9.7	No	Upstream end - 3/4"
15	51.6	13.1	No	Upstream 3nd - 2"
20	59.8	15.2	No	Upstream end - 2"
25	68.3	22.8	No	Upstream end - 2-1/2"
		Material A (20 pores/inch)		
0	25.6	6.3	No	Upstream end - 3/4"
0	25.6	7.8	No	Upstream end - 1/2"
5	34.3	7.8	No	Upstream end - 1/8"
10	42.9	10.2	No	Upstream end - 2-1/2"
10	42.9	11.2	No	Upstream end - 3"
10	42.9	18.0	No	Upstream end - 4"
15	51.6	15.1	No	Upstream end - 1"
15	51.6	18.4	No	Upstream end - 1-1/4"
20	59.8	42.8	Yes	Downstream end - 7-1/2"
20	59.8	43.3	Yes	Downstream end - 7"
20	59.8	48.6	Yes	Downstream end - 9"
		Material A (10 pores/inch)		
0	25.6	5.9	No	Upstream end - 1/2"
5	34.3	16.0	Yes	Downstream end - 1"
10	42.9	28.0	Yes	Downstream end - 1-1/2"
15	51.6	58.6	Yes	Downstream end - 1-1/2"

1/ Corresponds to expected pressure rise for combustion of gas only in the ignition void length, ℓ_1.

2/ Observations made visually and by flame sensors (thermocouple or photo-volt multiplier).

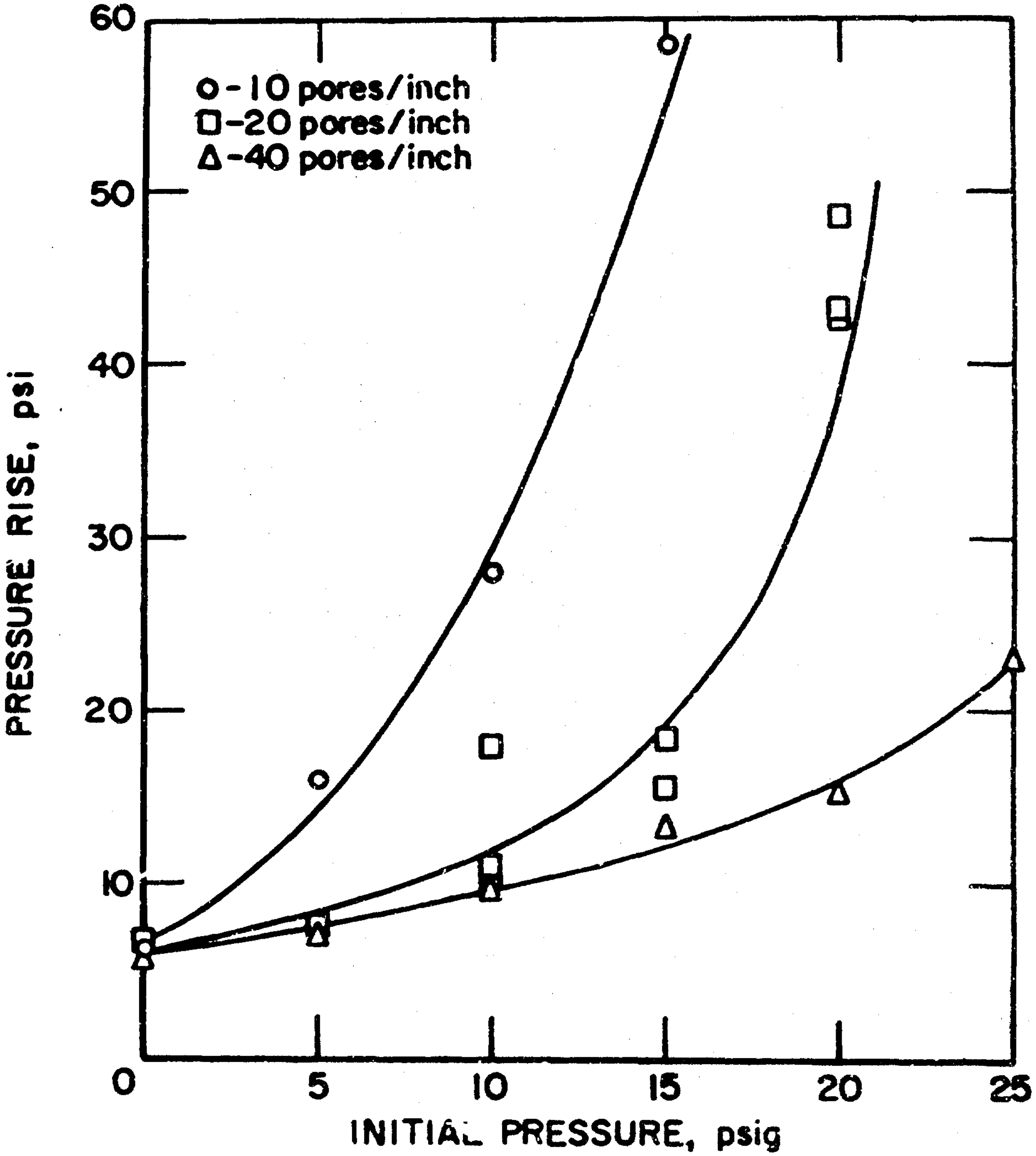


FIGURE 4. - Effect of initial pressure on pressure rise in experiments with 10, 20 and 40 pores/inch arrestor material and ~2.5 percent n-pentane-air mixtures. Arrestor length/ignition void length = 30"/18"; 1 ft^3 cylindrical steel vessel (6" diameter and 60" length).

Since an arrestor material in a fuel tank can be wet or dry, it is important to know its effectiveness under both conditions. Figure 5 compares the pressure rise data obtained at various initial pressures for the 20 pore/inch dry foam and the same foam previously soaked in kerosine; the ℓ_2/ℓ_1 ratio was 1.67. These results show that the wet arrestor model was effective in quenching flame propagation over the entire range of test pressures, 0 to 20 psig. Also, at initial pressures above 10 psig, its effectiveness was greater than that found with dry arrestors of the same material. With more volatile fuels than kerosine, the effectiveness of the dry or wet arrestor materials would be expected to be equal to or greater than that shown here, since nonflammable mixtures (fuel-rich) would be possible.

The effectiveness of the 20 pore/inch foam did not vary greatly with increased temperature (75° to 200°F) at initial mixture pressures from 0 to 10 psig. Generally, the effect of increased temperature was less than that of increased mixture pressure. Figures 6 and 7 show the variation of the pressure rise with initial pressure that was observed in experiments with the 10 and 20 pore/inch materials, respectively, at the constant ℓ_2/ℓ_1 ratio of 1.67. At pressures greater than 10 psig, the pressure rise data displayed greater variation with temperature but were not entirely consistent. The overall effectiveness of the 20- or the 10-pore/inch materials at the increased temperatures was about equal to or greater than that observed at 75°F. It was also observed that the foam displays a measurable amount of shrinkage at temperatures slightly above 200°F, resulting in a decrease in pore diameter; thus, flame propagation could be retarded noticeably in those areas of the foam where a significant amount of shrinkage occurs because of the increased temperatures.

Other flame arrestor experiments were initiated with the 20 pore/inch foam material to obtain data on various arrestor-void configurations for possible use in internal (integral) fuel-tank applications. Cylindrical arrestor segments, 2, 4, and 9 inches long (ℓ_2), were used in the 6-inch diameter vessel and the ignition void length (ℓ_1) was varied from 2 to 36 inches. The experimental arrangement was the same as in the previous experiments. Figure 8 shows the pressure rises measured in these experiments for various ignition void lengths at ambient temperature and atmospheric pressure. At ignition void lengths up to 12 inches, the pressure rises were less than 5 psig for the three arrestor sizes employed, and none of the arrestors failed to prevent flame propagation. The critical ℓ_1 values above which the arrestors failed were 12 inches ($\ell_2/\ell_1 = 0.17$) for the 2-inch segments, 24 inches ($\ell_2/\ell_1 = 0.17$) for the 4-inch segments, and 27 inches ($\ell_2/\ell_1 = 0.33$) for the 9-inch segments. Thus, the critical ℓ_2/ℓ_1 ratio for arrester failure does not appear to be a constant for such packing configurations.

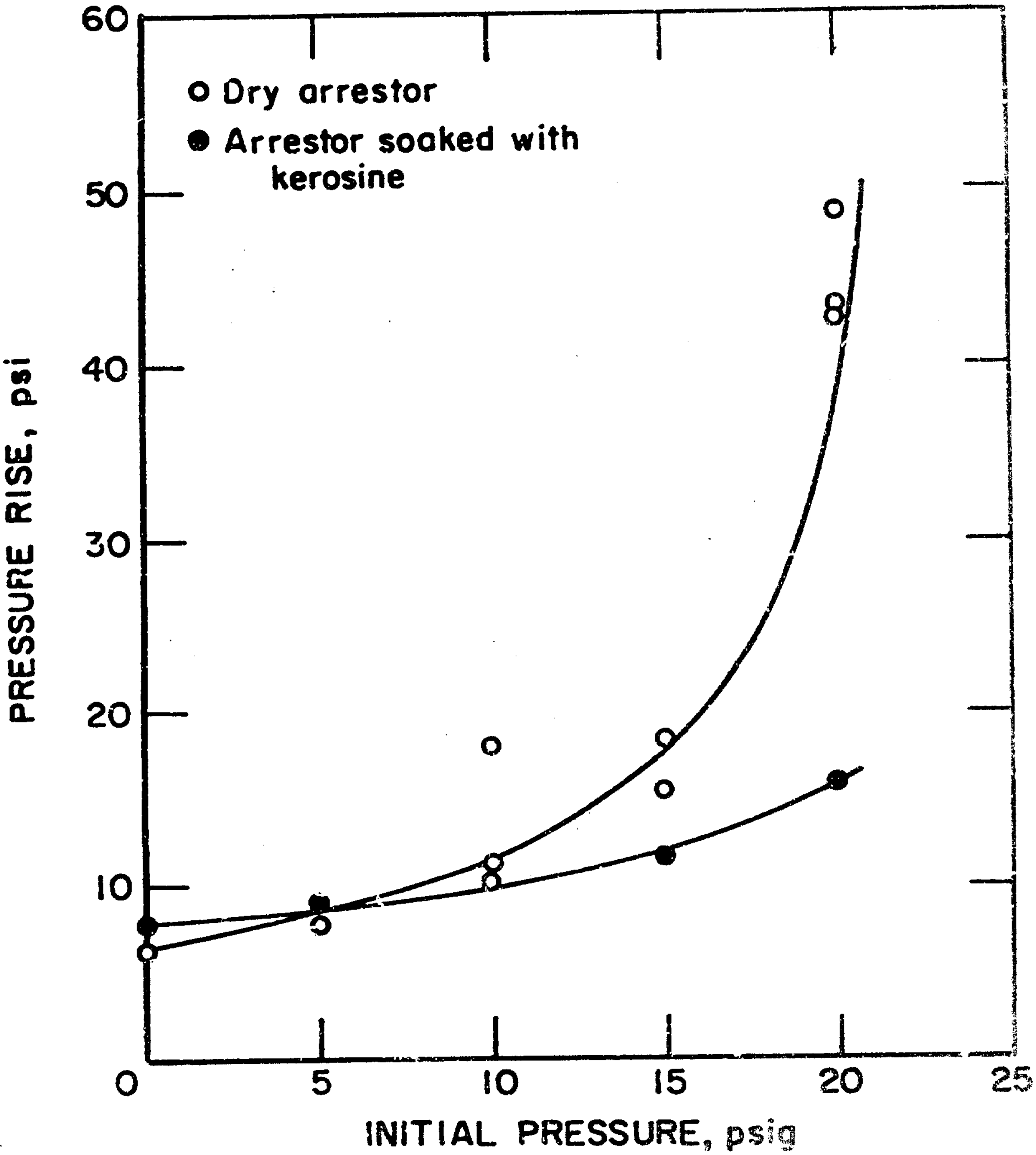


FIGURE 5. - Effect of initial pressure on pressure rise in experiments with wet and dry arrestor material A (20 pores/inch) and ~2.5 percent n-pentane-air mixtures. Arrestor length/ignition void length = 30"/18"; 1 ft^3 cylindrical steel vessel (6" diameter and 60" length).

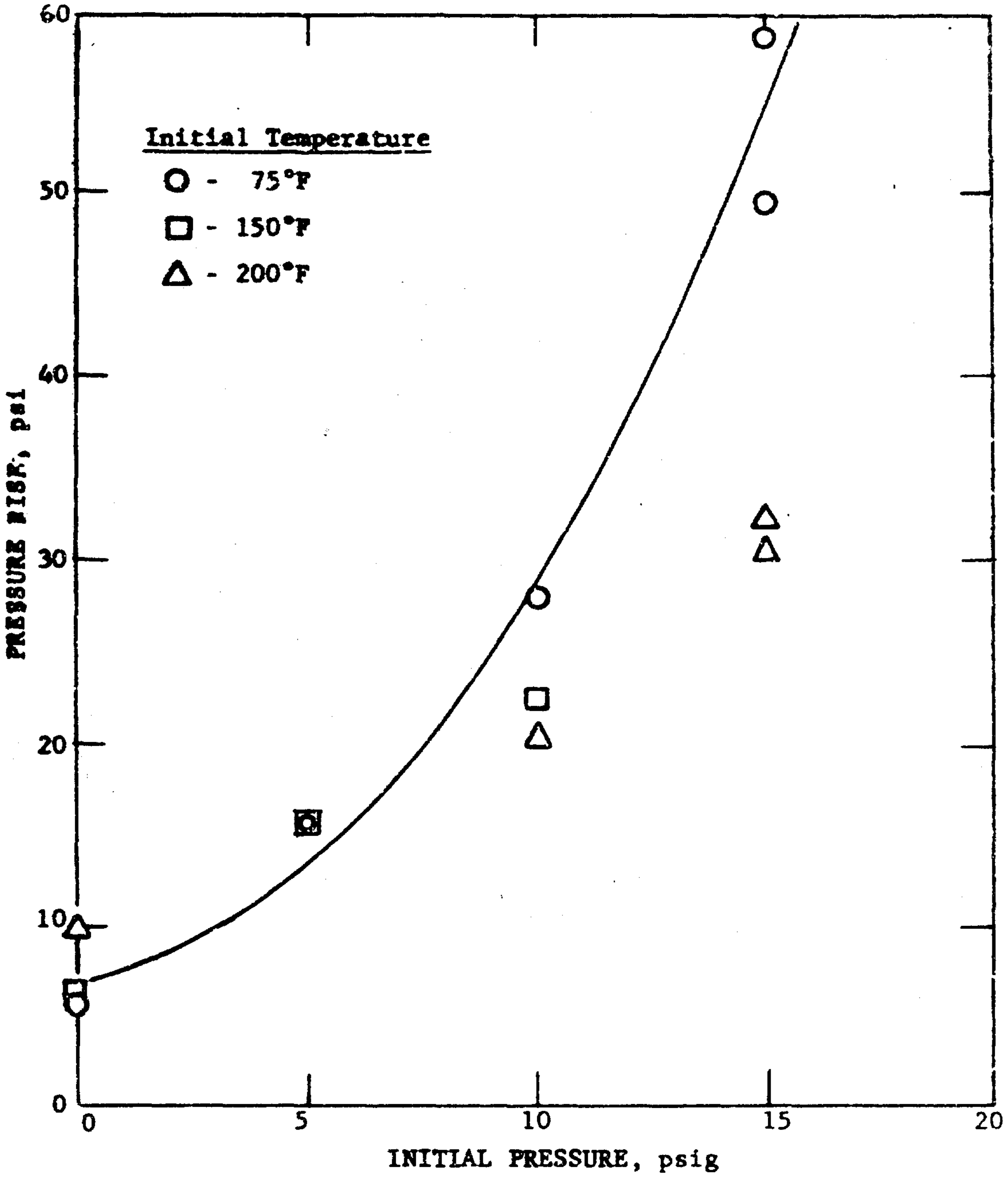


FIGURE 6. - Pressure rise vs initial pressure for experiments with arrestor material A (10 pores/inch) and ~2.5 percent n-pentane-air mixtures at various initial temperatures. Arrestor length/ignition void length = 30"/18"; 1 ft^3 cylindrical steel vessel (6" diameter and 60" length).

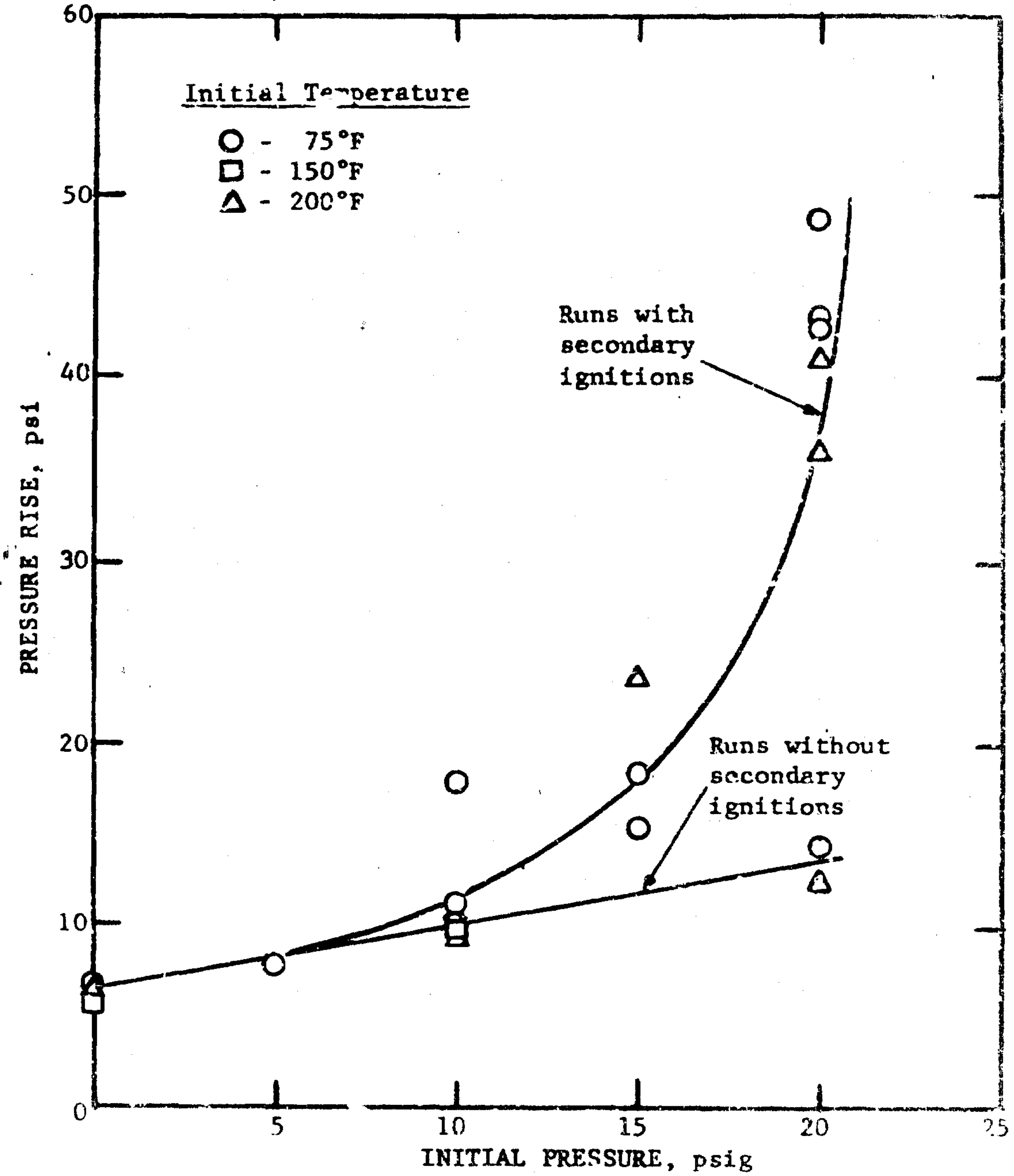


FIGURE 7. - Pressure rise vs initial pressure for experiments with arrestor material A (20 pores/inch) and ~2.5 percent n-pentane-air mixtures at various initial temperatures. Arrestor length/ignition void length = 30"/18"; 1 ft^3 cylindrical steel vessel (6" diameter and 60" length).

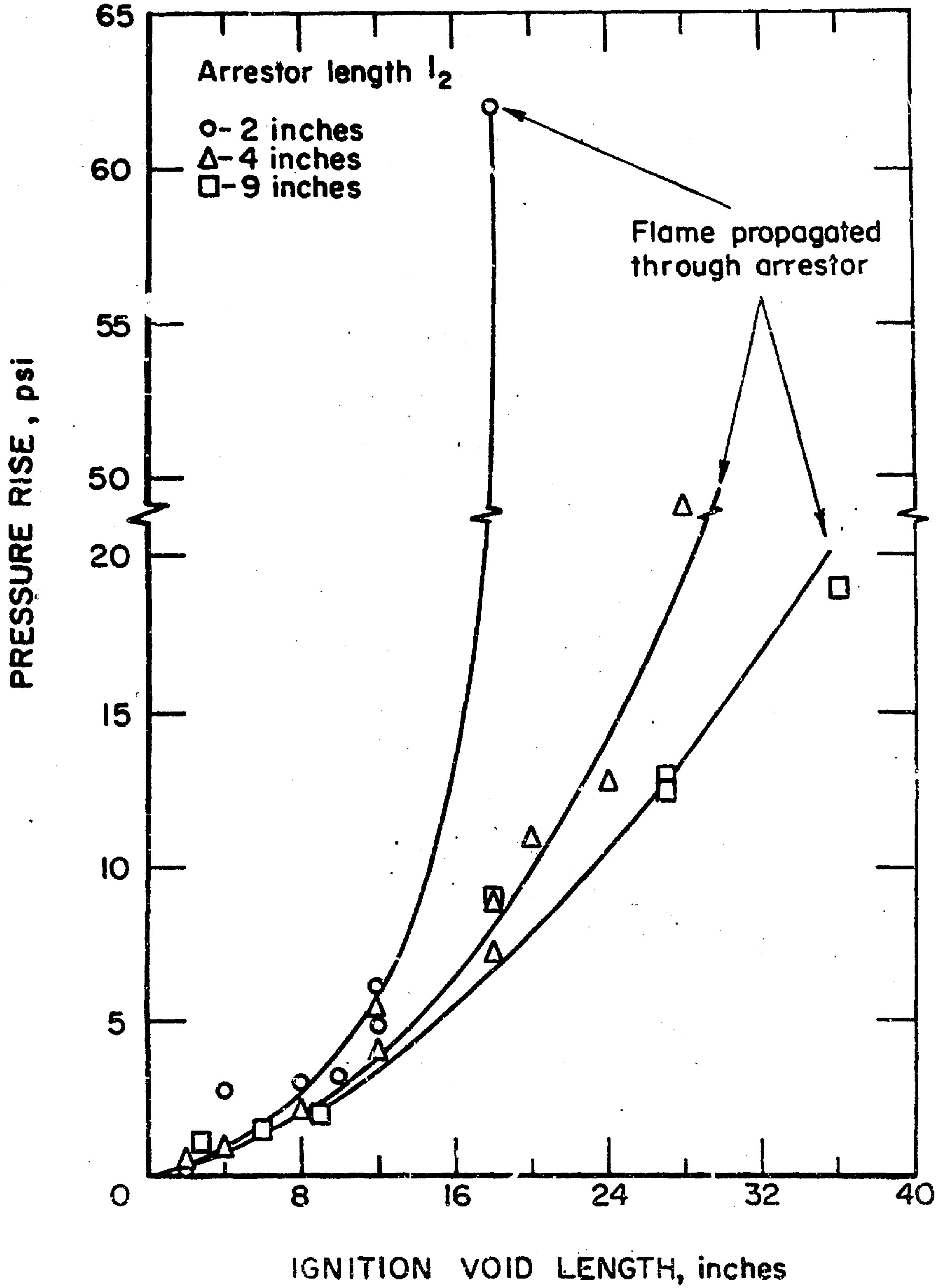


FIGURE 8. - Effect of ignition void length on pressure rise in experiments with 2, 4, and 9-inch segments of the 20 pores/inch arrestor material A and ~2.5 percent n-pentane-air mixtures at atmospheric pressure; 1 ft^3 cylindrical steel vessel (6" diameter and 60" length).

In similar trials with multiple arrestor segments, 2 or 4 inches long, the effect of introducing a gap between arrestor segments was also investigated. Here, the ignition void (ℓ_1) was between two arrestor segments so that voids were located on both ends of each segment. The data from these experiments were comparable to those obtained using only a single arrestor segment at ignition void lengths from 2 to 12 inches; the pressure rises were less than 5 psi for both the 2 and 4-inch segments. Although these data are incomplete, it appears that "cored" arrestor models with gross voids, approximately 6 inches in diameter by 12 inches long, will require arrestor walls with a minimum thickness of 2 to 4 inches to be effective for fire protection in internal fuel-tank applications. Additional work is required on the effectiveness of other arrestor packing configurations and on scaling to determine the optimum arrestor design for such applications.

2. Full-Scale Experiments With Polyurethane Foam Materials in 450-Gallon Fuel Tanks: Spark Ignition Source

Experiments in the 450-gallon (60 ft^3) aircraft fuel tank were conducted with the 20 pore/inch polyurethane foam using near-stoichiometric mixtures of n-butane and air, instead of n-pentane and air, to avoid possible fuel condensation. The experimental arrangements used in the first two experiments (46.5 percent gross void, $\ell_4/\ell_3 = 1.29$) are shown in figure 9; here, ℓ_4 represents the length of the middle arrestor section and ℓ_3 the length of the ignition void between the nose and middle arrestor sections. These experiments were conducted at ambient temperature (70° ± 10°F) and 0 and 5 psig mixture pressures. An electric spark ignition source was located near the middle of the gross void space ℓ_3 as shown in figure 9. This figure also indicates the extent of burning that resulted to the three arrestor sections located in the nose (ℓ_2), middle (ℓ_4), and tail (ℓ_6) of the tank. The data obtained from gas temperature rise and pressure rise measurements are summarized in table 3.

The maximum pressure rises observed in the above experiments at 0 and 5 psig initial pressure were 4.6 and 11.8 psi, respectively. Under similar experimental conditions, a pressure rise of 9.4 psi was previously obtained for the 10 pore/inch foam material at 0 psig initial pressure (Ref 1); with this pore size, secondary ignitions occurred with gross voids of 46.5 and 38.1 percent. The pressure-time traces obtained in the present experiments (Test No. 1, 0 psig and Test No. 2, 5 psig) are shown in figure 10. According to these records, the initial pressure rises that occurred varied only slightly and were between 3.7 and 4.6 psi; also, their initial rates of pressure rise, equal to or less than 31 psi/sec, were low compared to those found in most gas ignitions. No secondary ignitions were observed in the experiment at 0 psig. However, in the one at 5 psig, secondary ignition did occur and the final maximum pressure that developed was close to 12 psi.

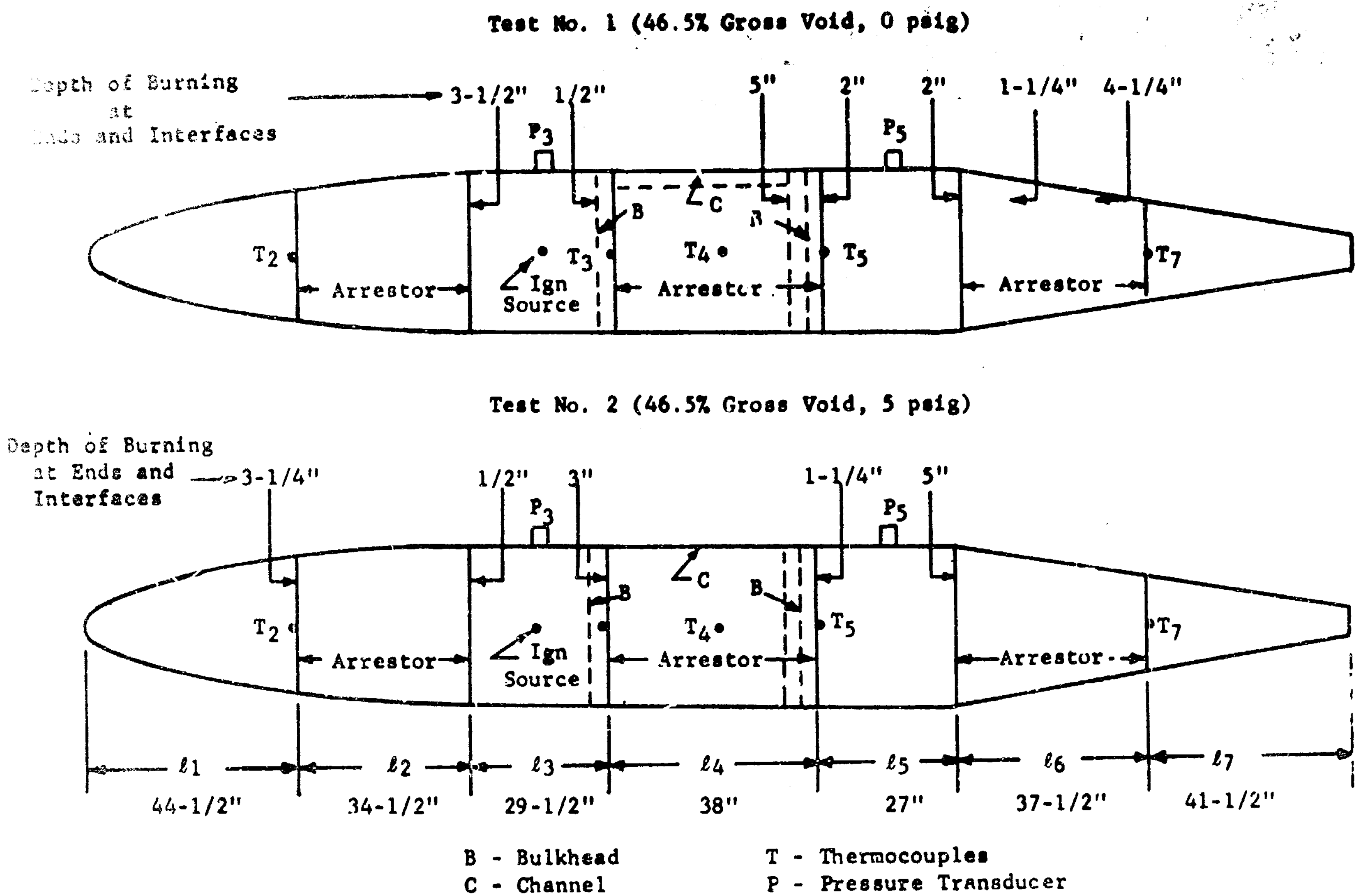


FIGURE 9. - Arrangement for full-scale experiments with flame arrestor material (20 pore/inch) and ~3.2 percent n-butane-air mixtures at 0 and 5 psig in 450-gallon aircraft fuel tank (27 inches maximum diameter); spark ignition source.

TABLE 3. - Gas Temperature, Pressure, and Flame Speed Data From Flame Arrestor Experiments in a 450-Gallon Aircraft Tank With ~3.2 Percent n-Butane-Air Mixtures at 0 and 5 psig. (Arrestor Material A - 20 pores/inch)

	Test No. 1 (46.5% Gross Void), 0 psig					Test No. 2 (46.5% Gross Void), 5 psig				
Thermocouple Station	T_2	T_3	T_4	T_5	T_7	T_2	T_3	T_4	T_5	T_7
Distance from ign. point, inches	49.5	14.5	37	52.5	117	49.5	14.5	37	52.5	117
Peak temp., °F	None	>2100	830		None	>120	>1400	None	>1400	None
Time of initial temp. rise, sec.	--	0.1	0.4		--	0.45	0.1	--	0.53	--
Flame speed, ft/sec	--	12.5	6.2		--	9.2	12.5	--	8.3	--

	Test No. 1		Test No. 2	
Pressure Transducer Station	P_3	P_5	P_3	P_5
$\Delta P_{initial}$, psi	4.1	4.6	3.7	3.9
Time to peak pressure, sec.	0.24	0.28	0.2	0.2
Initial rate of pressure rise, psi/sec	27.5	26.1	31.1	28.3
Secondary rate of pressure rise, psi/sec	None	None	9.74	9.8
ΔP_{final}, psi	4.1	4.6	11.6	11.8
Time to peak pressure, sec	--	--	0.86	0.90
Final rate of pressure rise, psi/sec	--	--	35.2	40

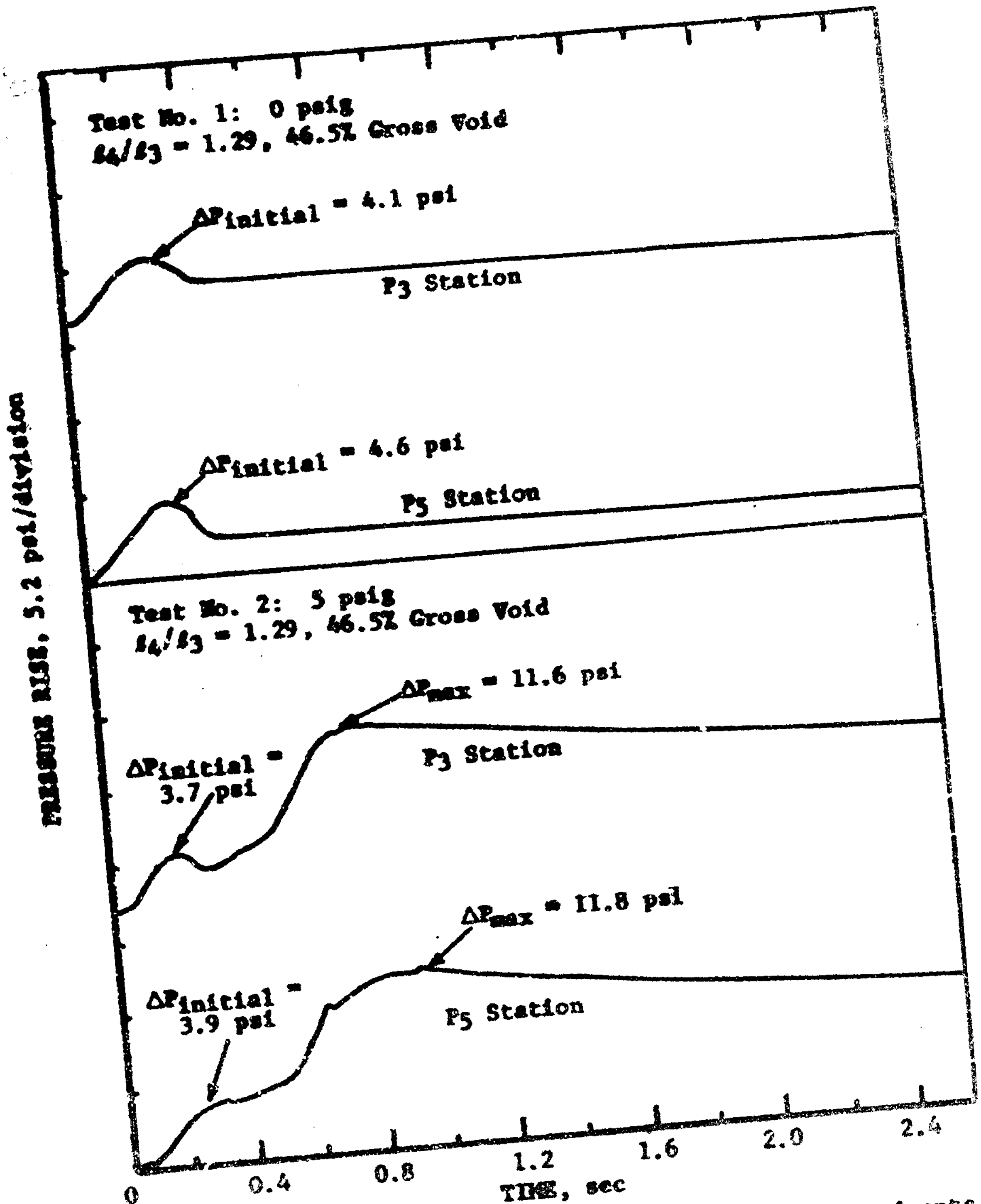


FIGURE 10. - Pressure-time traces for flame arrestor experiments in 450-gallon aircraft fuel tank conducted with ~3.2 percent n-butane-air mixtures at initial pressures of 0 and 5 psig; 20 pore/inch arrestor material (4).

According to the gas temperature and flame speed measurements in table 3, the data at 0 psig initial pressure indicated that flame (or hot gases) propagated through the cylindrical arrestor section ℓ_4, but was quenched in the nose (ℓ_2) and tail (ℓ_6) arrestor sections. Similar data obtained at 5 psig revealed that flame propagated through the ℓ_2 and ℓ_4 arrestor sections, but not through the tail section which was farthest from the ignition void (ℓ_3). Generally, any arrestor burning that occurred tended to be more noticeable at or near the arrestor faces (figure 9). Maximum flame speeds were not over 12.5 ft/sec and these were found in the ignition void. In comparison, they were as high as 25 ft/sec in the earlier experiments with the 10 pore/inch material at 0 psig; also, the maximum values were obtained in the nose or tail sections of the fuel tank (Ref 1).

In another full-scale experiment (Test No. 3), the arrestor material was arranged as shown in figure 11 to allow a gross void of 40 volume percent. For this trial, five void spaces were used as compared to four in the above experiments. With this packing configuration, the possibility of flame propagating alongside a longitudinal channel (C in mid-section, figure 11) within a foam-filled section was reduced. Ignition of the combustible mixture was effected by an electrical spark ignition source located in the bulkhead space of the tank; here, the arrestor length/ignition void length ratios of ℓ_4/ℓ_5 and ℓ_6/ℓ_5 were held constant at 1.58. Table 4 summarizes the data obtained at an initial pressure of 0 psig. With this packing arrangement, flame propagated only through the cylindrical arrestor section ℓ_4 and was quenched after traveling part way through the arrestor sections ℓ_2 and ℓ_6 (figure 11); maximum flame speed in the ignition void was 12.8 ft/sec. As noted in table 4, flame was not detected in the ℓ_1 (nose), ℓ_9 (tail), and ℓ_7 voids of the tank. It is also important to note that the maximum temperature rise measured at one station T_4 occurred approximately 5 minutes after the ignition source was fired. Apparently, a hot gas ignition occurred about this time and resulted in the fire damage that occurred on the upstream end of the nose arrestor section (ℓ_2). Nevertheless, the maximum pressure rises were not over 1.5 psi. Thus, the arrestor configuration used in this experiment appears to be much more favorable for partially packed fuel tank applications than the one used in Tests No. 1 and No. 2.

Since an aircraft fuel tank may be purged with air during flight as a normal operation or as a result of gunfire, a full-scale experiment (Test No. 4) was conducted in the 450-gallon fuel tank to determine the flame arrestor performance of the 20 pore/inch foam material with the addition of air following ignition of the combustible mixture. This experiment was performed at an initial mixture pressure of 0 psig. The arrestor packing configuration, shown in figure 12, was the same as that used in Test No. 3 with fuel wetted foam, soaked in kerosine. To simulate a flow condition which may be encountered in practice, air at a flow rate of 15.2 SCFM was introduced through a 3/8-inch diameter inlet in the nose of the tank within 2 seconds after igniting the combustible mixture; ignition was effected in the ℓ_5 gross void space of the tank with an electrical spark energy source. The air was discharged at a sonic velocity through a 3/8-inch diameter outlet at the tail of the tank.

TABLE 4. - Gas Temperature, Pressure, and Flame Speed Data From Flame Arrestor Experiments in a 450-Gallon Aircraft Fuel Tank With a ~ 3.2 Percent n-Butane-Air Mixture at 0 psig. (Arrestor Material A - 20 pores/inch)

Test No. 3 (40% Gross Void, 0 psig)

Thermocouple Station	T_2	T_4 1/	T_5	T_5'	T_6	T_8
Distance from ign. point, inches	104.75	44.75	10.75	10.75	44.75	104.75
Peak temp., °F	None	≥2100	≥1700	>1700	None	None
Time of initial temp. rise, sec	--	--	0.07	0.07	--	--
Flame speed, ft/sec	--	--	12.8	12.8	--	--

Pressure Transducer Station	P_3	P_5
$\Delta P_{initial}$, psi	1.5	1.5
Time to peak pressure, sec	0.16	0.16
Initial rate of pressure rise, psi/sec	14.9	16.9
ΔP_{max}, psi	1.5	1.5

1/ Temperature rise occurred approximately 5 minutes after ignition.

Test No. 3 (40% Gross Void, 0 psig)

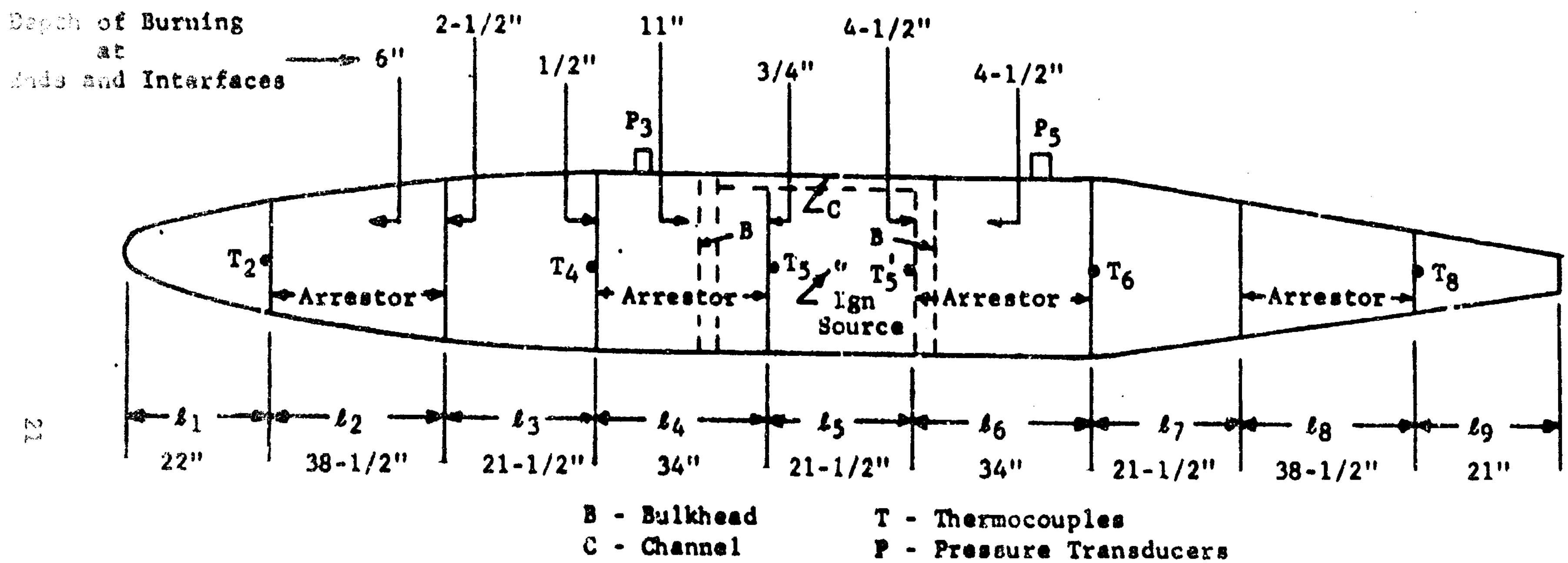


FIGURE 11. - Arrangement for full-scale experiment with flame arrestor material (20 pore/inch) and ~3.2 percent n-butane-air mixture at 0 psig in 450-gallon aircraft fuel tank (27 inches maximum diameter); spark ignition source.

Test No. 4 (40% Gross Void, 0 psig)

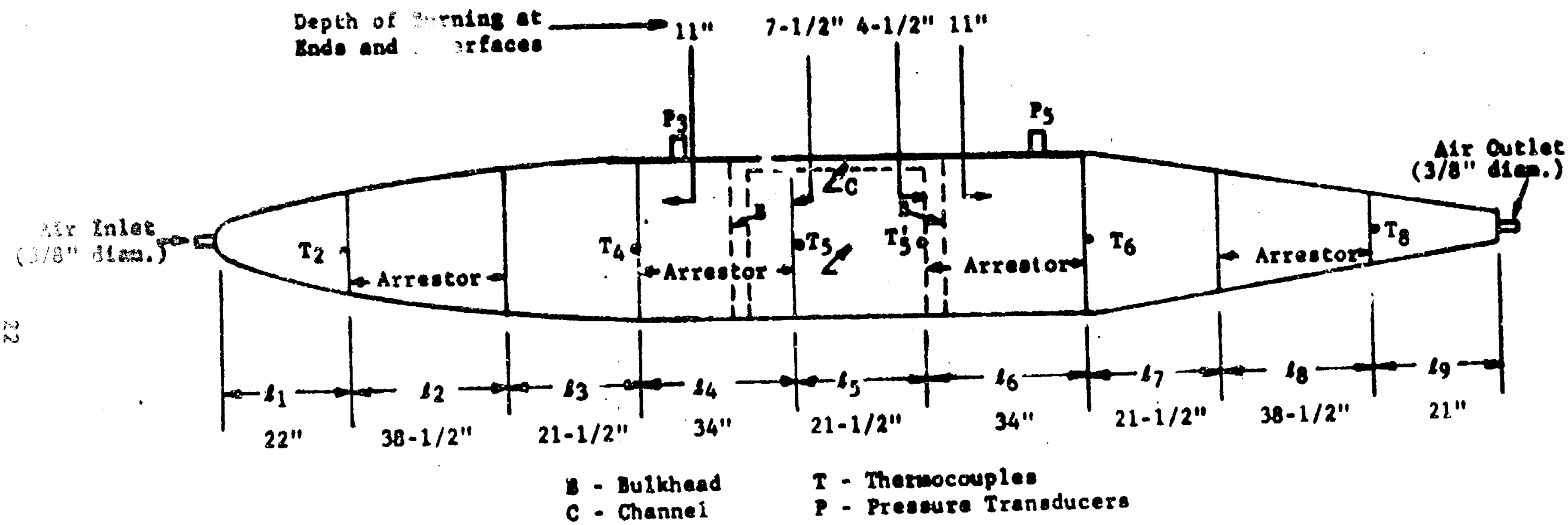


FIGURE 12. - Arrangement for full-scale experiment with flame arrestor material (20 pores/inch) and ~3.2 percent n-butane-air mixture at 0 psig in a 450-gallon aircraft fuel tank (27 inches maximum diameter). Spark ignition with subsequent addition of air at a flow rate of 15.2 SCFM.

The maximum pressure rise (1.9 psi) due to ignition was not much higher than that previously observed in Tests No. 1 through 3. Following the ignition and the addition of air, the tank pressure increased to 14.4 psig at the P_3 station and to 12.6 psig at the P_5 station. Approximately 3.8 minutes after ignition a tank patch ruptured and the test was terminated about 5 minutes after ignition. Arrestor burning contributed little to the total pressure developed. Flame sensors and a visual examination of all the arrester sections revealed that the arrestor burning that occured was confined to arrestor sections ℓ_4 and ℓ_6; nearly 33 inches of the ℓ_4 arrestor segment burned as compared to only 15-1/2 inches for the ℓ_6 segment. External skin temperatures were maximum ($\leq$ 300°F) in this area but there was no visual evidence of metal failure. The extent of arrestor burning in the ℓ_4 and ℓ_6 sections was noticeably greater in this test than that observed in Test No. 3, which was conducted without air flow. However, in the latter test, a secondary or hot gas ignition had also occurred in the ℓ_3 gross void at approximately 5 minutes after firing. The results observed under the two different test conditions are not totally unexpected. The possibility of hot gas ignitions should tend to be reduced when the combustible vapor-air mixtures present are diluted by the addition of air and vented from the tank. At the same time, the fire hazard associated with arrestor burning should tend to be greater with the addition of air, as observed here, depending upon the rates at which the air is supplied and the combustion products are vented.

3. Small-Scale Gun Firing Experiments in 5-Gallon Steel Containers

Small-scale gun firing experiments were performed in 5-gallon steel containers, 11 inches in diameter and 0.018-inch thick walls, to determine the general firing conditions required to ignite near-stoichiometric mixtures of n-butane and air using 30 caliber tracer and incendiary ammunition. The ammunition was fired with an Army M-1 rifle. Ignitions of the combustible mixtures were examined with and without the 20 pore/inch arrestor material at ambient temperature and pressure. The data found in these trials were used to plan the full-scale gun firing experiments in the 450-gallon aircraft fuel tank. In these gun firings, 30 caliber incendiaries (50 grains)*, which have a reported muzzle velocity of approximately 2800 ft/sec, and partially loaded tracers (10 to 15 grains)* with various muzzle velocities (~800 ft/sec for 11-grain tracer) were fired into the containers at a distance of 90 or 150 feet. A summary of the test conditions and the results obtained in these experiments is given in table 5.

With no foam present, the combustible mixture was ignited with the incendiary ammunition at a firing distance of 150 ft, or at 90 ft when a 3/8-inch aluminum striker plate was used inside the container; 10 or 11-grain tracers also gave ignitions at 150 ft. In the other firings with 11-grain tracers at 150 ft, the test mixture also was ignited when the tracers were fired into the gross void of the container partially packed with dry foam (50% gross void); however, no ignitions occurred with wet or dry foam if the firings were made into the foam rather than the void. With the container fully packed with dry foam, no ignitions of gas mixtures were observed with tracers (11 grains) or incendiaries at a firing distance of 150 ft.

* Refers to propellant powder.

TABLE 5. - Results from Gun-Firing Tests With ~3.2 Volume Percent n-Butane-Air Mixtures at Atmospheric Pressure in 5-Gallon Steel Containers.

Rifle - U.S. Army M-1, 30-'06

Test No.	Bullet Type	Amount of Powder, grains	Firing Distance, feet	Muzzle Velocity, ft/sec	Remarks
			Combustible Mixture Only		
1	Tracer	10	90	< 810	No ignition.
2	"	11	90	810 1/	" "
3	"	12	90	> 810	" "
4	"	12	90	"	No ignition. 2/
5	"	15	90	"	" "
6	"	15	90	"	" "
7	"	10	150	< 810	Ignition.
8	"	11	150	810	"
9	"	12	150	> 810	No ignition.
10	Incendiary	50	90	~2800	" "
11	"	50	90	"	Ignition. 2/
12	"	50	150	"	No ignition.
13	"	50	150	"	Ignition.
		Combustible Mixture and Dry Foam (50% Gross Void Volume)			
14	Tracer	11	150	810	No ignition 3/
15	"	11	150	810	Ignition. 4/
		Combustible Mixture and Wet Foam (50% Gross Void Volume)			
16	Tracer	11	150	810	No ignition. 3/
17	"	11	150	810	No ignition. 4/
		Combustible Mixture and Dry Foam (0% Gross Void Volume)			
18	Tracer	11	150	810	No ignition.
19	Incendiary	50	150	~2800	" "

1/ Measured with a chronograph.

2/ A 3/8-inch thick aluminum striker plate was centrally located in the test container.

3/ Ammunition fired into foam.

4/ Ammunition fired into void.

4. Full-Scale Gun Firing Experiments in 450-Gallon Fuel Tank

In the full-scale gun firing experiments, the effectiveness of the 20 pore/inch arrestor material was examined with near-stoichiometric mixtures of n-butane and air which were ignited in various gross void spaces of the 450-gallon (0.063-inch wall) aircraft fuel tank. Both 30 caliber tracer (11 grains) and incendiary (50 grains) ammunition were used as the ignition sources and were fired with the M-1 rifle at a distance of approximately 150 feet. Since multiple ignitions could not be obtained by firing a single projectile of this ammunition, electric spark sources were also used as ignition sources to simulate multiple ignitions that might be encountered in gun firings. Also, some shots were made by firing tracer or incendiary ammunition into an arrestor section instead of into a gross void within the tank. The arrestor packing configuration (40 percent gross void volume) was the same for all the firings and the combustible test mixtures were at ambient temperature and an initial pressure of 0 psig, except for one trial which was made at 5 psig. Instrumentation of the fuel tank for determining the extent of flame propagation was essentially the same as that employed in the other full-scale experiments with spark ignitions.

A summary of the pressure data obtained in each of these experiments is given in table 6. In test No. 1, the firing of a tracer into the ℓ_5 gross void of the fuel tank ignited the combustible gas mixture present, but the flame propagation was quenched by the adjacent dry arrestor sections ℓ_4 and ℓ_6. As noted in figure 13, the amount of arrestor burning was small and was confined to the ℓ_4 and ℓ_6 arrestor sections. The maximum pressure rise was only 1.5 psi; this value is the same as that found in the corresponding full-scale experiments with an electric spark ignition source (table 4). Essentially the same results were also obtained with wet foam and firing the tracer or incendiary ammunition into a gross void (ℓ_3) containing the combustible gas mixture; the foam was previously soaked in kerosine (Test No. 2 and 3).

Firing into the foam itself appears to present somewhat less fire or explosion hazard than firing into the gas-filled voids. In Test No. 4, a tracer was fired into a dry arrestor (ℓ_2) and did not ignite the foam or the combustible gas present. In comparison, an incendiary firing into the foam did produce an ignition (Test No. 5), but the pressure rise (1.3 psi) was not any greater than observed in any of the previous ignitions; flame was detected only in the ℓ_3 void.

Where ignitions occur in more than one location in a fuel tank, the extent of flame propagation will depend upon the time sequence of the ignitions. In Test No. 6, the ignitions effected in two separate gross voids (ℓ_3 and ℓ_5) by use of a tracer and by an electric spark source 2.9 seconds later, resulted in pressure rises of 1.8 psi or less. Here, the spark source ignition

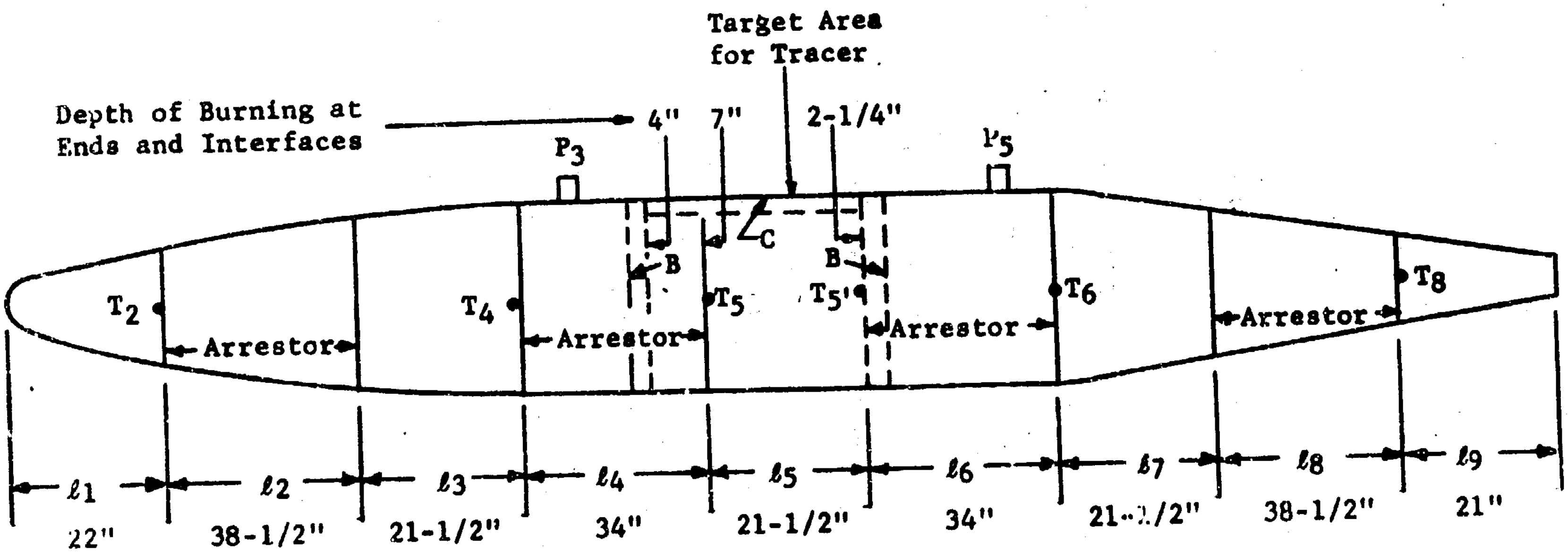
TABLE 6. - **Pressure Data From Flame Arrestor Experiments in 40-Gallon Aircraft Fuel Tank at 0 or 5 psig Using 30-Caliber Tracer and Incendiary Ammunition and Electric Sparks as the Ignition Sources.**

Arrestor Material A (20 pores/inch); ~3.2 n-Butane-Air Mixtures

Test No.	Ignition Source[1] and Location in Tank	Peak Press., psig P_3	Peak Press., psig P_5	Time to Peak Press., sec P_3	Time to Peak Press., sec P_5	Init. Rate of Press. Rise, psi/sec P_3	Init. Rate of Press. Rise, psi/sec P_5	Condition of Foam
1	Tracer into ℓ_5 void	1.5	1.4	0.46	0.41	10.6	9.2	Dry
2	Tracer into ℓ_3 void	1.5		0.05	--	38	--	Wet[2]
3	Incendiary into ℓ_3 void	1.5	1.5	0.13	0.16	20.7	14.1	Wet[2]
4	Tracer into ℓ_2 arrestor	None	None	--	--	--	--	Dry
5	Incendiary into ℓ_2 arrestor	1.3	1.2	0.3	0.3	6.3	4.6	Dry
6	Tracer into ℓ_3 void	0.4	1.8	0.06	0.14	--	15	Dry
	Electric spark in ℓ_5 void (2.9 sec later)	0.4	2.2	3.1	3.1	--	16.5	
7	Electric sparks in ℓ_3 and ℓ_5 voids (Simultaneous firings)	3.8	3.6	0.26	0.26	21.7	--	Dry
8	Incendiary into ℓ_5 void at 5 psig mixture pressure	8.2	8.8	0.05	0.04	87.9	115.7	Dry

1/ Tracer and incendiary ammunition fired ~150 feet from target.
2/ Arrestor material soaked with kerosene.

Test No. 1 (40% Gross Void, 0 psig)



B - Bulkhead
C - Channel

T - Thermocouples
P - Pressure Transducers

FIGURE 13. - Arrangement for full-scale experiment with flame arrestor material (20 pore/inch) and ~3.2 percent n-butane-air mixture at 0 psig in a 450-gallon aircraft fuel tank (27 inches maximum diameter); 30 caliber tracer ignition source.

was probably suppressed greatly by the gaseous products which formed earlier during the tracer ignition in an adjacent void. By firing the ignition sources simultaneously, the pressures developed were higher. A pressure rise of 3.8 psi was obtained in Test No. 7 in which electric spark ignitions were effected simultaneously in the same two gross voids (ℓ3 and ℓ5) referred to in Test No. 6. Nevertheless, as noted in figure 14, the flame propagation was quenched by the foam arrestor sections (ℓ2, ℓ4, and ℓ6) adjacent to the voids where the ignitions were initiated; also, any arrestor burning was largely confined to the arrestor faces in the ignition voids. Accordingly, the arrestor packing configuration used here with the 20 pores/inch foam material appears to be effective for single and multiple (2) ignitions which may result from gun firings into fuel tanks at an initial pressure of 0 psig. The 20 pore/inch dry foam was also effective as a flame arrestor at an initial combustible mixture pressure of 5 psig. The packing configuration and gross void volume (40 percent) was the same as that employed in the firings at 0 psig. In this particular run, ignition was initiated in the ℓ5 gross void space of the tank with a 30 caliber incendiary. The pressure rise data are summarized in table 6 and show that the maximum pressure rise that developed upon ignition was 3.3 psi as compared to 1.5 psi that was obtained at 0 psig with single firings of tracer or incendiary ammunition. In addition, flame did not propagate into the ℓ3 and ℓ7 gross void spaces of the tank, although the two arrestor sections (ℓ4 and ℓ6) adjacent to the ignition void burned to a depth of 33 and 18 inches, respectively. These results appear to indicate that the foam would probably fail at initial pressures noticeably above 5 psig using the above arrestor packing configuration.

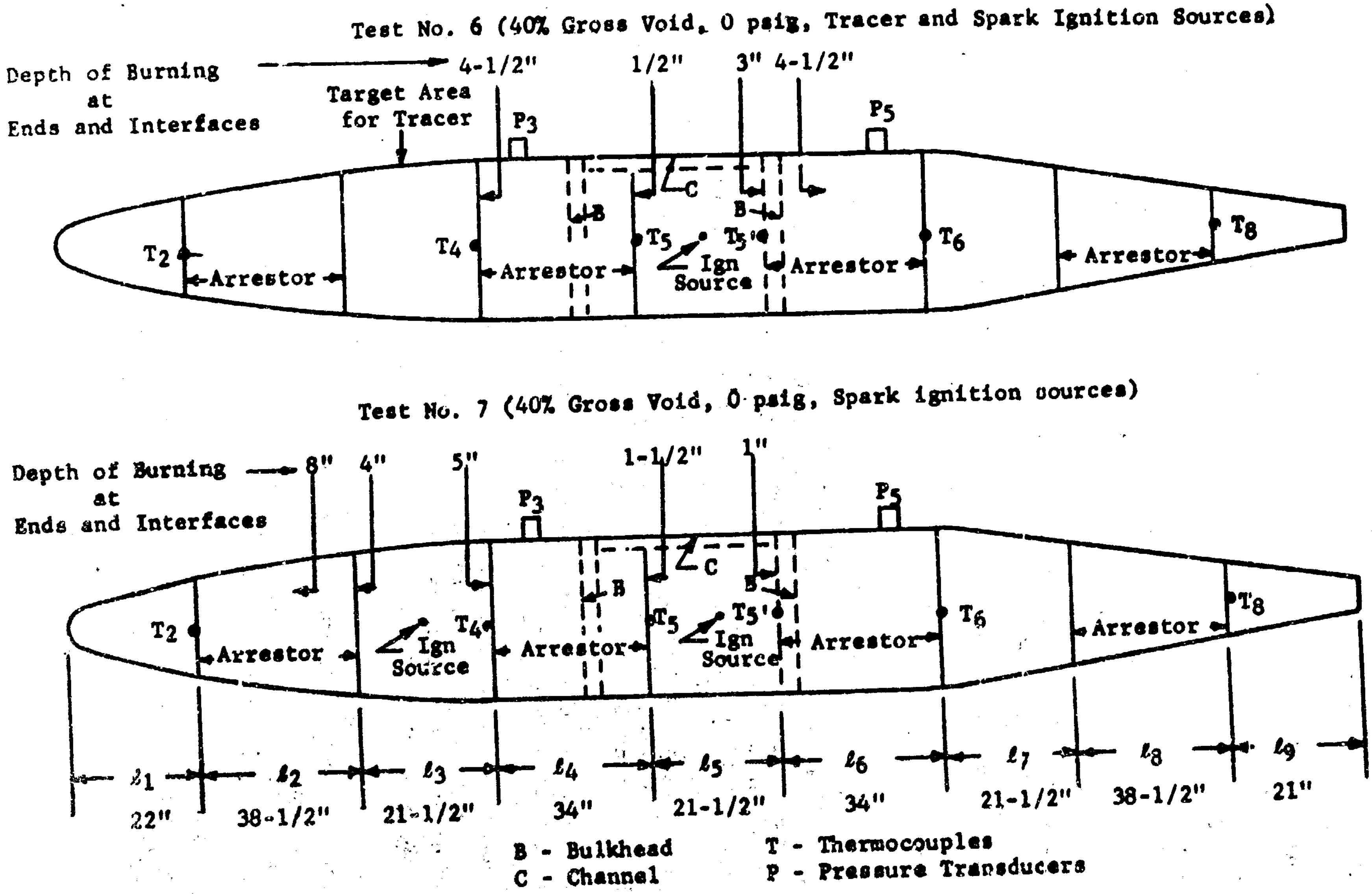


FIGURE 14. - Arrangement for full-scale experiments with flame arrestor material (20 pore/inch) and ~3.2 percent n-butane-air mixtures at 0 psig in 450-gallon aircraft fuel tank (27 inches maximum diameter); 30 caliber tracer and spark ignition source.

CONCLUSIONS AND RECOMMENDATIONS

The flame arrestor effectiveness of the 20 pore/inch polyurethane foam is noticeably greater than that of the 10 pore/inch material. At ambient temperature and pressure, 6-inch diameter cylindrical segments of the 20 pore/inch dry foam are effective in preventing flame propagation at arrestor length/ignition void length ratios (ℓ_2/ℓ_1) as low as about 0.17 (3"/18"). With high ℓ_2/ℓ_1 ratios ($\sim$1.5), it is effective as a flame arrestor in 6-inch diameter vessels at pressures up to about 15 psig and temperatures to 200°F; wetting the foam with liquid fuel tends to increase its effectiveness. A minimum wall thickness of 2 to 4 inches appears to be required for possible internal fuel-tank applications where "cored" arrestor models with gross voids of about 6 inches diameter are considered. With a 40 pore/inch material, the flame quenching effectiveness of the foam may be extended to about 20 psig at high ℓ_2/ℓ_1 ratios.

For external fuel-tank applications, the 20 pore/inch dry foam is suitable as a flame arrestor in a 450-gallon fuel tank to pressures of at least 5 psig, depending on the arrestor packing configuration. Fire and explosion protection in such large fuel tanks can be obtained with an arrestor packing configuration ($\ell_2/\ell_1 \cong 1.6$) which permits a gross void volume of approximately 40 percent. The above packing configuration can be expected to be effective where the fuel tank is exposed to various ignition sources, including live ammunition. For applications at pressures of about 10 psig or more, the arrestor length/ignition void length ratio should be greater than 1.6; or a foam of greater porosity rating (>20 pores/inch) should be used. In all applications, the effectiveness of this foam can be greatly limited if the packing is not fitted tightly to the walls of the tank.

It is recommended that the following additional studies be made with the present type of arrestor materials:

1. Continue small-scale experiments to determine various arrestor packing configurations with the 20 pore/inch polyurethane foam material for use in internal fuel-tank applications. Conduct selected large-scale experiments for determining scaling factors.

2. Determine flame arrestor effectiveness of 20 pore/inch foam material under simulated flight conditions of pressure altitude and temperature.

3. Investigate flame inhibiting coatings for improving effectiveness of combustible cellular arrestor materials.

In addition, it is recommended that other arrestor materials, including perforated plastic spheres, be investigated for use in internal or external fuel-tank applications.