Results of Experiments on Rigid Polyurethane Foam (RPF) for Protection from Mines

Ronald L. Woodfin, Sandia National Laboratories
Charles O. Schmidt, Los Alamos Technical Associates
Marvin Banks, New Mexico Institute of Mining and Technology

Abstract—Sandia National Labs has been investigating the use of rigid polyurethane foam (RPF) for military use, particularly for mine protection for the past two years. Results of explosive experiments and mine/foam interaction experiments are presented. The RPF has proved to be effective in absorbing direct shock from explosives. Quantitative data are presented. As reported elsewhere, it has proved effective in reducing the signature of vehicles passing over anti-tank (AT) mines to prevent the mine from firing. This paper presents the results of experiments done to understand the interaction of RPF with anti-craft (AC) mines during foam formation in shallow water in a scaled surf environment.

I. INTRODUCTION AND HISTORY

Sandia National Laboratories has used RPFs for many years in a wide variety of applications. This paper describes one of the latest of these. This work was sponsored under joint funding from the Department of Energy and the Department of Defense, Office of Munitions, through their long-standing Memorandum of Understanding. Under this program, Sandia attempts to use technology developed by DOE to apply to DoD problems. In this case, the problem was posed by the Navy and Marine Corps. We were asked to investigate ways to use RPF to enhance amphibious assaults and protect assault forces against mines in the very shallow water and surf zone regions and on the beach. The emphasis of this effort focused on three types of mines: anti-craft (AC) mines, such as the Soviet PDM series, which are expected in water up to a few feet deep (Figure 1); anti-tank (AT) mines, which may be encountered on the beach, seaward to the lowest low tide line; and anti-personnel (AP) mines, such as those found among the passive barriers along the coast of Kuwait during the Persian Gulf War. The defeat of the barriers themselves was another primary object of this project.

We first did a set of experiments and analyses to determine the suitability of this material for military uses. We studied the ability of the material, when used as a roadway, to carry military traffic; we investigated the flammability of the material in the context of hostile fire conditions; we measured the craters formed by surface detonations of explosives; we investigated the effects of common military petroleum products, sunlight, and aging on the RPF roadways; and we determined the effects on blocks of RPF struck by small arms and cannon caliber munitions. We analyzed the quantities and delivery methods required for various military applications. This work is reported in Reference 1, which discusses the suitability of the material for military use.

Following this work, we developed techniques for constructing prefabricated barges using nylon fabric for the exterior and internal compartment walls. These compartments are filled with RPF on-site, resulting in simplified transport and a very durable, low draft barge, capable of heavy lift. RPF can be transported in bulk in a ship's cargo tanks. With an expansion ratio of up to 60:1 in volume it requires far less shipping space than conventional barges or pontoons. Figure 2 illustrates an artist's drawing of a full-size barge (a) and a photo of the scaled nylon envelope (b).

We have developed techniques, using commercially available materials, for constructing RPF floats capable of carrying vehicles in both still water and moving surf. This work was done at scale sizes with analysis as required to relate it to full-scale applications. Figure 3 illustrates the results of the construction of a float in a surf pond. The float was 14 x 16 ft x 12 in. thick, formed around the tilt rod of a dummy PDM-1M AC mine and comfortably floated a dozen people and the front wheels of a heavy pickup truck. (It was too short for the whole truck.)

II. PROTECTION AGAINST MINES

A. Preventing a Mine from Functioning

Presuming that one has determined to cross a minefield, there are at least four ways to protect oneself or one's vehicle against the mines: (1) Find some way to prevent the mine's functioning; (2) Protect oneself or the vehicle from the effects of the mine detonation; (3) Make the vehicle strong enough to be able to absorb the mine effects with acceptable damage; or (4) Cause the mine to function at a sufficient distance that it does no damage. RPF has some potential application in each of the first three methods. We have investigated the first two and hypothesized an adaptation to the third. Method four has been demonstrated using RPF to function trip wire mines during the construction of a roadway before vehicular traffic.

We constructed a roadway approximately 21 x 56 x 2 ft over a field containing training mines and pressure sensors along with trip wires. This work followed analysis, using the finite element method, which predicted that a roadway of 4 lb/ft^3 RPF, 2 feet thick would be sufficient to prevent an M60 battle tank from exerting enough pressure on an AT mine to cause it to function.

Figure 4 illustrates the results of this analysis. The experimental work, which was sponsored separately by the U.S. Army Waterways Experiment Station, is being reported in detail in Reference 2. Actual loading was with an M88A1 Tank Retriever. The results were consistent with the analysis. For magnetically fuzed AT mines, the RPF roadway will inhibit most fuze functioning by increasing the distance between the tank's magnetic mass and the mine fuze. This is demonstrated by analysis in Reference 1.

We investigated separation of the vehicle from sea mines in two ways: by forming a float in the scaled surf and by constructing the RPF-filled barge described above. In either case, the vehicle on the barge or float can be protected from many mines. Because the RPF barge is so light for the strength required to support heavy payloads, its draft is minimal, preventing contact with many AC and AT mines.

B. Mitigating the Effect of a Detonating Mine

We conducted a series of experiments to study the effects of a detonating mine under a block of RPF, representing the roadway described above. These experiments are described in detail in Reference 2. They were conducted on thinner blocks of RPF with charges appropriate to AP mines. This allowed us to explore the phenomena without expending the large quantity of RPF required for AT mine protection. (In fact, even the small RPF thicknesses used in the experiment would have prevented mine function by anybody walking on the block.) Cavities formed were consistent with prediction techniques described in Reference 1.

We considered it necessary to better quantify the energy absorbing capability of the RPF. Consequently, we designed and conducted the set of experiments described in Section III.

We also conducted another set of experiments to investigate the case of a RPF block floating above a detonating underwater mine. This produced some interesting results. When the mine simulating charge was in contact with the bottom of the RPF block, the results were essentially the same as when we placed a block over a similar charge in air on sand. (Ref. 2) A predictable cavity was formed. However, when we placed the charge in the water 12 inches below the block and about 30 inches above the mud bottom of a pond, the results were dramatically different. No cavity was formed. Instead, the block fractured in the classic pattern of a brittle failure, reminiscent of a window pane broken by a rock. Figure 5 illustrates this failure mode. The nearly circular ring of fracture measures about 35 inches in diameter. The hole in the center of the block is from a patched area from a previous experiment fired on sand. The patch was torn out as a result of this water shot.

Even though the block experienced brittle fracture in this experiment, we hypothesize that if the RPF were bonded to a metal plate on the free side, the material would fail by crushing and become a more effective energy absorber. When funding permits, we will test this hypothesis.

If this hypothesis is proved, a possibility for an entirely new type ship protection design may be available. By the addition of a second hull, filling the voids with RPF, and covering the exterior with sheet polyurethane, the ship would gain additional protection against mines and would reduce its acoustic signature. See Figure 6.

While underwater mine explosions provide no real fragment danger, some types of land mines do use fragments as well as blast to damage their targets. We have a concept for constructing a fragment protection composite panel using RPF as the matrix. As this paper is written, we are examining this concept.

III. BLAST ENERGY ABSORPTION

We designed a set of experiments to measure the ability of the RPF to absorb energy from an explosive charge. We generated an approximately plane blast wave to accelerate a circular steel plate with its velocity vector normal to its surface. We then measured the velocity of the plate. Successive shots were made with varying thicknesses of RPF of two different densities placed between the explosive and the plate to evaluate the decrease in the kinetic energy of the plate due to the presence of the RPF. We then equated the decrease in kinetic energy to the energy absorbed by the RPF.

We also conducted a second form of experiment where we fired the explosive against a block of RPF and measured the volume of the resulting cavity. The reduced data from these experiments are reported here. Interpretation is currently underway and will be reported verbally.

The energy absorption seems to be primarily due to compression of the gas in the cells of the RPF. For low density RPF, only a few percent, by volume, of RPF is solid polyurethane.

We can easily show that the proportion of the gas in any RPF of any density is

$$\frac{v_g}{v_f} = \frac{\left(\frac{\rho_f}{\rho_p} - 1\right)}{\left(\frac{\rho_g}{\rho_p} - 1\right)}$$

where

v_g is the volume of the gas
v_f is the volume of the RPF
ρ_f is the density of the RPF as formed
ρ_p is the density of solid polyurethane
ρ_g is the density of the gas in the RPF

The gas filling freshly formed RPF is HCFC 141B. As the RPF ages, diffusion replaces this gas with air. Graph 1 illustrates the variation in polyurethane content of RPF as a function of RPF density.

IV. BLAST ENERGY ABSORPTION QUANTIFICATION EXPERIMENTS

A set of experiments attempting to quantify empirically the blast absorption of RPF materials was conducted at the Little Eagle site, EMRTC-NMT[*], Socorro, NM on 6 – 7 November and 17 – 18 December 1997. Detasheet (PETN) in 1, 2, 4, and 6 mm thicknesses was made up as a quasi-plane wave charge and arranged to fire through a variable thickness of RPF to propel a flyer plate into a set of 6 piezoelectric pins. The experimental setup is shown in Figure 8. The output from the pin circuits was measured as time from firing to plate contact with each pin and recorded on a digital time interval recorder in the site control room.

The RPF samples used were circular, 12 to 15 in. in diameter and of two different densities: ~3.3 lb/ft^3 and ~5.7 lb/ft^3. Most of the RPF samples were left in the cardboard cylinders in which they were cast prior to being cut to specified thickness. This reduced late time tension failures which would have been irrelevant to the experiment and simplified handling. Shots followed an experimental matrix as shown in Tables 1 and 2.

The 3.3 lb/ft^3 density RPF was subjected to 15 shots. The 5.7 lb/ft^3 RPF was subjected to 21 shots including the shots in Tables 1, 2, and 6. Initial kinetic energy for the flyer plates without foam is calculated and shown in Table 3 and graph 6. All the data reduced to date and presented herein is from the December series with 5.7 lb/ft^3 foam.

TABLE 1
NOVEMBER EXPERIMENT

11/6-7/97		Charge (mm)	
		1 mm (27.5 g)	2 mm (45.4 g)
RPF thickness (inches) 3.3 lb/ft^3	0	1	2
	2	1	2
	4	1	2
	6	1	2
	9	1	2
	12	1	2

TABLE 2
DECEMBER EXPERIMENT

12/17-18/97		Charge (mm)		
		2 mm (45.7 g)	4 mm (95.5 g)	6 mm (160±6 g)
RPF thickness (inches) 5.7 lb/ft^3	0	2	4	6
	2	2	4	6
	4	2	4	6
	6	2	4	6
	9	2	4	6
	12	2	4	6

TABLE 3
TABLE OF FLYER PLATE INITIAL KE

V km/s	Kinetic Energy		
	K Joules	ft-lb	BTU
.233	11.3	8,393	10.7
.374	29.3	21,625	27.8
.550	63.4	46,761	60.1

In the December experiments (5.7 lb/ft^3), the RPF was found to decrease the flyer plate velocity from 0.233, 0.374, and 0.550 km/s (764, 1227, and 1805 ft/s) for the 2, 4, and 6 mm Detasheet to near zero velocity for a RPF thickness of 9 inches. The intermediate velocities can be found in Table 4 and graphs 4 and 5. The velocities resulting from the varying explosive masses and the different RPF thicknesses, are used to estimate the energy absorption capacity of this material.

Six piezoelectric pins were glued into a phenolic base plate as shown in Figure 7. The pins were spaced at 1 mm intervals starting at the flyer plate. The pin signals were collected by a time interval meter (TIMS) having a 2 ns resolution. Although the TIMS has a tape printer for recording the data, timing results were also recorded by hand in duplicate.

The energy of the flyer plate can be approximated by the formula: $E = D^2/2$ with units of Mj/kg (Ref 3), where D represents the velocity in km/s. Calculations were performed on each RPF thickness for each thickness of Detasheet to determine the fraction of available kinetic energy absorbed. The results of these calculations are listed in Table 5 and plotted in graph 3.

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[*] Energetic Materials Research and Test Center-New Mexico Institute of Mining and Technology

TABLE 4

FLYER PLATE VELOCITIES FOR C-2, C-4, AND C-6 DETASHEET

RPF Thickness in.	Plate Velocity mm/us			
	C-1 1 mm	C-2 2 mm	C-4 4 mm	C-6 6 mm
0	One	0.243	0.374	0.555
2	Test	0.123	0.215	0.298
4	No	0.039	0.127	0.148
6	Data	0.016	0.058	0.084
9			0.018	0.024
12				0.003

TABLE 5

ENERGY ABSORBED VARYING RPF THICKNESS.

RPF Thickness in.	Energy Absorbed %			
	C-1 1 mm	C-2 2 mm	C-4 4 mm	C-6 6 mm
0	One			
2	Test	74.0	66.9	58.2
4	No	97.4	88.5	92.8
6	Data	99.6	97.6	97.7
9			99.8	99.8
12				

When the energies were calculated, we discovered some variations of the data. Four variables were present and might have caused the unexplained variations of the velocity:

> A review of the log sheets showed a 13 gram mass variation, within a series, in the amount of the Detasheet used to construct the top hat plane wave generators. This would change the velocity of the flyer plates. The RPF discs were cut to thickness with a band saw. Since they were not machined to thickness, any variation of thickness would influence the resulting velocity. The flyer plates were cut from sheet steel which may vary in thickness and surface smoothness and may result in nonparallel surfaces or a surface that did not contact the pins in an even manner. The density of the RPF discs was subject to some small variation which would cause a variation in the velocity.

The experiments were designed for low cost and the results are considered very good. The variations discussed above produced results with the 4 inch RPF discs which showed an unexplainably high velocity for the C-4 and a low velocity for the C-6. Upon examining the graphical representation of the results, a trend between the energy absorbed and the thickness of the RPF becomes apparent (Graph 3 and Graph 4). The graphs of the velocity results indicated predictable trend lines except at the 4 inch RPF disc position. Graph 5 demonstrates that the relationship between the thickness and the kinetic energy absorbed is exponential. Graph 6 depicts the kinetic energy absorbed by 5.7 lb/ft^3 RPF in British Thermal Units (BTU) and the thickness of RPF required to absorb 100% of the energy. Hence, the conclusion that this relation exists is supported. However, it will be necessary to conduct further experiments and analysis to fully understand the mechanisms and mechanics behind this relation.

In addition to the flyer plate charges, blocks of RPF 20 to 24 inches in diameter and about 24 in. high were subjected to the same size charges without a flyer plate or pin holder to get some idea of the size and shape of the blast cavities. Cavity sizes were obtained by direct measurement at three different points and averaging the readings.

TABLE 6

CAVITY EXPERIMENTS

	RPF (lb/ft^3)	Charge	Vol. (in.^{3})
Shot A7	3.3	1 mm (27.5 g)	93
Shot A12	3.3	2 mm (45.4 g)	166
Shot B9	5.7	2 mm (45.7 g)	78
Shot B21	5.7	4 mm (95.5 g)	324
Shot B20	5.7	6 mm (166.9 g)	375

VI. CONCLUSIONS

These experiments have indicated that RPF can be used to absorbed blast energy from explosions to mitigate the damage to military equipment and vehicles. Considerably more work is required to develop specific applications. Work to complete the interpretation of the experiments is underway.

References:

1. R. L. Woodfin, *Rigid Polyurethane Foam (RPF) Technology for Countermine (Sea) Program - Phase 1,* Sandia Report, SAND96-2841, Sandia National Laboratories, Albuquerque, NM, January 1997.

2. A. Alba, X. Maruyama, R. Woodfin, C. Schmidt, & G. Mason, *The Use of Rigid Polyurethane Foam as a Landmine Breaching Technique*, published elsewhere in these proceedings.

3. P. Persson, R. Holmberg, and J. Lee, *Rock Blasting and Explosives Engineering*, CRC Press, Ann Arbor, MI, 1994.

FIGURE 1
PDM-1M ANTI-CRAFT MINE

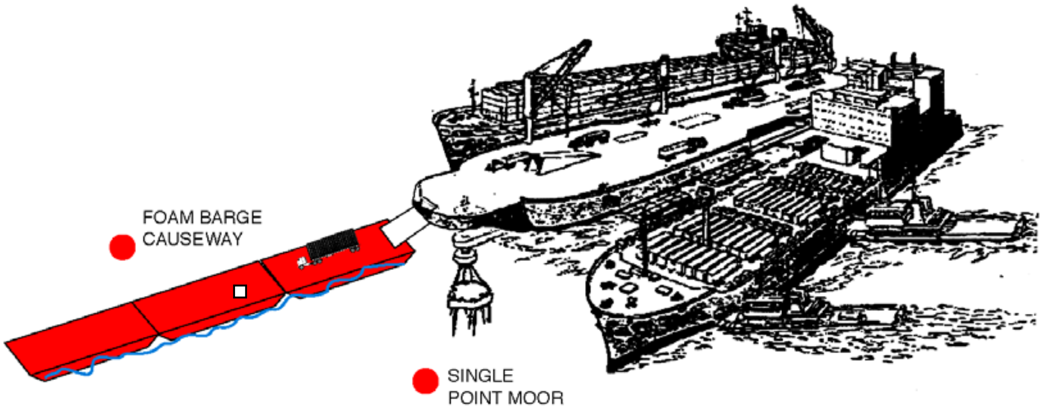


FIGURE 2A
ARTIST CONCEPT OF BARGE

FIGURE 2B
PHOTO OF RPF FILLED BLOCK

FIGURE 3
RPF FLOAT IN SCALED SURF POND

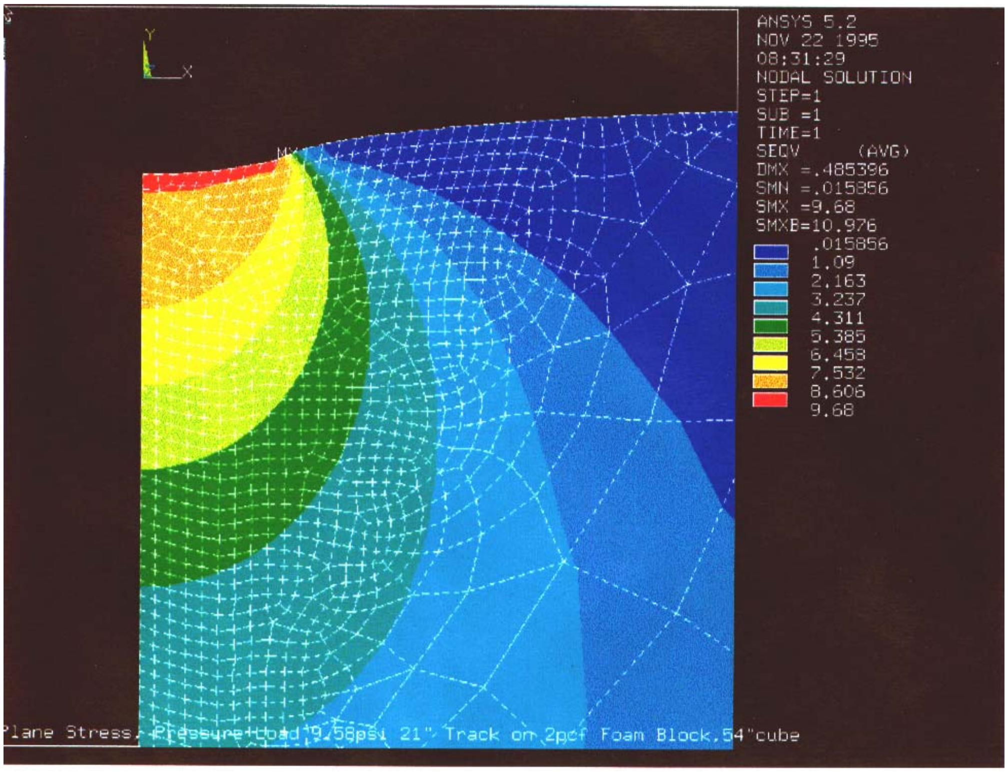


FIGURE 4
PLANE STRESS CONTOURS FROM ANALYSIS OF 54-INCH CUBE OF 4 LB/FT^3 RPF LOADED BY M60 TANK
(AXIS OF SYMMETRY IS ON LEFT EDGE; SIDEBAR NUMBERS ARE IN PSI.)

FIGURE 5
Upper Side of RPF Block Fractured by Detonation of 30 Grams of PETN
Positioned 12 Inches Below the Center of the Pattern.

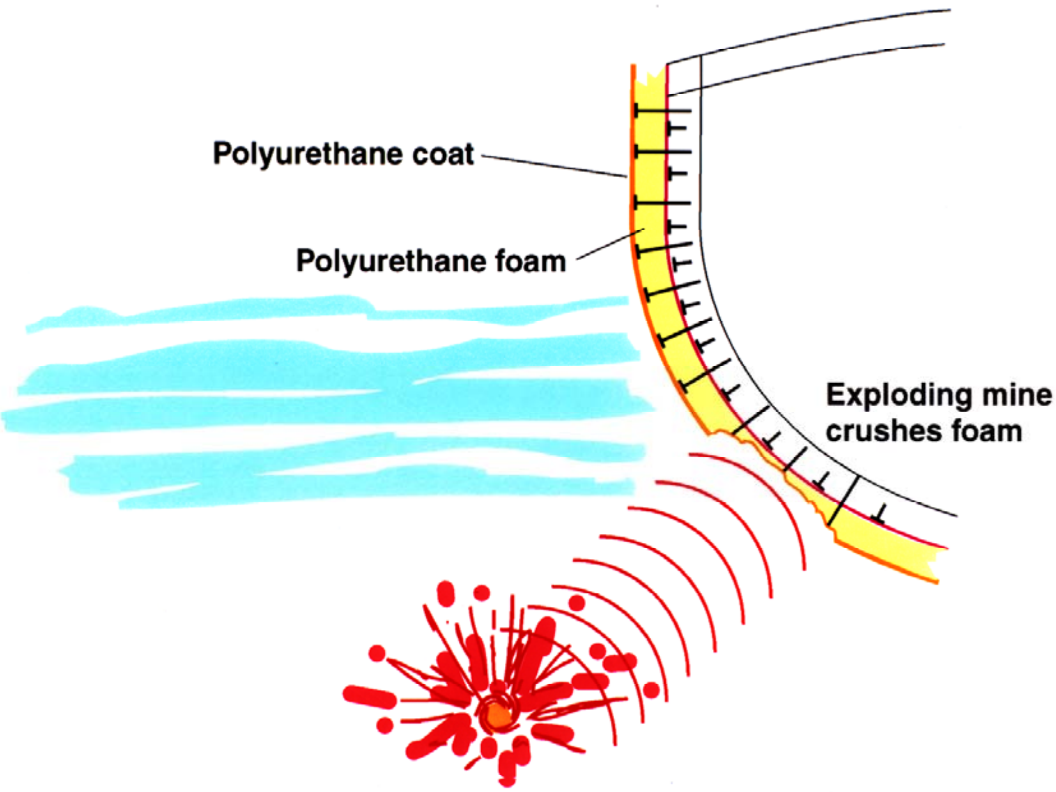


FIGURE 6
RPF In Ship Structure

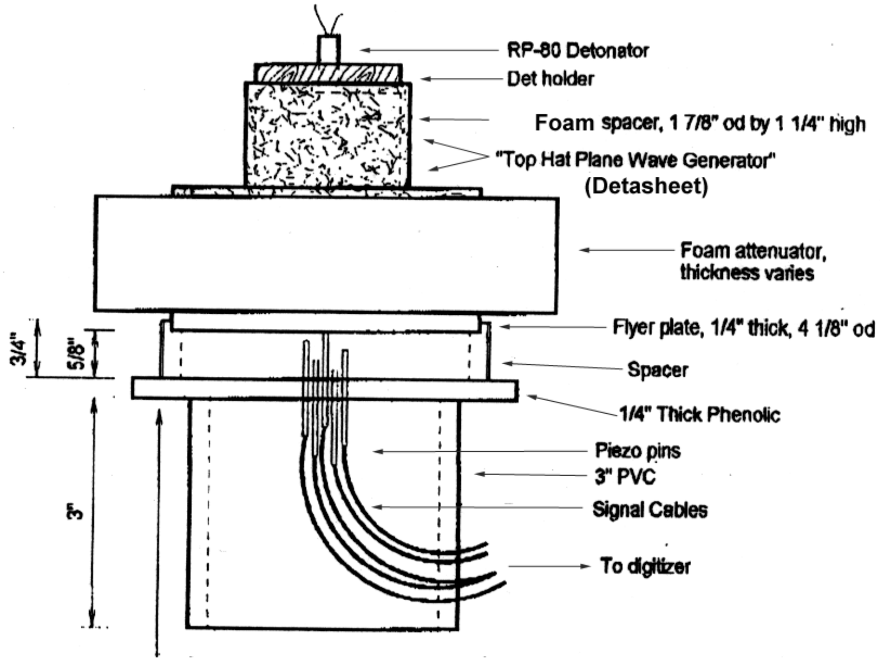
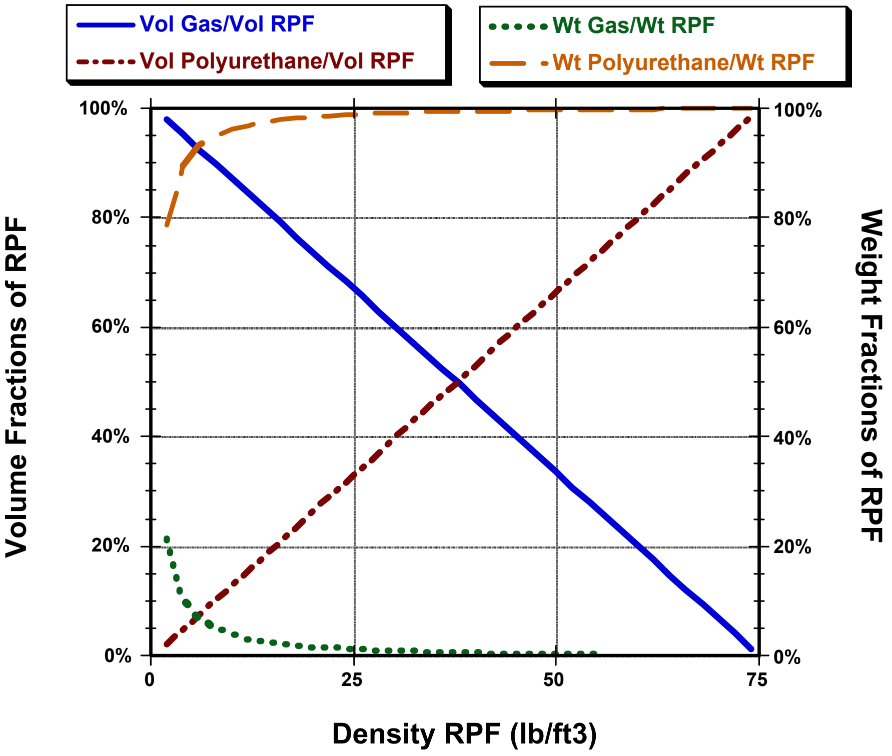
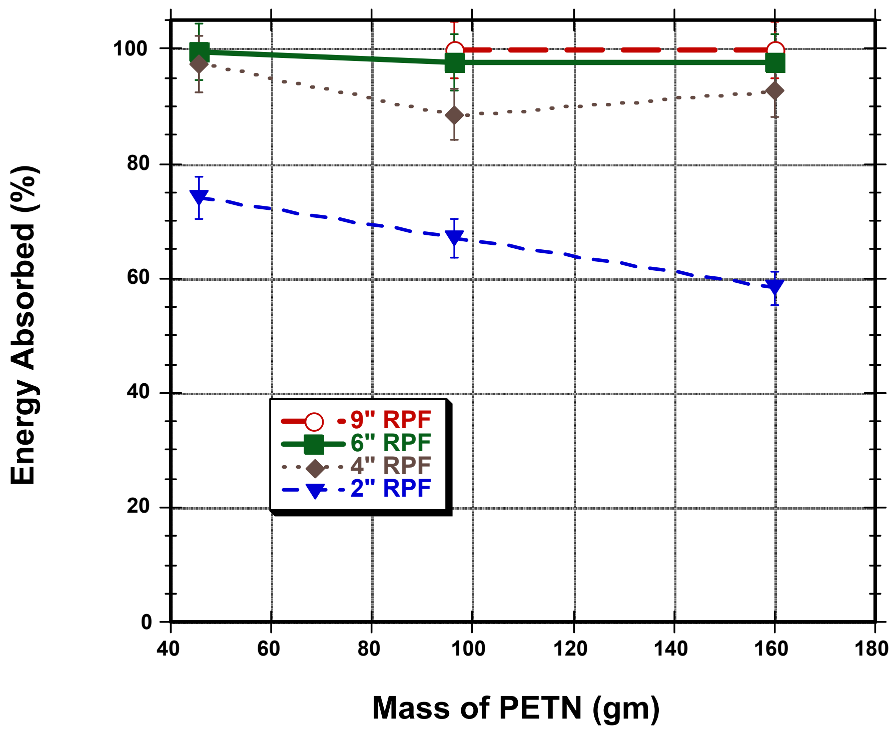


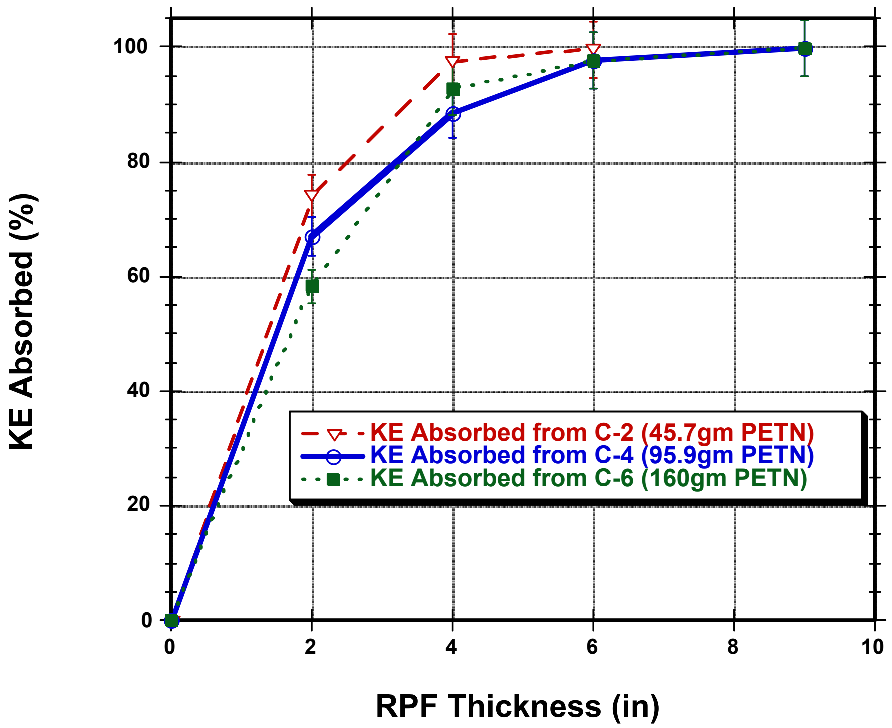
FIGURE 7
FLYER PLATE EXPERIMENT ASSEMBLY



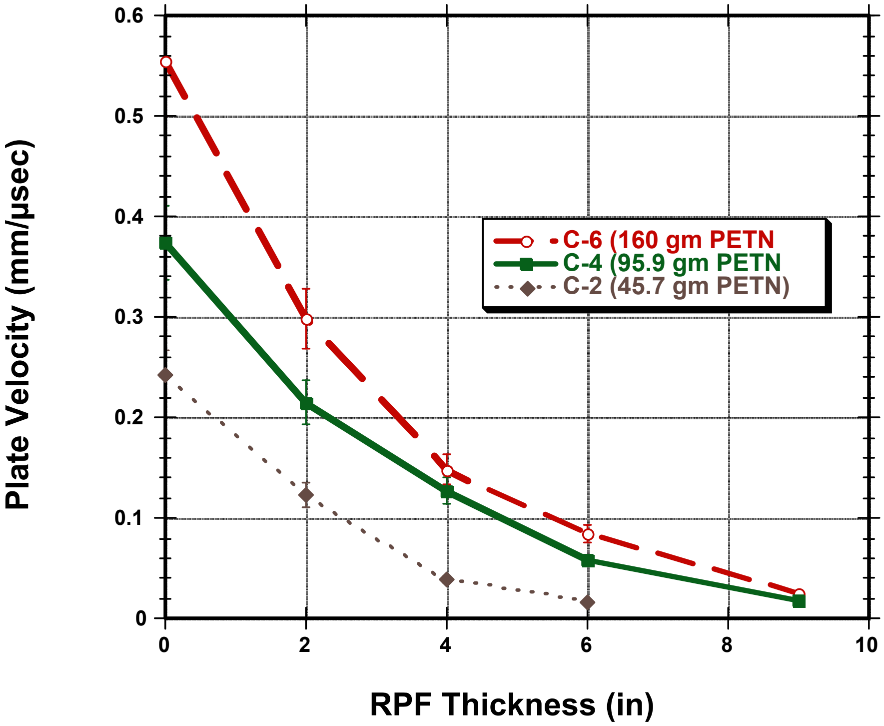
GRAPH 1
POLYURETHANE VS. RPF DENSITY



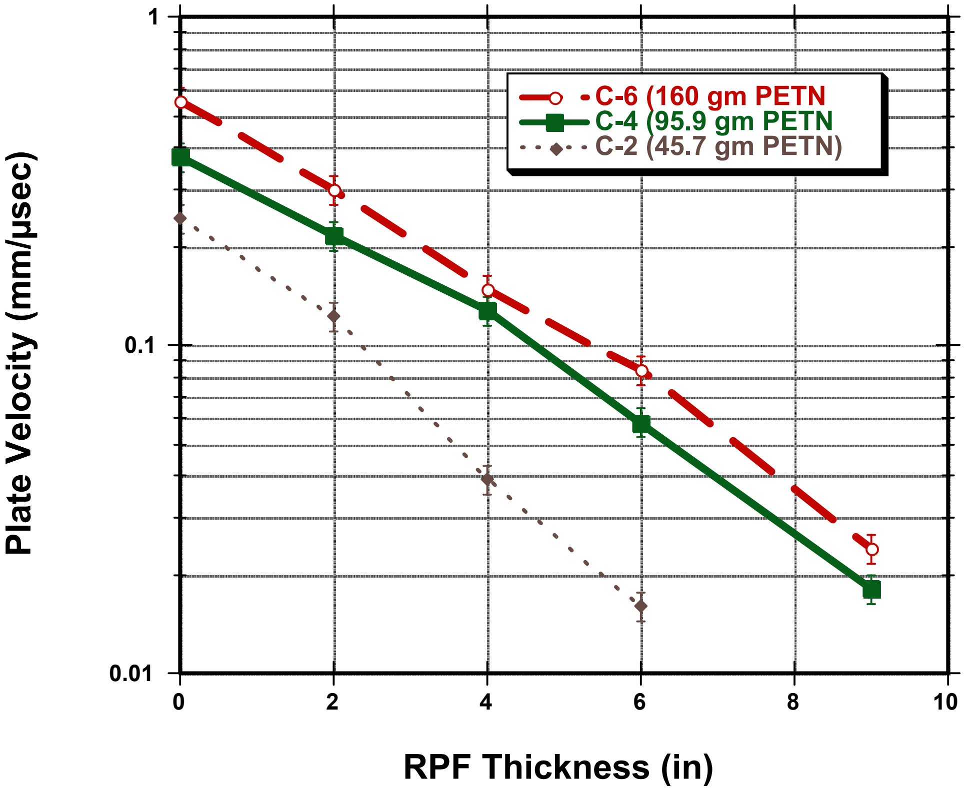
GRAPH 2
ENERGY ABSORBED BY 5.7 lb/ft³ RPF



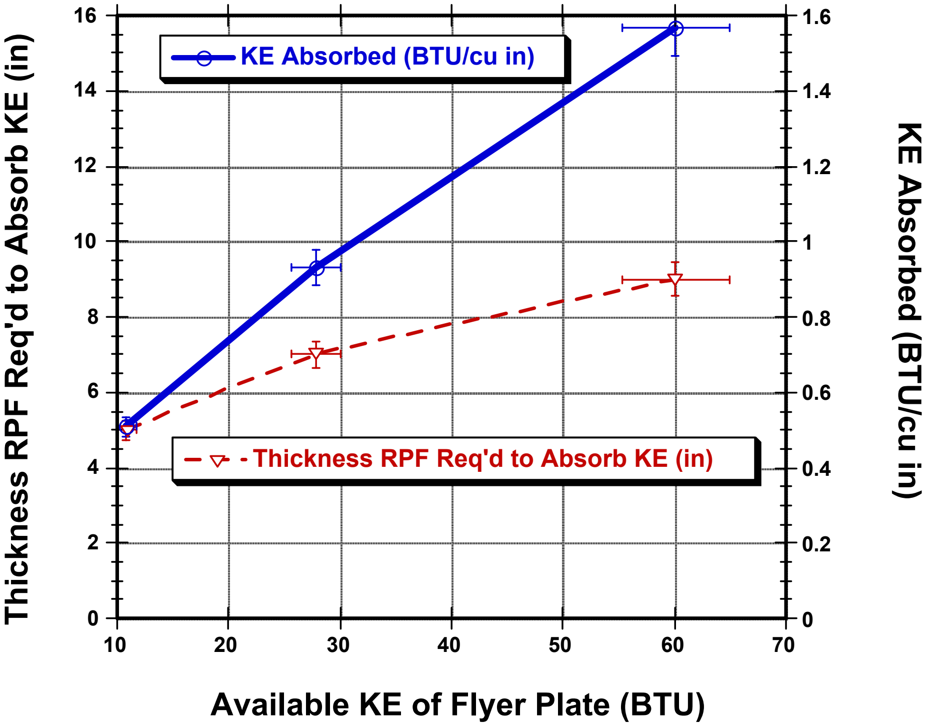
GRAPH 3
KINETIC ENERGY ABSORBED BY 5.7 lb/ft³ RPF



GRAPH 4
DATA AS RECORDED (LINEAR VIEW)



GRAPH 5
DATA AS RECORDED (LOG. VIEW)



GRAPH 6
ENERGY ABSORPTION OF 5.7 lb/ft^3 RPF