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Rigid Polyurethane Foam (RPF) Technology for Countermines (Sea) Program, Phase II

R. L. Woodfin, D. L. Faucett, B. G. Hance, A. E. Latham, and C. O. Schmidt

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Phase II

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Abstract

This Phase II report documents the results of one subtask initiated under the joint Department of Energy (DOE)/Department of Defense (DoD) Memorandum of Understanding (MOU) for Countermine Warfare. The development of Rigid Polyurethane Foams for neutralization of mines and barriers in amphibious assault was the objective of the tasking. This phase of the program concentrated on formation of RPF in water, explosive mine simulations, and development of foam and fabric pontoons. Field experimentation was done primarily at the Energetic Materials Research and Testing Center (EMRTC) of the New Mexico Institute of Mining and Technology, Socorro, NM between February 1996 and September 1998.

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Jeff Johnson, PMS-407
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Don Robeson, CSS
Wally Ching, Presearch
George Pollitt, COMINEWARCOM
George Hogue, NSWC
Mike Howard, MCIA

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Nomenclature

AAV	amphibious assault vehicle
ACTD	advanced concept technology demonstration
AFB	Air Force Base
AP	anti-personnel (mine)
AT	anti-tank (mine)
cal	caliber
CSS	Coastal Systems Station
DoD	Department of Defense
DOE	Department of Energy
EMRTC	Energetic Materials Research and Testing Center
ft	foot
ft-lb	foot pound
ft/s	feet per second
FY	fiscal year
g	gram
gr	grain
KE	kinetic energy
lb	pound
LCAC	landing craft air cushion
MCM	Mine Countermeasures
min	minute
MLO	mine-like object
mm	millimeter
MOU	Memorandum of Understanding
mph	miles per hour
ms	millisecond
NCFI	North Carolina Foam Industries
O.D.	outside diameter
oz	ounce
pcf	pounds per cubic foot
PETN	pentaerythritol tetranitrate
POL	petroleum oil lubricants
psi	pounds per square inch
PVC	polyvinyl chloride
QA	quality assurance
RPF	rigid polyurethane foam
SAR	synthetic aperture radar
SAS	synthetic aperture sonar
TBD	to be determine
TCG	Technology Coordination Group
USMC	United States Marine Corps
UV	ultraviolet
UXO	unexploded ordnance
WBS	Work Breakdown Structure
WES	Waterways Experimental Station

Executive Summary

This project began with a request from the Navy and Marine Corps, through the Office of Munitions, for new technologies to assist with Mine Countermeasures (MCM), specifically for Amphibious Assaults. Sandia was asked to consider all possibilities. After several months of information gathering from Navy/USMC agencies we proposed about a dozen different technologies which could potentially contribute to the solution of some existing and identified problems in this area. We invited representatives from the cognizant Navy and Marine Corps commands to review these possibilities and choose those which they thought would be most beneficial.

The project, as then structured, had three parts. Each was to be investigated and the most promising were to be pursued under the guidance of the Technology Coordination Group (TCG XV). These three parts were:

1. Investigation of the potential of rigid polyurethane foams (RPF) to form roadways over the barriers and/or minefields encountered in the beach and surf zone regions during an amphibious assault,

2. Investigation of the possibility of classification and/or identification of mine-like-objects (MLO) by chemical point sensing (sniffing) of the object, and

3. Assessment of whether Sandia synthetic aperture radar (SAR) algorithms could be employed in Navy synthetic aperture sonars (SAS) to enhance their performance.

After the initial period of work the investigation was redirected, with the concurrence of the TCG. The SAR algorithms did not seem adaptable directly to SAS because the ratio of the sonar propagation velocity to the platform velocity was so much smaller than the ratio of the radar propagation velocity to its platform velocity. Consequently, this part of the project was dropped.

In its place, however, we substituted an investigation of the possibility of distributed chemical labeling of MLOs, with the potential for remote mapping and classification. This work has resulted in some technical progress, but has not progressed sufficiently to be reported at this time.

This report describes the progress made in the final two year's work on the RPF investigation. A previous report, SAND 96-2841, reported the initial investigations. The chemical point sensor work is described in SAND 98-2279 Volumes 1 (U) and 2 (S).

The first series of analyses and experiments were designed to determine the feasibility of the RPF material for military use. These are the subject of SAND 96-2841. They may be summarized as:

- RPF can be formed with the required structural properties,
- RPF poses no extraordinary fire danger,

- RPF absorbs substantial blast energy with controllable and repairable results,
- RPF can be formed in/under water with acceptable properties,
- RPF is not destroyed by bullet impacts but neither does it offer substantial ballistic protection to troops,
- RPF material is environmentally benign when cured; however, one of the constituents is a respiratory irritant and must be handled with care,
- RPF may be formed with acceptable properties over a useful range of water and air temperatures, and
- RPF may be formed with acceptable properties without requiring precise mix ratios.

The second series, reported here, examined the military utility of the material and the feasibility of deploying it in militarily realistic situations. Because of the large quantities of material calculated to be used in actual military operations, and the current unavailability of dispensing equipment large enough for those applications, all experiments were done with commercially available, small capacity, dispensing equipment. Nevertheless, by judicious scaling, we have investigated the issues thoroughly enough to realistically infer the parameters required for full scale use and to project their likelihood of success.

We conducted the majority of the experiments at the Energetic Materials Research and Testing Center (EMRTC) of the New Mexico Institute of Mining and Technology (NM Tech). All these experiments were sponsored under the memorandum of understanding (MoU) between the Department of Energy (DOE) and the Office of Munitions, in the Office of the Undersecretary of Defense (OUSD(OM)). One small, auxiliary experiment was funded by the Army (Ft. Leonard Wood) and conducted at the Waterways Experiment Station, Vicksburg, MS (WES). The final demonstration of the "Surf Road" concept was jointly conducted by Sandia and the Naval Coastal Systems Station, Panama City, FL (CSS), since it incorporated a basic concept originated by CSS and implemented with Sandia assistance. A small proof of principle experiment on the hex hinge concept was conducted earlier at CSS.

These second phase experiments and analyses have demonstrated with substantial certainty that:

- RPF material can be deployed in moving surf to form a bridge capable of carrying military traffic

- RPF filled fabric pontoons can be prefabricated in a wide variety of sizes for on-site construction, and used for bridges, floats, boats and similar floating items

- RPF roadways can be made adequate to protect traffic from either anti-tank (AT) or anti-personnel (AP) mines on land

- RPF roadways can be laid, with almost no preparation, over soft sand, deep mud, or swampy ground sufficiently rapidly to enhance military operations

- RPF will absorb a substantial and predictable quantity of blast energy from an adjacent explosion

- RPF can be used to protect ship and/or craft structures from damage by underwater explosions

- RPF can be quickly formed from small kits for many auxiliary military uses including small foot bridges, tent floors, maintenance pads, helicopter landing or service pads, repair of shell craters in roads and runways, stabilization of loose terrain, habitability enhancement of tents in very hot or very cold conditions, and other uses not yet imagined

- The RPF industry in the US has the capability to produce appropriate dispensing equipment and chemical formulations for military applications

- RPF can be used to fill a number of military roles, particularly in Logistics-Over-The-Shore (LOTS) and enhancing mobility in restrictive terrain. It promises operational advantages to both the field commander and the logistician that have not yet been explored. Operational advantages are:

    - Expanded geographic choices for LOTS site gives CINC added operational flexibility

    - Rapid emplacement enables earlier force closure

    - Greatly reduced weight and cube compared to steel structures, additional watercraft, etc.

    - Maintenance burden reduced – no rust, dents

    - New material with untapped military potential

        - Engineer mobility/counter mobility

        - Motor pool hard stands

        - Dry floor for field billet applications

        - Helicopter landing pads; less FOD

        - Bridging/rafting materials for light forces

This report describes the experiments and analyses in a roughly chronological manner, with most details recorded in the attached appendices. The MoU funding for this work expired at the end of FY98. Several follow-on projects have been contemplated and/or proposed, but have not been funded as of the publication of this report.

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SECTION 1

Background

In the Phase I report [Reference 1], details of experiments conducted using prefabricated two and four pounds per cubic foot (pcf) RPF were discussed. Experiments were conducted at Energetic Materials Research and Testing Center (EMRTC), a separate entity of New Mexico Tech in Socorro, NM between September 1995 and February 1996. Laboratory experiments to characterize the foam material and to select foam and foam machinery vendors were conducted in-house at Sandia. References 2 through 6 are the semi-annual reports made to the Technology Coordination Group (TCG).

Phase I work was primarily directed toward determining whether RPF materials had the requisite strength, density, and formability to be useful in military applications. The foam was also subjected to fire, gunfire, surface and embedded explosions, common petroleum products, and other environments intended to determine if the material would be compatible in a military field environment. The Phase 1 Work Breakdown Structure (WBS) in Figure 1 shows the experiments and analyses conducted. Completed events are shown by a diagonal line. Some planned experiments were eliminated as we learned more about RPF. Others were dropped based on changing Navy interest and TCG guidance.

Phase I Conclusions: The objective of Phase 1 was to examine those areas of concern in this application of RPF material, expressed by the TCG and other Navy and Marine Corps advisors. We wanted to rapidly determine whether RPF material was suitable for military use in an assault roadway.

The results of this phase of the work clearly indicate the following:

- RPF can be formed with the required structural properties,
- RPF poses no extraordinary fire danger,
- RPF absorbs substantial blast energy with controllable and repairable results,
- RPF can be formed in/under water with acceptable properties,
- RPF is not destroyed by bullet impacts but neither does it offer appreciable ballistic protection to troops,
- RPF material is environmentally benign when cured; however, one of the constituents is a respiratory irritant and must be handled with reasonable care,
- RPF may be formed with acceptable properties over a useful range of water and air temperatures, and
- RPF may be formed with acceptable properties without requiring precise mix ratios.

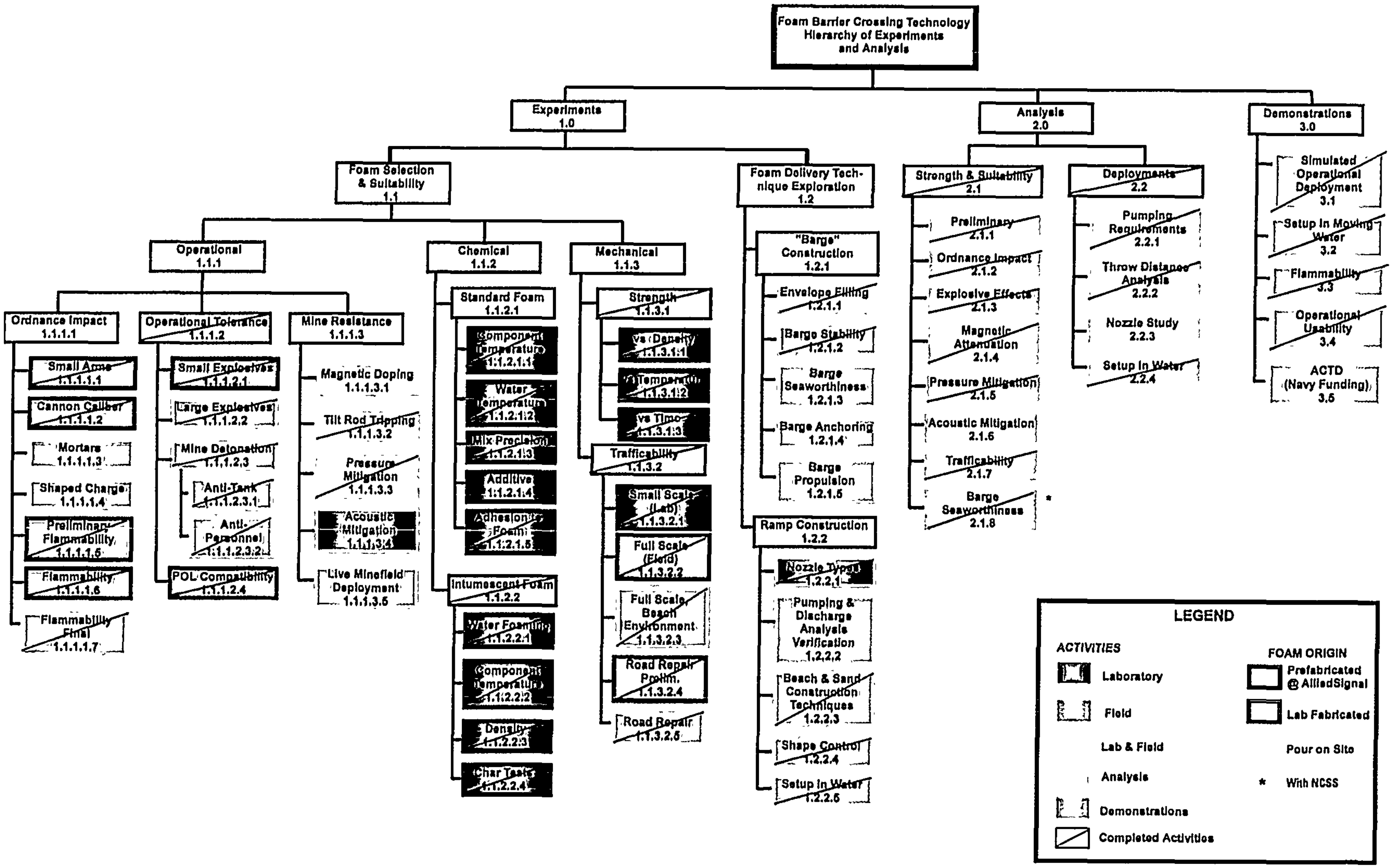

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Figure 1. Work Breakdown Structure (as of Sep 98)

SECTION 2

Phase II RPF Experiments

Introduction

Phase II of the RPF Experiments began in February 1996 and continued through 1 October 1998 when the funding expired. This 2 ½ year period was used to explore new concepts for foam use, test many of the concepts in scaled field experiments, document experimental results, and introduce some manufacturers of foam products to military requirements.

Experiments were conducted at EMRTC and Waterways Experimental Station (WES), Vicksburg, MS. Results of the experiments were reported to TCG XV for advice and new direction. In conducting these field experiments, new concepts became apparent on a regular basis. Several of these spin-off ideas were integrated into the experiment matrix and tested under field conditions. The ultimate goal: to demonstrate an operable foam causeway through the surf zone and onto a beach was accomplished in September 1998 at Panama City, FL. Description of the work leading up to that demonstration follows.

RPF System: NCFI 811-91-3.3

The NCFI 811-91-3.3 foam system (North Carolina Foam Industries, Mt. Airy, NC) consists of an "A" component (PMDI or polymeric methylene diphenylene di-isocyante) and an "R" component (the polyol resin). This material was chosen primarily for its performance in underwater applications and secondarily for its robust reaction characteristics under other adverse conditions such as off-ratio mixes and temperature extremes. All the RPF products tested were standard two-part materials. Laboratory work to characterize foam reactions under these conditions is reported in reference 1.

RPF Dispenser: Decker Model DC80

A Decker Model DC80 (Decker Industries, Port Salerno, FL) polyurethane foam dispensing machine was used to dispense NCFI 811-91-3.3 RPF in all large-scale experiments conducted by Sandia National Labs. This machine is designed to dispense two-part foam systems at a maximum delivery rate of 80 lbs/minute. It has a variable A:R mix ratio capability, however, the experiments described in this work were generally limited to about a 1:1 ratio by volume. Figure 2 shows the front of the dispenser with one of the foam component barrels in the background.

The Decker DC80 consists of gravity fed, low pressure recirculating gear pumps to deliver the A and R components to the static mix head where the foam forming reaction is initiated. Sandia National Labs' machine is fitted with in-line heaters to allow some temperature control over the chemical components prior to mixing. A solvent/air flush capability is also incorporated to ensure that the static mixing chamber remains obstruction-free. A 90 psig compressed air or nitrogen source and 20A, 208V electrical service are required to operate this machine.

In order to have the foam dispenser mobile, it was mounted to a trailer that held the dispenser, nitrogen bottle, and foam barrels. Figure 3 shows the Decker DC80, on it's trailer, alongside the EMRTC experiment pond.

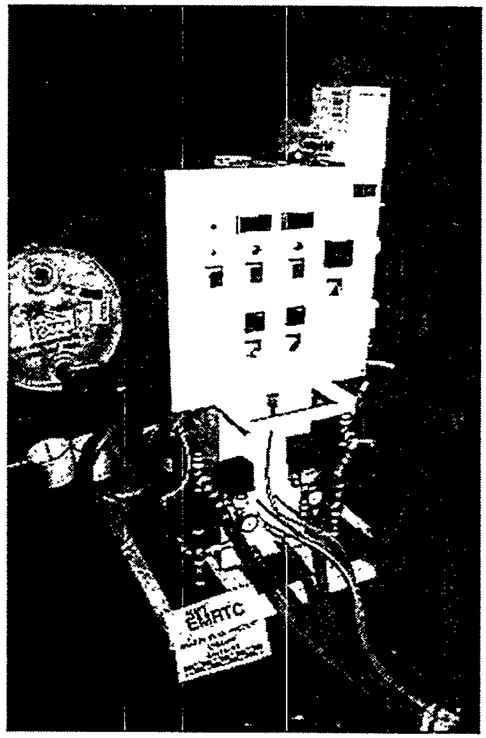

Figure 2. Decker Foam dispenser

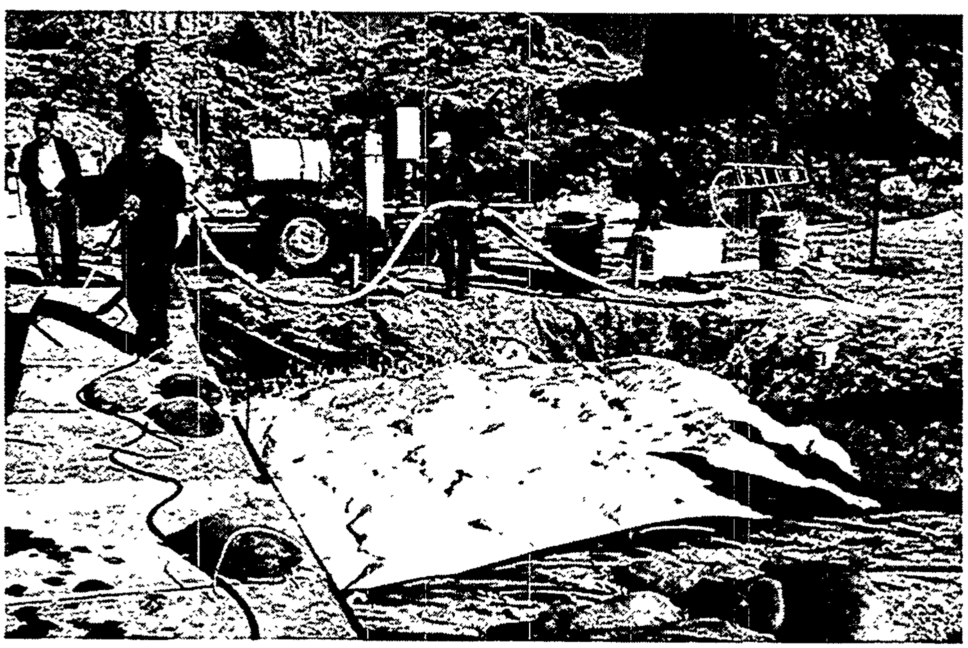

Figure 3. Decker Foam dispenser on Trailer

Fabric Envelope Experiments

In January 1997, Sandia began experimenting with the Decker foam dispenser under multiple controlled conditions. This is a foam pouring dispenser normally used to make small foam parts. A series of preliminary experiments pouring foam into cardboard boxes and into a 4 x 10 ft water-filled tank expedited the learning process. Eight fabric envelopes made of nylon pack cloth were designed by Sandia and manufactured by EMRTC in two different designs. The first design did not allow filling the envelope evenly and was discarded. The second series of envelopes, numbered 5 through 8, worked well using a four-way PVC manifold to fill the centers of the four specially designed, internally communicating compartments in the 40 x 40 x 22-inch envelope. By calculating the interior volume and filling it with foam to 100, 105, and 110% of volume, tight, well-formed foam blocks were produced. Precise calculation of the amount of liquid foam required to foam-fill a fabric envelope is quite difficult. The interaction between the stretching of the fabric and the confinement of the foam changes the final density of the RPF. One of the blocks, No. 8, has been shipped, several times, around the country as a demonstrator for various meetings. These blocks weigh between 85 and 95 pounds and each is capable of supporting about 1,300 pounds of non-bouyant load in water. They demonstrated the feasibility of constructing barges or floating piers on-site to support surf zone or river crossing of vehicles and troops. Figure 4 shows the design details of the successful design.

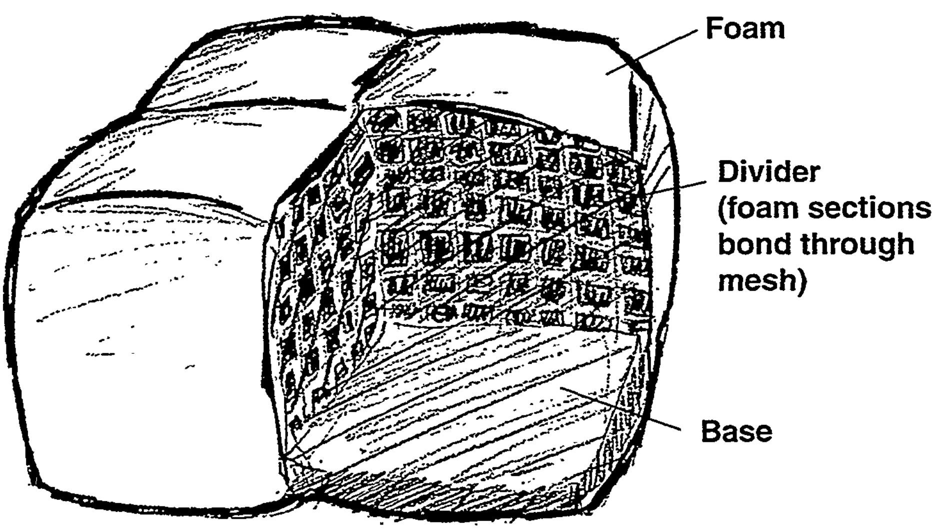

Figure 4. Fabric Envelope Design

Figure 5 is a photograph of block No. 6 taken immediately after it had been filled. The bulged sides illustrate the way the fabric stretches. These blocks formed the prototypes for larger, multi-celled pontoons.

Figure 5. Fabric Envelope Foam Block

EMRTC Surf Pond

In the fall of 1996, a pond was constructed at EMRTC to accommodate experiments in moving water. The pond was excavated to approximately 9 ft depth at the deep end and was 100 ft x 16 ft wide. The bottom sloped up to a sand beach at the east end. A motor-driven, wave-making machine was built at the west (deep) end and was capable of producing scale-size wavelets about 2 to 3 inches high. Scaling of the pond was designed at 1:20 based on 60 pounds/minute foam capability versus 1,200 pounds/minute anticipated as the full-scale requirement. Two-inch wavelets, therefore, equate to surf about 3 ½ feet high for our purposes. After being lined with a heavy poly liner and filled with water, the pond was used on a regular basis to learn how to form RPF rafts on the beach and the water surface. Later addition of a propane pool heater allowed use in cold weather. Figure 6 shows the pond during construction.

Figure 6. Excavation for Surf Pond

Figure 7 shows the surf pond and foam raft formed in the surf, during practice for the TCG meeting in January 1998. The truck had to stop short of the footbridge at the far left center of the picture.

Figure 7. Foam Easily Supports Chevy S-10 Truck

Hexagonal Blocks and CSS Experiments

After seeing the prototype foam barges, CSS developed the idea of using hexagonal RPF blocks to form the joint between two fabric envelope "barges." The relatively loose coupling between the hex blocks allows them some motion in all three dimensions. This dissipates some of the energy of the wave action and prevents damage to the rigid barges.

In mid-July, 1997, CSS, Panama City, FL shipped three plastic, hexagon-shaped molds to Sandia, two were 0.875 cubic ft in volume and one 7.0 cubic ft. Each panel of the mold mounted to the base plate with three screws. Polyethylene sheet was used as mold release. Three 12-inch segments of PVC pipe were suspended within the mold across the lateral cross section of each pair of opposing plates. Three straps secured the side plates together until the foam hardened (approximately 20 minutes). 3.75 lb. of NCFI 811-91 foam were poured into the smaller mold with a mass ratio of 1.06A to 1.00R where A is the isocyanate and R is the urethane resin. Fabrication of the smaller blocks took place on July 25, 28, and 29. The foam was mechanically mixed in a small pail through the cream time (approximately 60 seconds) and then poured into the bottom of the mold. The rise time was approximately three minutes. Each PVC pipe segment bowed approximately ½ inch after the block had completely finished out-gassing (approximately 24 hr. was allowed). The resulting foam was measured to be approximately 4.41 pcf. The mold was disassembled after every pour in order to remove the block, and the polyethylene sheets were replaced after every 2 to 3 pours. A number of the blocks had cracks across the top from 7 to 12 inches, though this was deemed inconsequential if the depth of each crack was minimal. Twenty-two blocks were fabricated; 15 of which were shipped to CSS for experimentation.

On July 30, two pours into the larger molds were conducted using the method adopted for the smaller molds. In this experiment, steel rods were slipped through the PVC pipe segments to prevent significant bowing. The first estimate was 30.9 lb. of foam and the block was removed from the mold after 30 minutes. The steel rods were bent approximately ½ inch and removal was somewhat difficult. The resulting block extruded over the mold an excess 3 inches in height and displayed a convex base. In an attempt to correct these problems, 28.6 lb. of foam was mixed for the second trial. It was allowed to cure for 45 minutes before disassembly. The resulting foam block had a stable base and good height, though a crack propagated across the top. These experiments illustrated the inherent non-linearity of RPF materials.

CSS put these blocks through extensive explosive experiments and subjected them to other insults. By rafting them together suitably they become a secure but flexible joint that could be used to hold a causeway together. This concept was field tested in September 1998 at Panama City in the Gulf Surf zone. Another 70 hexagons were cast by Sandia for the Panama City tests. Figure 8 shows the initial stability experiments at CSS.

Figure 8. Foam Hexagon Raft Experiments at CSS

Waterways Experimental Station (WES) Foam Roadway Experiments

In August 1997, a Sandia Team took the Decker foam dispenser to Vicksburg, MS to perform landmine interaction and vehicle traction experiments for the U.S. Army.

During late July and early August of 1997, a series of field tests were conducted at the Army Corps of Engineers' Waterways Experiment Station (WES) in Vicksburg, MS. The tests were divided into two categories: RPF applications for mine protection and traction enhancement using RPF. Only the mine protection tests will be addressed here (refer to Appendix C for traction enhancement study report).

The test area was located in an agricultural field on the Louisiana side of the Mississippi River. It was graded level where the foam slab was to be constructed. A sandy area was prepared near the center of the graded area in which an array of pressure transducers and training anti-tank mines were placed. At one end of the graded area, several tripwires connected to whistle-type pyrotechnics were emplaced.

Over the course of a day, an RPF slab approximately 56 ft. long, 21 ft. wide and 2 ft thick was poured using 10,000 lbs of NCFI 811-91-3.3 material and the Decker dispenser which was producing about 80 pounds per minute at the lower altitude and high temperature. Figure 9 shows the experiment setup.

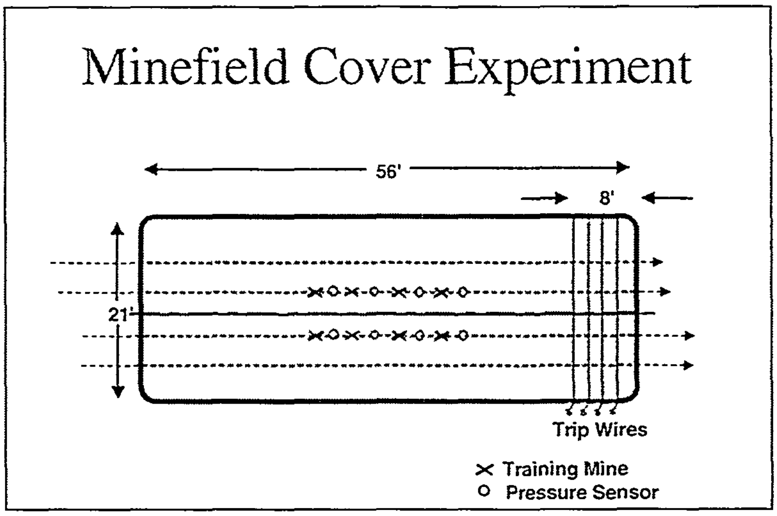

Figure 9. Foam Roadway Experiment

When RPF was poured in the vicinity of the tripwire test area, the tripwires were encapsulated, pulled up, and the pyrotechnics were triggered by the force of the rising foam. This result can be expected from nearly any tripwire fuzed device.

The foam slab was allowed to sit over the weekend before vehicle testing commenced, however, it was suitably cured and could have been used 20 to 30 minutes after it was finished.

The slab was evaluated for its ability to diffuse vehicle pressure signatures by driving both a HMMWV (4.3 tons) and an M88 Armored Recovery Vehicle weighing about 56 tons over it numerous times while monitoring the pressure transducers and the micro-switch equipped training mines. The HMMWV made 30+ passes without triggering any mines or causing any visible damage to the RPF slab. The M88 also made 30+ passes without triggering any mines. The foam showed some wear (approx. 3-4 inch deep ruts after 30 + passes). The HMMWV barely left an impression of its tires on the foam. One training mine did get triggered during a pass when an abrupt stop/start was made with the M88 generating extra pressure. Figure 10 shows the ruts generated during the experiment

Figure 10. Three to Four Inch Ruts Created By M88 During Mine Protection Experiment

The M88 vehicle generates a track pressure of about 17 psi. The layer of foam did successfully reduce this pressure to below the 7 psi firing pressure of the training mines. The average pressure registered by the pressure cells was 5.4 psi from the M88. This was predicted by the finite element analysis reported in reference 1.

Land Mine Simulation Experiments

In August 1997, Captain (Armor) Albert L. Alba, U.S. Army, a Master's degree candidate at U.S. Navy Postgraduate School, became part of Sandia's team. Sandia conducted a number of explosive characterization experiments for his thesis research that leveraged the research Sandia was doing. In the first series of experiments, 10 and 30 g C4 and PETN charges were detonated under flat, 4 pcf foam slabs 65 and 85 inches square by 6, 12, 18, and 30 inches thick. The shots were conducted with the charge placed immediately below the lower surface of the foam in a bed of smoothed sand. The foam was weighted with sandbags as shown in Figure 11. All charges were flat, circular "patties" (not unlike a small hamburger), designed to simulate small anti-personnel mines.

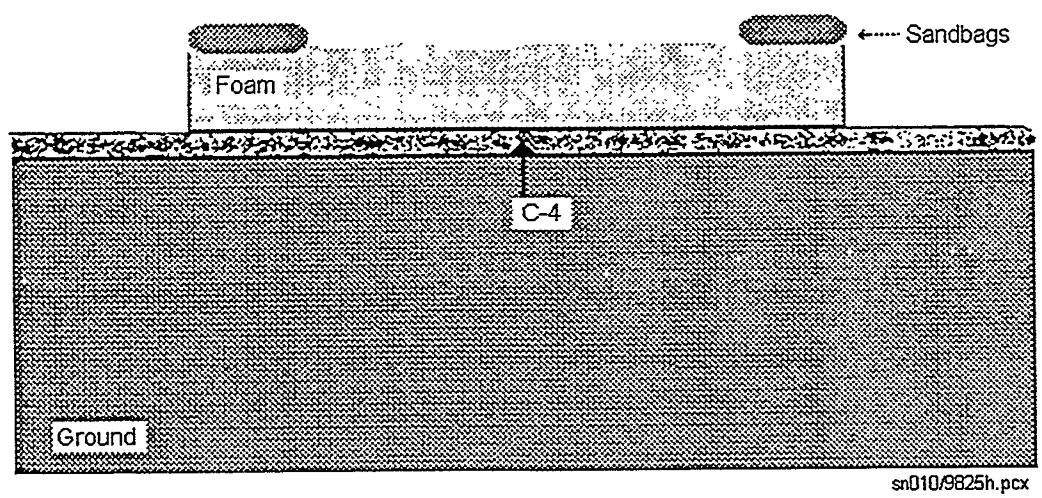

Figure 11. Setup for Land Experiments

Thirteen experiments were conducted in this series, nine resulted in perforation of the foam slab through production of a conical shear plug in the upper half of the block. Four resulted in an unvented cavity. No edge effects were apparent. Figure 12 presents the individual shot parameters and results in tabular form.

Expt #	Task #	Medium		Block Size (in)	Charge Size (gms)			
		Land	*Sea*		*10*	*30*	*Cavity Diameter (inches)*	*Cavity Depth (in)*
L1	L610	X		65X65X6	X		5.75	perforated
L2	L616	X		65X65X6	X		8.50	perforated
L3	L630	X		85X85X6		X	4.75	perforated
L4	L636	X		85X85X6		X	8.25	perforated
L5	L1210	X		65X65X12	X		8.50	7.00
L6	L1216	X		65X65X12	X		11.50	perforated
L7	L1230	X		85X85X12		X	4.50	perforated
L8	L1236	X		85X85X12		X	7.75	perforated
L9	L1810	X		65X65X18	X		6.00	6.00
L10	L1816	X		65X65X18	X		9.75	perforated
L11	L1830	X		85X85X18		X	5.75	6.50
L12	L1836	X		85X85X18		X	8.50	perforated
Mod1		X		85X85X30		X	5.75	11.85

Figure 12. Land Mine Simulation Experiment Matrix

The results tabulated above indicate that more than 18 inches but less than 30 inches of foam are required to completely absorb the effects of a 30 g anti-personnel (AP) mine. We later conducted another series of explosive experiments in water. Figure 13 shows block L-13 before and after a 10 g detonation.

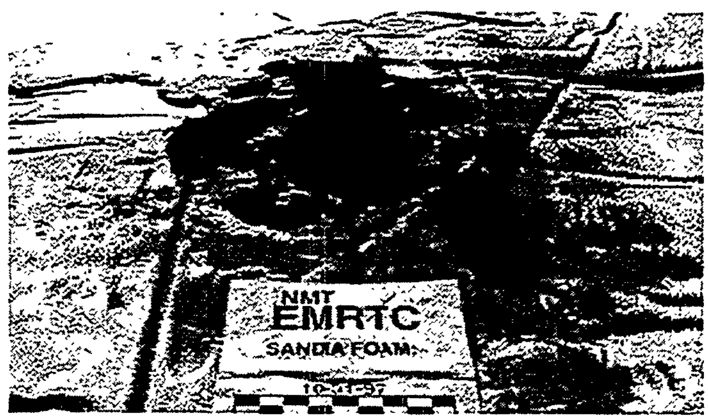

Figure 13. Test Block L-13

Foam Formation in the Surf Zone

Beginning in October 1997, Sandia conducted several experiments to characterize the reaction of NCFI 811-91 foam when poured into moving water. All experiments were conducted in the surf pond at EMRTC and, until early January 1998, most were poured into cold water. In general, the foam reacted well and rafted up even when formed in 50° water as long as the components were warmed to about 70° F. Foam was poured in a number of ways: from the beach down into the water's edge; into deeper water and back up onto the beach; in between wooden containment bars and onto a floating plastic mesh. There was no significant difference between the finished foam rafts. In all cases, the NCFI foam first sank toward the bottom, then began reacting, floated, and began consolidating into a surface mat. While it was still thin, the mat undulated with the wave action and, under some conditions, developed cracks from the motion. After a number of trials, a system was developed that worked quite well; pour great volumes of foam as fast as possible.

One problem that became apparent early was the criticality of timing a second layer pour. If the initial layer had not solidified well, the weight of the second layer of foam caused it to punch through the first layer and expand underneath. By waiting 5 to 7 minutes between layers, more regular layers were formed. It was discovered that four pours, about 7 minutes apart, would form a 12 to 18-inch thick foam raft. The bottom ½ inch was not full strength foam, becoming granular and crumbly due to entrainment of water. The rest of the layers were strong and bonded well to one another. Further lab work to define the layer timing was done in December 1997

By mid-January 1998, the efforts in earlier experiments culminated in a high degree of skill in pouring and producing the desired effects with RPF. It was possible to produce a foam raft 16 ft wide x 12 ft long and about a foot thick in 30 to 40 minutes (limited by the 60 lb/minute capability of the dispenser). This size raft could easily support more than 20 people and proved capable of supporting pickup trucks.

Figure 14 shows one of the early attempts to pour into moving water. Notice the irregularities.

Figure 14. Early Foam Raft in Surf

Figure 15 shows a better looking, more even raft poured in January 1998 in preparation for the TCG briefing.

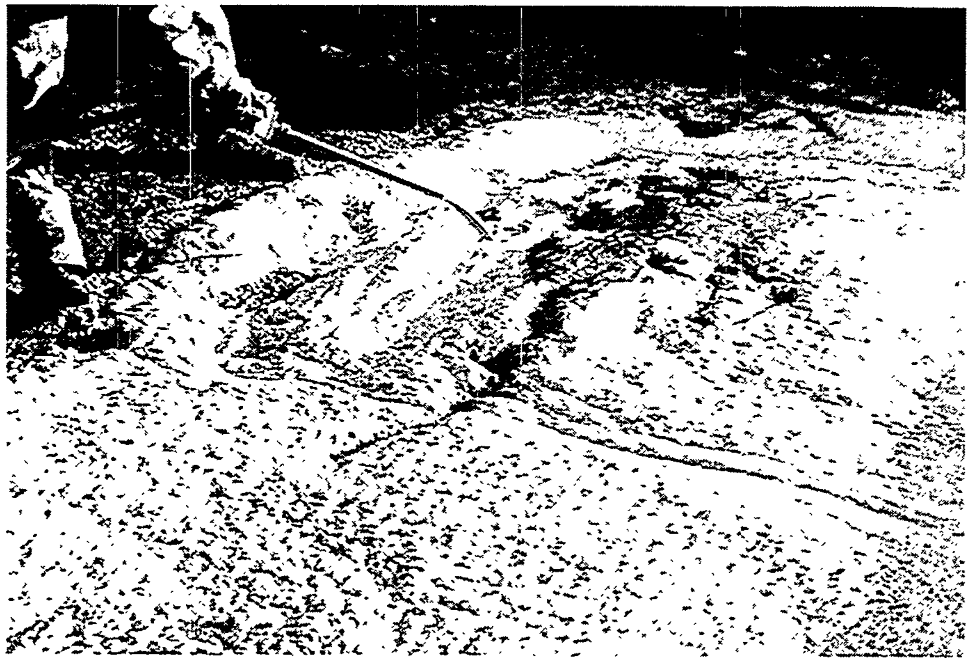

Figure 15. More Regular Raft Being Poured in January 98

The results obtained in the surf zone foam experiments indicate that the concept is quite feasible. Further experiments, with much larger equipment capable of pouring or spraying at least several hundred pounds/minute, are needed to establish utility in an assault role. Frothed foam (with air entrained), demonstrated by industry, appears to do an excellent job in surf and may become the material of choice. See page 2-24.

Underwater Mine Simulation Experiments

In late October 1997, we began to characterize the result of firing a simulated mine under foam in shallow water. EMRTC excavated a second, smaller pond adjacent to the south side of the surf pond. A series of underwater shots was conducted using 10 and 30 g PETN "patties" and nonelectric detonators. Charges were fired in contact with the underside of the foam; at 12 inches standoff; and at 24 inches standoff. Figure 16 shows the pond setup for a shot with the foam block still attached to the crane.

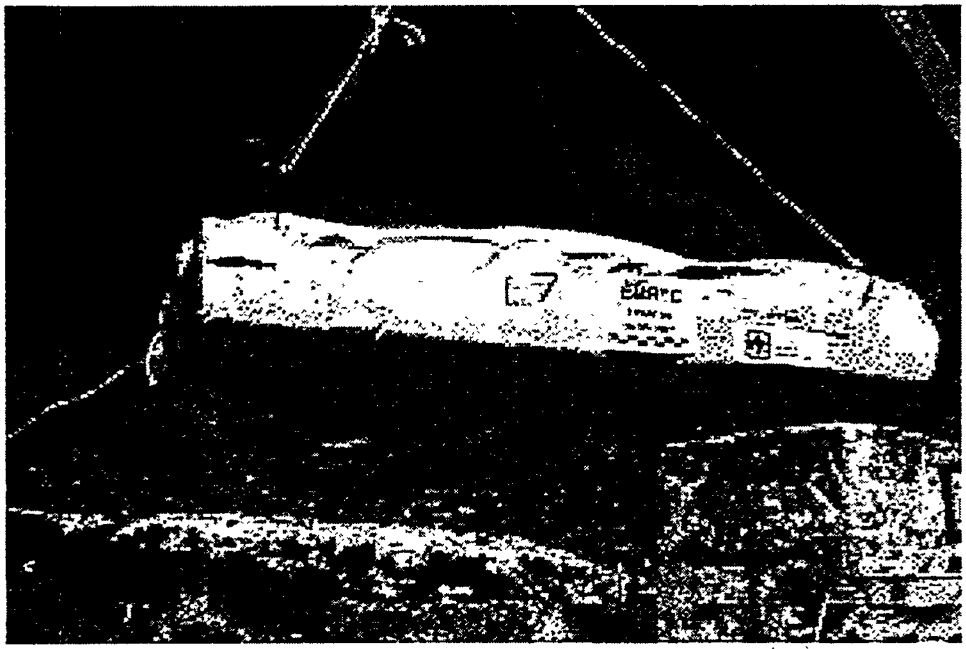

Figure 16. Pond Experimental Setup

Figure 17 shows the method of attaching a PETN charge below the foam. Screw eyes and nylon twine were used to suspend the charge a measured 12 or 24 inches below the block.

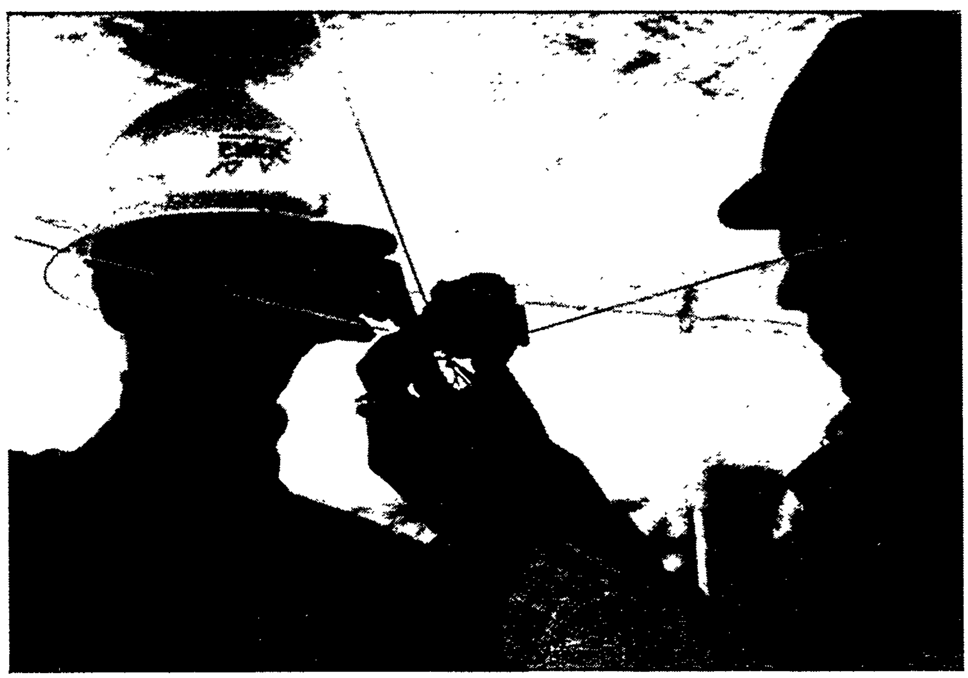

Figure 17. Ordnanceman Larry Kennedy and EMRTC Engineer Terese Anderson rig a 12 in. suspended charge, 50 g PETN, for the water shot.

Some of the blocks used in these underwater shots had been used for the previous land shots and the holes plugged with fresh foam. Where this occurred, the charge was offset to one corner of the block to impact on solid foam. Details of the experiment are in Appendix D.

The contact shots either fractured the block into large debris (30 g) or blew a shear plug out of the block (10 g). The standoff shots; **b**, **c**, and **d**, produced glass-like, round, brittle fractures that ranged from 22 to 40 inches in diameter depending on the charge size and distance. Shot **g**; 10 g PETN at 24 inches standoff, broke the block into five large segments without the brittle fracture pattern. Figure 18 shows block W8; a new cast 85 x 85 x 6-inch block after firing a 10 g PETN charge at 12 inches standoff. The circular fracture is about 22 inches in diameter.

Figure 18. Block W8; Exit (Top) Side

If these detonations had taken place under a large foam block suitable for driving heavy vehicles ashore, the result would have been minimal damage that could have been easily repaired. The brittle fracture phenomena has not been thoroughly investigated at this time.

Timing of Second Layer of Foam on Water

In December 1997, a series of scaled laboratory experiments was performed to better understand the time required for a layer of foam to cure in order to support a second layer. When cure time of the first layer is insufficient to support the weight of the second layer of liquid foam, the liquid breaks through the first layer and expands underneath. This produces lumpy, uneven layers and the foam loses strength from entraining water.

In this experiment, 100 g and 300 g batches of NCFI 811-91-3.3 lot 933 were mixed in a rotary mixer and poured into a 3-ft wading pool. Test weights were fabricated from lead and paraffin wax weighing 47.3 and 183.29 grams that represented the footprint of 0.75 and 3.0 inches of liquid foam. Water temperature was varied (55 to 70° F) and reaction mass was considered. Figure 19 shows the plots of time vs depth of liquid foam developed from the data.

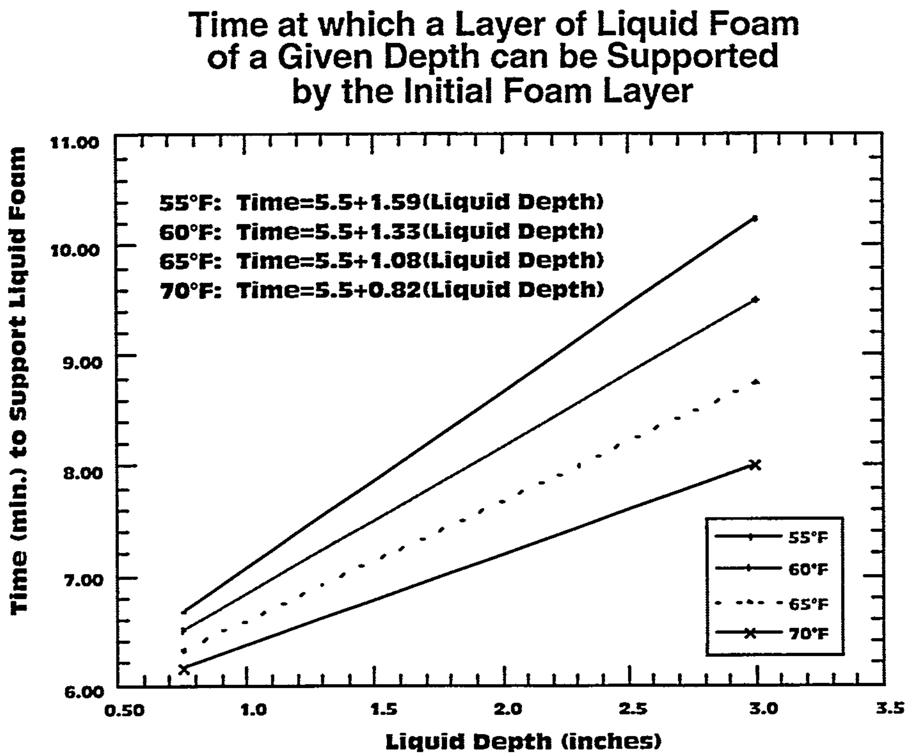

Figure 19. Time to Support a Second Layer

The conclusion from the generated data was that an eight-minute interval between the first and second pours should prevent any breakthrough. The memorandum experiment report is provided as Appendix E.

Mine Foam Interaction Experiment

In December 1997, an experiment was conducted to determine if fresh foam poured on an anti-invasion sea mine would stick, float, and move the mine enough to activate the fuze. A full-size mockup of a Soviet PDM tilt rod anti-invasion mine was made by EMRTC and placed on sand in a 7 x 9-ft steel tank. Water was added to cover the mine over the fuze with the tilt rod protruding above the surface. Approximately 100 lb. of foam was poured into the water and rose to form around the tilt rod to a thickness of 26 inches. No motion of the mine or tilt rod was observed. After the foam cured, it was easily lifted free of the tank and the foam block did not adhere to the mine or tilt rod. Inspection of the dummy mine revealed very minor traces of foam adhered to it, and almost none stuck to the fuze or tilt rod. It is apparent that it is highly likely that an anti-invasion mine would not fire when large volumes of foam were poured on it unless the tilt rod was encapsulated and the foam block shifted. RPF is not expected to neutralize tilt rod fuzed mines.

Figure 20 shows the dummy mine tilt rod sticking up through two feet of expanding foam.

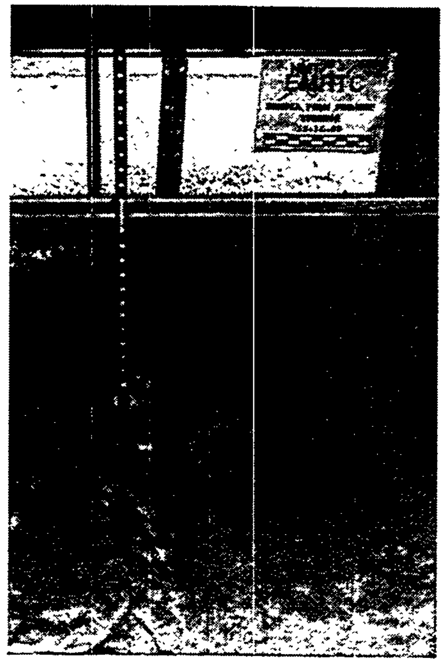

Figure 20. Dummy Mine Covered by Foam

Figure 21 shows the dummy mine after removal from the experiment tank.

Figure 21. Dummy Mine after Foam Interaction Experiment

Energy Absorption Experiments

In November and December 1997 a series of experiments was conducted to characterize the ability of RPF to attenuate the blast wave of an explosive detonation. "Top Hat" charges were assembled from PETN Detasheet at weights between 27 and 165 g to produce plane wave blast charges. The charges were mounted on the face of circular foam blocks 2, 4, 6, 9, and 12 inches thick by 15 inches in diameter. Below the foam was a ¼-inch thick steel plate and a set of piezoelectric pins to record the velocity of the flyer plate. Figure 22 shows the makeup of the charges and Figure 23 depicts the experimental setup.

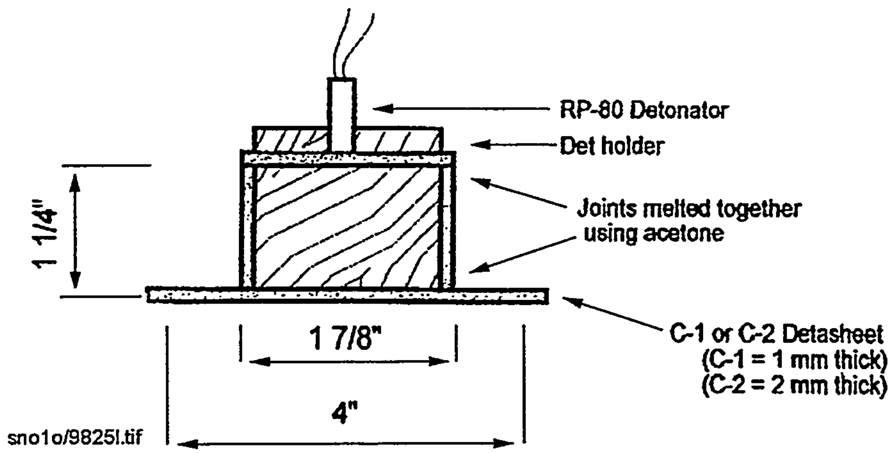

Figure 22. "Top Hat" PETN Charge

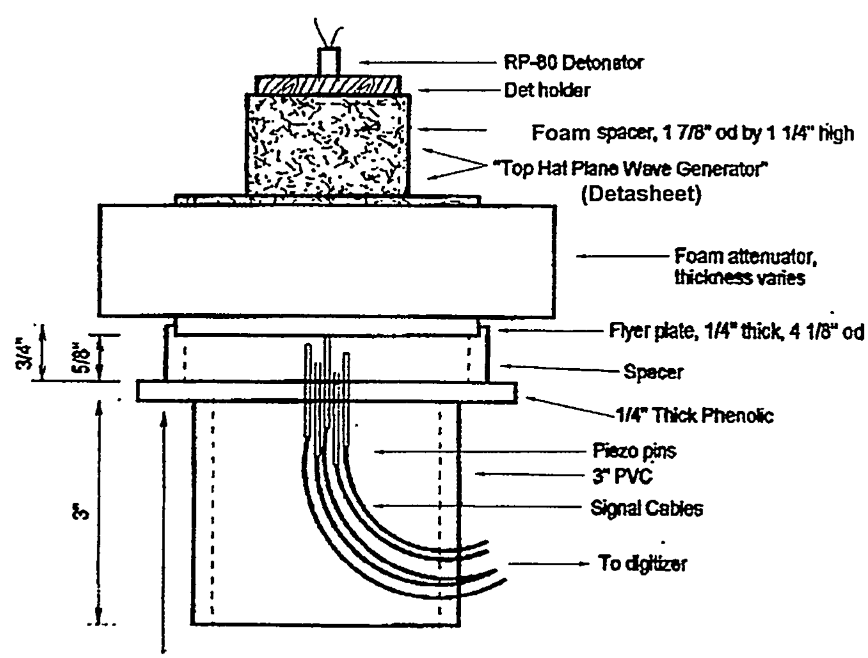

Figure 23. Experimental Setup

The output of the six piezo pins, spaced at 0.000, 0.050, 0.100, 0.130, 0.250, and 0.350 inches, was direct wired to a digital time interval recorder in the control room. All shots were fired remotely in a steel blast cell on the Little Eagle Range at EMRTC. In addition, plastic bags of cured 3.5 and 6 pcf foam were shot with the same size charges to obtain an idea of the cavity formation.

Fifteen shots were fired in 3.5 pcf foam with 1-mm thick charges (27.5 g) and 2 mm charges (45.5 g). Twenty-one more shots were fired in nominal 8 pcf foam (average density ~ 5.9 pcf) with charges of 1 mm (27.5 g), 2 mm (45.7 g), 4 mm (95.5 g), and 6 mm (153 – 166 g). Figure 24 shows one charge assembled on a 12-inch foam block.

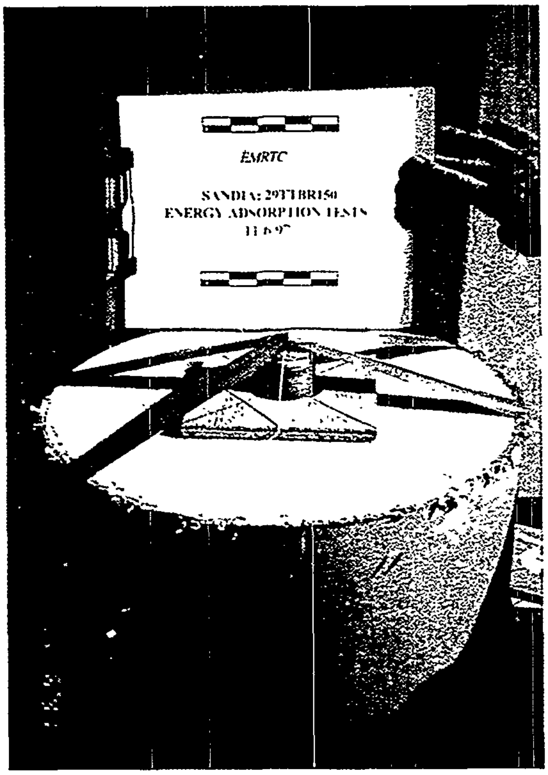

Figure 24. Assembled Foam and Charge

The general results of the two sets of attenuation data show that RPF materials do efficiently attenuate the kinetic energy (KE) of an explosive blast. Six inches of foam dropped the flyer plate velocity by 93% with the 2 mm charges, 85% with the 4 mm charges, and 85% with the 6 mm charges. Figure 25 shows the KE absorbed by the foam for 2, 4, and 6 mm PETN shots.

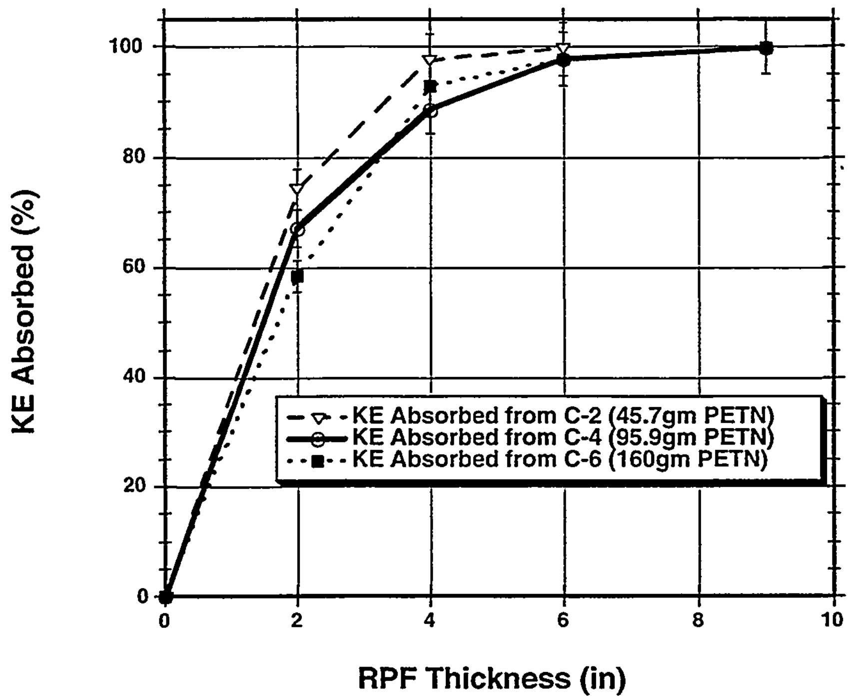

Figure 25. Percent of Energy Absorbed for 5.7 pcf Foam

Figure 26 plots the flyer plate velocity (mm / μ second) against foam thickness in inches.

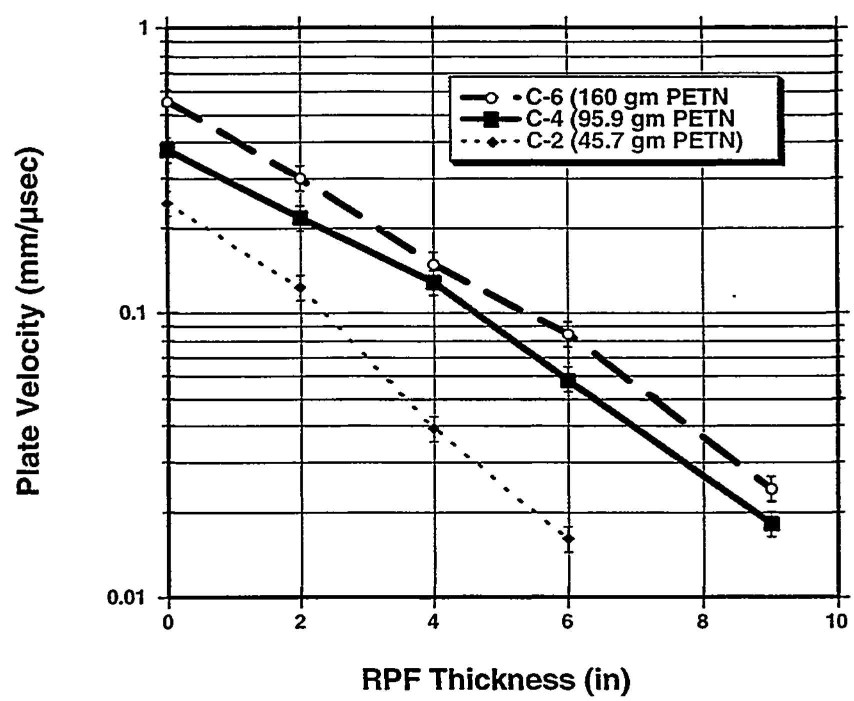

Figure 26. Data as Recorded (log scale)

Appendixes F and G present the original experiment summaries. Appendix H presents a technical paper summarizing the experiments that was submitted to the Mine Warfare symposium held at the Naval Postgraduate school, Monterey, CA in February 1998.

Surf Zone RFP Demonstration for TCG XV

In January 1998, as part of the regular semi-annual briefing of Sea Mine Countermeasures TCG, a demonstration of RPF in scaled surf was conducted at EMRTC. This half-day demo included pouring a four-layer raft of foam in the experimental pond with waves about 3 inches high. Following the linear scaling adopted (pg. 2-4), these waves represented the effects of surf about 5 feet high. The TCG also observed a 100 g PETN shot detonated under an 18-inch foam block and a 50 g shot underwater with a similar foam block. The foam raft in the surf pond took about 30 minutes to pour and easily supported a Chevy S-10 pickup after curing for another 15 – 20 minutes while the group watched the two explosive experiments. Figure 27 is a photo of the TCG members and attendees taken at the end of the Socorro demonstration.

Figure 27. TCG XV Group Photo 1/30/98

Figure 28 shows the Chevy truck being driven onto the foam as proof of its load carrying ability.

Figure 28. Chevy S-10 Truck on Fresh Foam Raft

The TCG demonstration was very successful. Driving the truck onto the foam raft that had just been poured favorably impressed the TCG members, and demonstrated the feasibility of the concept and method.

Sandia National Laboratories' Industry Workshop on RPF for Military Use

On May 12, 1998 Sandia hosted a workshop for vendors of RPF machinery and materials and interested military representatives. The purpose of the workshop was multifold:

- to inform industry of Sandia's research
- to expose new concepts for potential military uses of RPF
- to solicit industry responses on potential solutions to military needs, and
- to identify ways to develop new potential uses

The attendees were briefed on Sandia's perception of military requirements, some of the concepts being pursued, and the results of recent foam experiments. They were then informed of the basic requirements for a military foam dispenser that would have utility in an amphibious assault or combat support scenario:

- much higher application rates
- long throw distances

- multi-component mixes for a wide environmental range

Possible actions by the military services were hypothesized and discussed and Sandia's role in future foam system development was explained. Sandia solicited concept papers from industry discussing the ways foam and foam machines could be tailored to military needs.

A representative of the Coastal Systems Station briefed the group on the perspectives of the Navy Countermine community. The basic premises the Navy works from in assessing an assault from seaward were explained and the DET and SABER systems the Navy has in development were described. CSS described the hexagonal matrix that CSS and Sandia are working on as a joint between two foam barges. In explosive tests the hexagon mat stood up very well. It is expected that it will also withstand heavier seas than a rigid coupling would. Figure 29 illustrates the foam hexagon joint CSS is assembling.

Figure 29. CSS Foam Hexagon Mat

A Naval Facilities Engineering Service Center (NFESC) representative provided some additional concepts that are being examined by the Navy. NFESC views foam as most useful in the logistic role for getting heavy materials across a beach. Other possible uses might be for "disappearing packaging," stabilization of damaged buildings, barriers to channel enemy troops, and foam shelters for troops or humanitarian relief. Some of these ideas are listed in Figure 30.

Potential Uses

- **Surfzone interface for Lighterage**
- **Gap filler – Tank trap**
- **Beach roadway stabilizer**
- **Soft soil stabilizer**
- **Barriers – energy absorbing, deflecting**
- **Insulation**
- **Light structure support and construction**
- **Less than lethal technologies**

NAVAL FACILITIES ENGINEERING SERVICE CENTER

Figure 30. Potential Uses of RPF

A representative from ARA briefed the industry people on some Air Force concepts being investigated by the Air Force Research Laboratory (AFRL). Current interest is centered on rapid runway repair for the reuse of captured airfields. The Air Force is investigating foam to use in filling runway craters and in using the expansion to raise sunken runway slabs back into position. The Air Force would also like to see if they can use more dense foam to construct hardstands and taxiways for temporary use.

Sandia's transportation technology department representative briefed the industry attendees on some of the Army concepts for expeditionary harbors, causeways, and roadways to speed up the logistic process for combat resupply. They need to be able to offload into austere harbors in seas as high as sea state 3 and are looking for foam booms to mitigate the wave action and causeways to move trucks into and over the beaches. Roadways and hardstands are needed for mobility. Industry partners are needed to determine the limits of RPF in a military role and to develop machinery more suited to military use.

The group spent about half a day following the briefings in a brainstorming and informal data exchange session. Views, opinions, and technical data were brought forward and shared. The industry representatives provided data on alternative foam chemistries, equipment capabilities, logistics, and marketing. The military attendees provided details of their requirements, examples of operational constraints, some environmental concerns for testing, and questions on transportation issues.

Throwing foam out ahead of the machinery several hundred feet was a new concept to industry and poses a development challenge. Modifications to foam chemistry to change rise times or gain strength more rapidly appear to be more straightforward, but must be carefully coordinated with machinery design.

The informal discussions were both productive and enlightening. Both the military and industry attendees went away with a much better perspective of each other's constraints and strengths and a number of new foam use concepts.

Companies represented at the industry workshop were: North Carolina Foam Industries, General Plastics Manufacturing Company, Foamex International, Gusmer Corporation, Decker Industries, UCSC, and SWD Urethane.

Industry Foam Demonstrations

Following the Industry Workshop conducted by Sandia, several of the industry representatives suggested that demonstrations of foam technology for the military would be useful. On 15 and 16 June 1998, representatives of Gusmer Corp.; IPI International; Futura Coatings; and UCSC, Inc. brought their equipment and foam materials to EMRTC and provided demos of both machinery and foam products to Navy and USMC representatives. Sandia provided the EMRTC facilities and assistance.

IPI International demonstrated a canister foam machine using two 500 lb foam canisters and two nitrogen bottles for pressure. This machine was very compact and worked very well. The whole rig could have been strapped to one pallet and placed in the back of a HMMWV. It appears to be a design that would take very little modification to make a useful military machine. Figure 31 shows the IPI canister system.

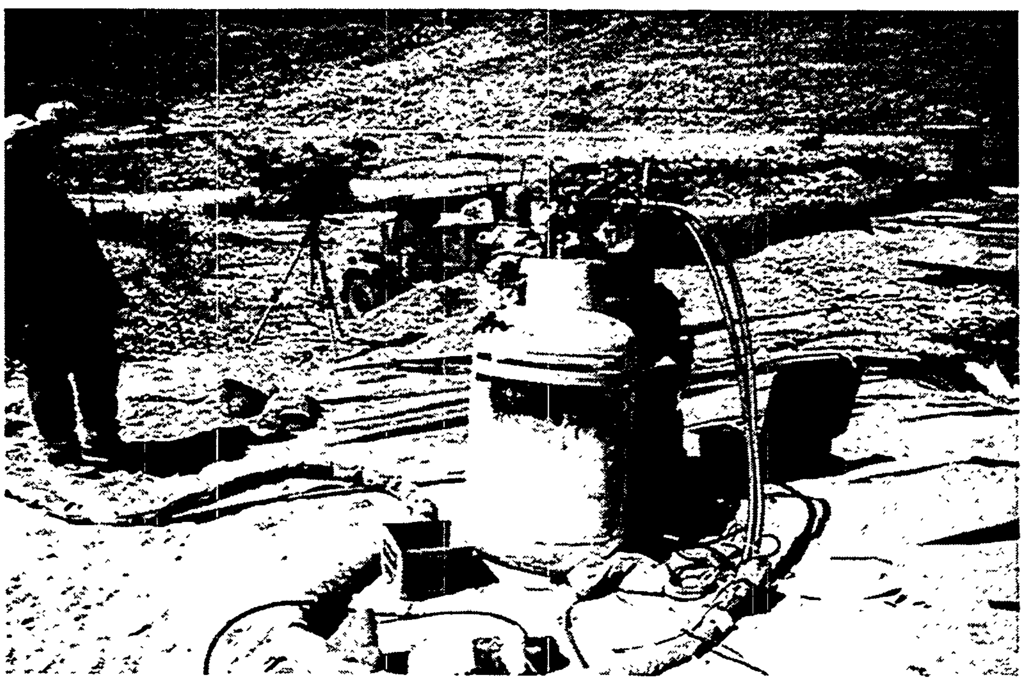

Figure 31. IPI Canister System

The IPI equipment is the simplest to operate seen to date and would be easy to train a military crew to use. The foam IPI used was a froth foam that did not sink in the water but floated and rafted up very rapidly. In about 15 minutes IPI built up a foam raft approximately 10 x 16 x 1 ft thick that was immediately capable of supporting a number of people. This frothing form of RPF is a recent development that has promise, in that it performs much better in water than the poured foam used in most of the experiments.

After the foam raft was finished, Futura Coatings demonstrated their polyurea elastomeric coating on both the foam surface and open water. This material would only support 100 lbs on open water but on the foam it produced a very tough, leathery surface that made the foam much more resistant to punctures or abrasion.

A second IPI/Futura demo was done to fill two "shell craters" dug in the dirt behind the experiment pond. These "craters" were 2 ½ to 3 ft. in diameter and about 2 ft. deep. IPI personnel filled them both to just below grade level and then Futura put a coating of their self-leveling elastomer on the top of one crater. After about 30 minutes cure time a 23,000 pound heavy forklift was driven over the craters and the patches remained intact. Figure 32 shows the craters and the improvised weight test.

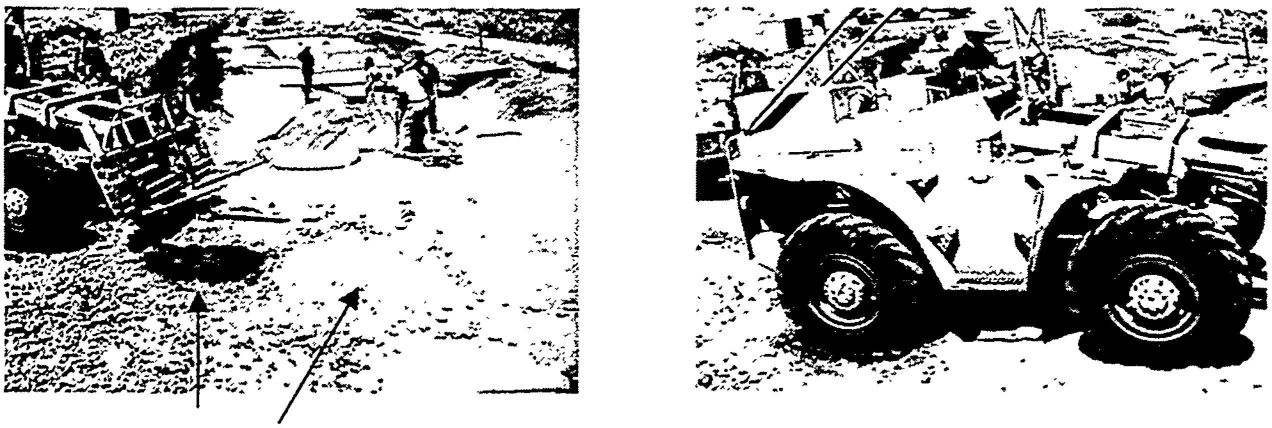

Figure 32. Load Testing Patched Craters

This method would provide a rapid way to patch road or runway craters caused either by nature or enemy action.

The third IPI demo constructed an expedient footbridge by spraying foam onto a 3 x 25 ft sheet of garden weedblock fabric. The foam was sprayed on one side only, about 4 inches thick in one 5 minute operation. After a few minutes curing time it was thrown into the experiment pond and proved capable of supporting a person with ease.

The last IPI demonstration was the formation of a small tent platform in a 4 x 8 ft. 2 x 4 frame. The frame was lined with sheet polyethylene and filled with foam to about 7 inches thick. The block came out of the mold smooth on the bottom side and would have made a fine tent floor. It also floated and proved capable of supporting a medium-size Marine.

Gusmer and UCSC conducted several demonstrations. UCSC demonstrated their Romer remote operated foam spraying vehicle. This machine uses Gusmer's H3500 foam mixer and lays down an even ribbon of foam 6 – 7 ft wide while moving at a constant rate on its own wheels. The Romer was designed to lay foam on large, flat warehouse roofs but if doubled in size would be capable of producing a foam roadbed. A larger but similar vehicle (described in the Phase I report) would be a real asset in making useable roads through soft sand or swampy areas. Figure 33 shows the Romer vehicle being set up and adjusted.

Figure 33. Romer Spray Machine

Gusmer Corp. demonstrated their H3500 foam machine with a fast froth foam. The foam had a very fast cream time but formed a very level raft on the water. The H3500, while more complex than the IPI rig, did an excellent job. Figure 34 shows the Gusmer H3500.

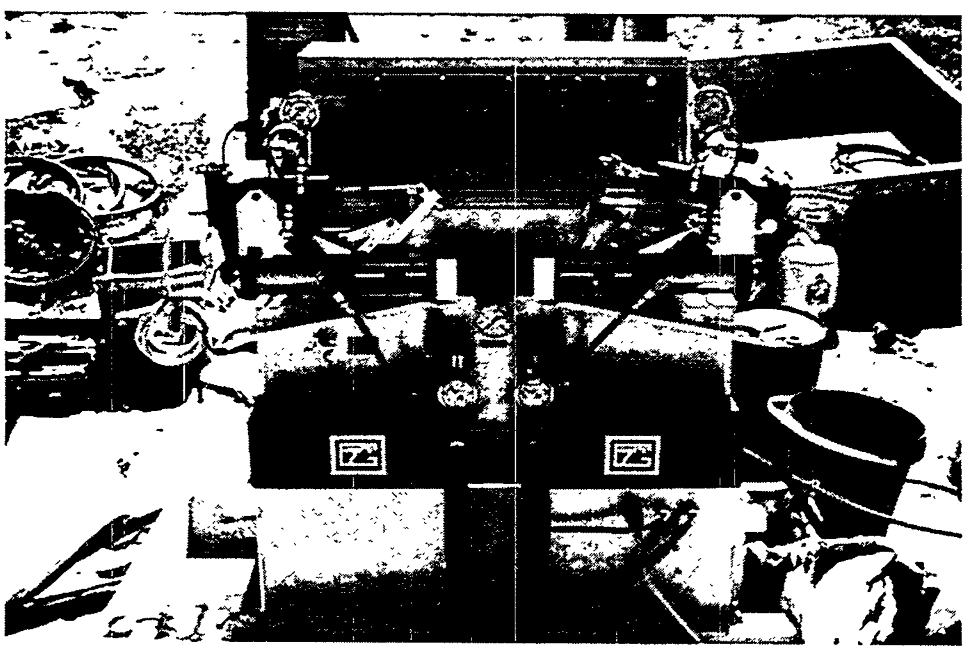

Figure 34. Gusmer H3500

Gusmer also demonstrated the making of an expedient footbridge on a material called Geotextile. A sheet about 4 x 16 ft was spread on the ground and foamed about 1 ½ inches deep on each side. The sheet was then cut through the center and the two pieces joined by ½ inch manila rope laid down and foamed over with another 2 inches of foam. The operation took about 10 minutes and resulted in a 6 inch thick bridge that folded to half its length. When thrown into the pond it easily supported two Marines. Figure 35 shows the results.

Figure 35. Hasty Folding Footbridge

The demos conducted by industry all worked quite well and showed the military people some different uses for foam. All the machinery can be simplified, militarized, and made "sailor proof" to some level. The IPI canister equipment appeared to be already hardened to the point where it could be easily adapted for use by soldiers or marines.

Ship Hull Preservation Experiments

In June 1998 an experiment was run to determine whether RPF material would absorb enough explosive shock to protect ship's hull plating from a nearby detonation.

Aluminum sheet, 0.19 inches thick by 24 wide and 36 inches high, was bolted into an angle iron stiffener frame to roughly simulate a ship hull. The plate readily available was Al 6061 alloy tempered to T-6; much harder than was really required. All shots were fired in EMRTC's pond which was, at the time, about 3 ft. deep. The shots were made up so that the plate was flat, right at the water surface, and the 250g PETN charge hung 24 inches below. One shot was fired on a bare plate. The other shots had 9, 3, and 1 ½ inches of 8 pcf foam glued to the plate between the aluminum and the explosive charge.

The bare plate sustained a large oval perforation roughly 5 ½ x 10 inches with the metal petaled back about 3 inches all around. None of the other plates sustained anything more than bowing in the center. The plate protected by only 1 ½ inches of foam was dished about ½ inch at the center.

From the experimental results, it appears that 8 pcf RPF did absorb much of the damaging blast and only 1 ½ inches of foam made a significant difference in damage sustained. A larger scale, more quantitative experiment is indicated to find the optimum thickness of foam. Figure 36 shows the plates from shots 2 and 5 after recovery.

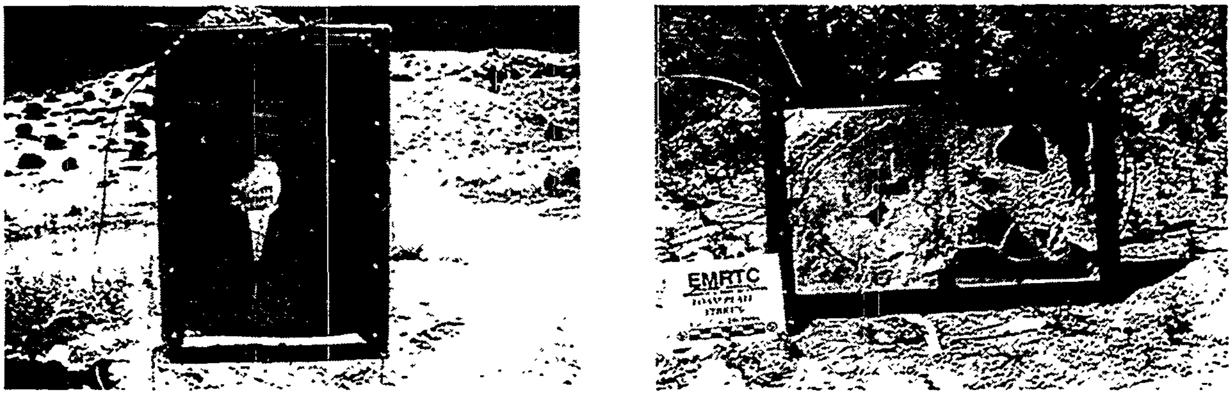

Figure 36. Comparison of shot 2 (bare) and shot 5 (1 ½ inch foam)

Because this may be a potentially patentable advanced process, a Technical Advance disclosure has been filed on the concept.

Bibliography of Foam Experiments

In order to fully explore the subject, a bibliography of previous foam experiments was assembled. All the listed documents are held by Sandia and some have been used in deciding what experiments were to be done. The bibliography is attached as Appendix K.

Foam Bridge Experiments and TCG Demonstration

During the week of 14 – 18 September 1998, a final series of experiments were conducted at Coastal Systems Station, Panama City, FL. These experiments were designed to prove the concept of constructing an RPF causeway in the surf zone using the CSS-designed hexagon raft as a connection between foam pontoons. A demonstration of the capability of the bridge to withstand wave action was conducted on September 18th.

The foam bridge experiments were conducted jointly by Sandia and CSS. Sandia designed and drew up specifications of RPF pontoons made up of heavy, waterproof nylon cloth which were then fabricated by CSS. These pontoon envelopes, in 8 x 16 x 1 ¼ foot sections, were shipped to New Mexico and filled with NCFI 3.3 pcf foam by Sandia personnel. CSS also fabricated six hexagonal molds 13 5/16 inches across the flats and 15 – 16 inches tall, similar in design to those described on page 2-6. The bridging material consisted of two 8 x 16 foot rigid pontoons connected by an 8 x 8 foot raft of hexagons lashed together with nylon line. Figure 37 shows one of the pontoons being filled by the Sandia crew. The matrix of nylon straps on the top and bottom provided shape control and connection strength to the pontoon ends. Thickness control was provided by insertion of a nylon lanyard of fixed length, at each intersection of the straps. These lanyards kept the top and bottom separated uniformly during curing. This technique proved simpler in the construction of the envelopes but caused the filling to be less uniform and more complex than that of the prototypes described on page 2–3. The lanyard system was adopted by the rigger who fabricated the envelopes because his sewing machine was not able to replicate the prototype in the pontoon size.

Figure 37. Filling RPF pontoons

Figure 38 shows one of the 70 hexagons with the foam growing up past the ½ inch PVC tubes used as fairleads for the nylon rope.

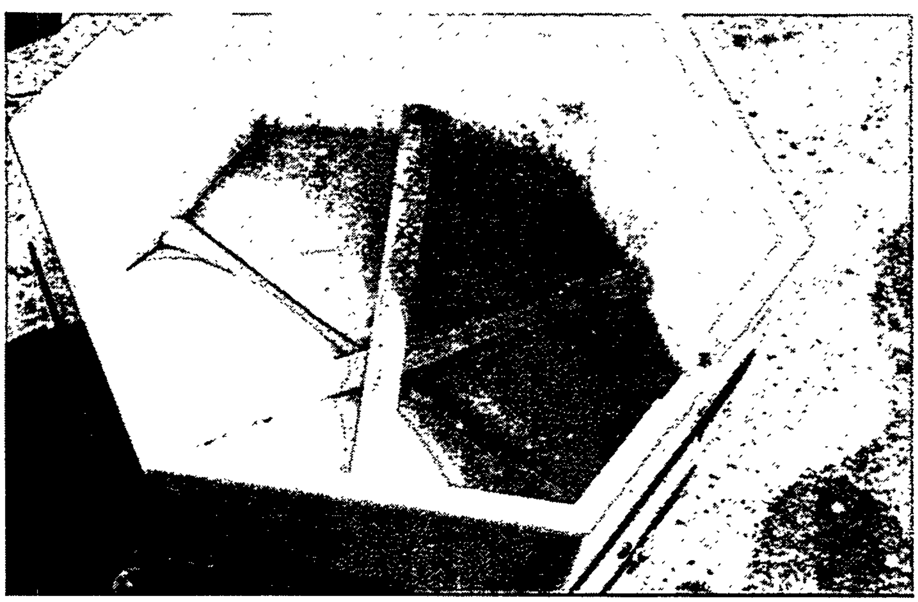

Figure 38. Foam Hexagon Pour

Scaling for these experiments was 1/5 of the full size bridge which would be 40 x 80 x 4 foot to take the loads of heavy tracked and wheel vehicles. The scaling in the model was distorted somewhat. These pontoons were about twice as thick as 1/5 scale would dictate. This made fabrication of the envelopes easier and the resulting pontoons were more robust for shipping. Sandia's coupling and configuration modeling is included as Appendix L. The flexibility of the matrix was adjustable by tightening or loosening the nylon lines.

Figure 39 shows the two rigid pontoons and the hexagonal raft connection. The small cart is loaded with a 1,000 lb lead block to provide a 1/5 scale approximation of an M1A1 tank.

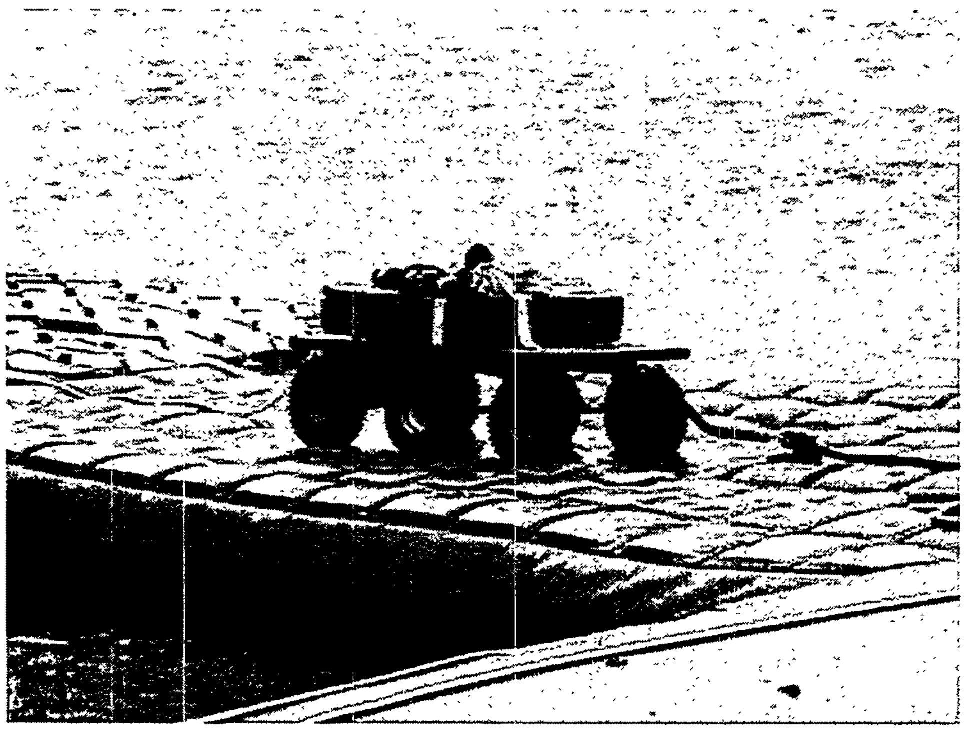

Figure 39. Foam Bridge and Cart

Three separate experimental series were conducted at CSS.

1. Deflection Experiment: 5 pound C-4 charges were detonated 10 feet from the bridge with the hex joint matrix in both tight and loose configurations.

2. Deflection/Tilt Experiment: The loaded cart was towed the length of the bridge, both on center and along the edge, without waves.

3. Deflection/Tilt Experiment in Surf: The loaded cart was towed the length of the bridge, both on center and along the edge, with wave action.

The CSS Test Plan "Foam Bridge Feasibility Study Demo Plan, 15 September 1998" contains all the details. [Reference 7]

In experiment 1, spherical C-4 charges were detonated 10 feet from the bridge and 2 feet below the surface of the test pool. In the first experiment the bridge remained stable and fairly rigid, sustaining no damage. The second shot, fired with the hex raft loosely connected, moved the bridge sections in all three dimensions. No damage to the RPF sections was caused by either detonation. Figure 40 shows the rather spectacular first test shot. Details of the experiments are provided in the memorandum reports in Appendix M and N.

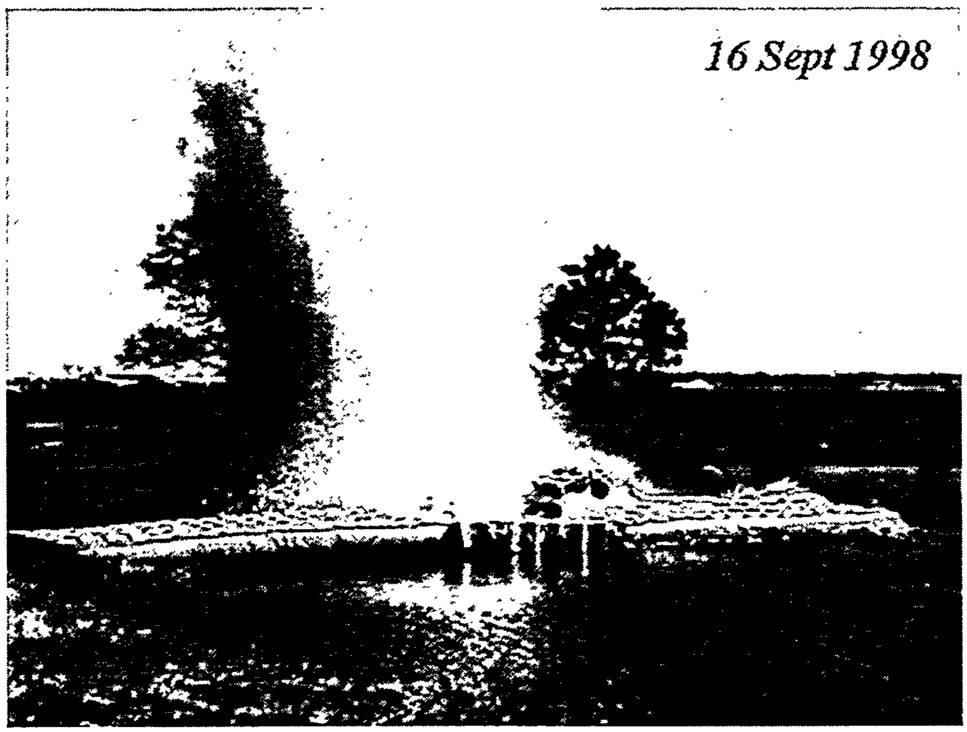

Figure 40. Explosive Experiment Number 1

Experiment 2 was conducted to verify the stability of the bridge under load but without wave action. The cart with its 1,000 lb load was towed from the seaward end of the moored bridge across the hex raft to the shore end, several times. It was towed the full length of the bridge on the centerline and also down one edge. Power was provided by a half ton pickup at the shore end. During the edge trial the bridge sections tilted only slightly, at an angle of something less than 10°. No problems were encountered in traversing the hex raft section.

Experiment 3 was a duplication of experiment 2 with the addition of 12 – 15 inch waves scaled to simulate 5 – 7 foot surf and created by a Zodiac boat. The waves were coming in from quartering to broadside of the length of the RPF bridge and sometimes broke across the seaward end. The bridge flexed in all three dimensions due to the wave action but the loaded cart traversed the full length of the bridge several times without problems. Traverses were made both on the bridge centerline and along the edge.

The RPF bridge is shown in Figure 41 during one traverse of the cart in experiment 3. The motion of the hex blocks and the different attitudes of the two rigid pontoons are clearly visible.

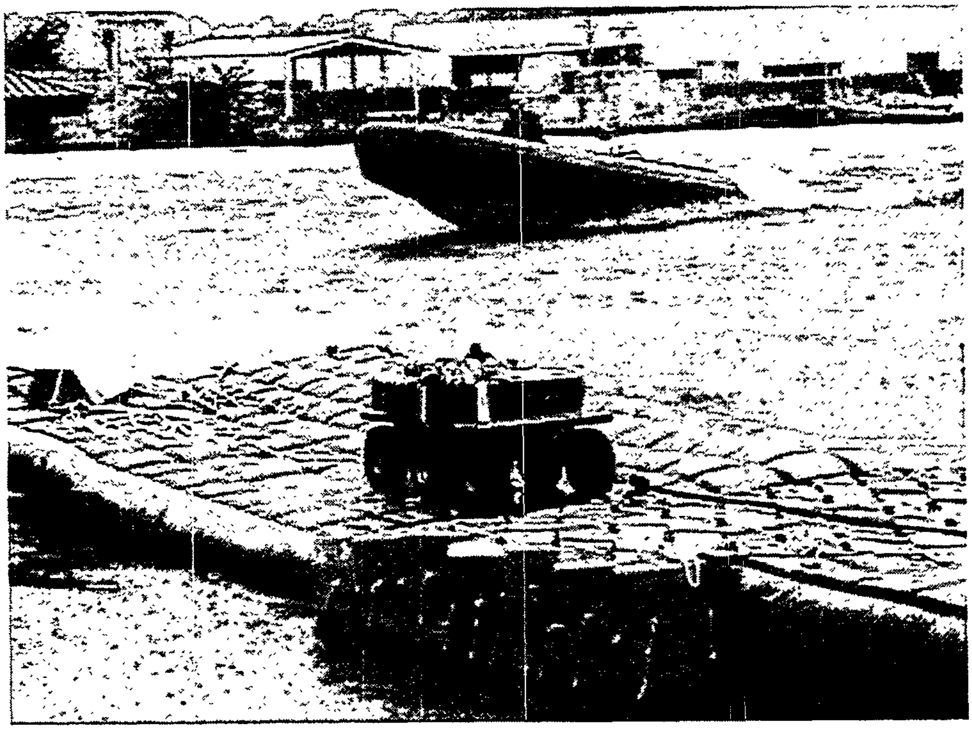

Figure 41. Experiment 3 Wave Action

It was concluded that a RPF bridge, pier, or causeway can be constructed in this manner and is capable of surviving surf or wave action. The hexagonal joint allows the rigid pontoons to move and flex without damage. Even with wave action that would scale to 5 or 6 feet there were no problems moving the cart with moderate towing power. This demonstration indicates that a foam causeway could be built to expedite the landing of either tracked or wheeled vehicles from an anchorage to an unimproved beach. It also shows that our prototype pontoon at 40 X 80 X 4 feet is probably overdesigned. The thickness could probably be reduced by nearly half and still be strong enough to carry the traffic. Future analyses will refine this design.

SECTION 3

Other Potential Uses for RPF

RPF can be used to fill a number of military roles, particularly in Logistics-Over-The-Shore (LOTS) and enhancing mobility in restrictive terrain. It promises operational advantages to both the field commander and the logistician that have not yet been explored. Figure 42 lists a few concepts with operational advantages.

Operational Advantages

- **Expanded geographic choices for LOTS site gives CINC added operational flexiblity**
- **Rapid emplacement enables earlier force closure**
- **Greatly reduced weight and cube compared to steel structures, additional watercraft, etc.**
- **Maintenance burden reduced - no rust, dents**
- **New material with untapped military potential**
  - **Engineer mobility/counter mobility**
  - **Motor pool hard stands**
  - **Dry floor for field billet applications**
  - **Helicopter landing pads; less FOD**

Figure 42. RPF Operational Advantages

Hard stands, for use as tent flooring, vehicle repair areas, and helo landing or repair areas were briefly explored during the demo by industry in June 1998. It was shown that foam pads of nearly any size can be quickly produced and can be formed over dirt, soft sand, swamp, or shallow water.

Foam road construction appears to be straightforward as shown by the Romer spray machine demonstrated by UCSC (see Figure 33). An enlarged version of this vehicle, discussed in Reference 1, would be capable of building an "instant road" over almost any terrain it could traverse. This would greatly enhance mobility, allowing combat resupply trucks/tracks to cross soft sand, shallow streams, swamps, or permafrost to deliver their supplies efficiently. It might also allow a commander to attack through an area known to be impassable to armor, thus creating a large tactical advantage. Figure 43 shows the concept.

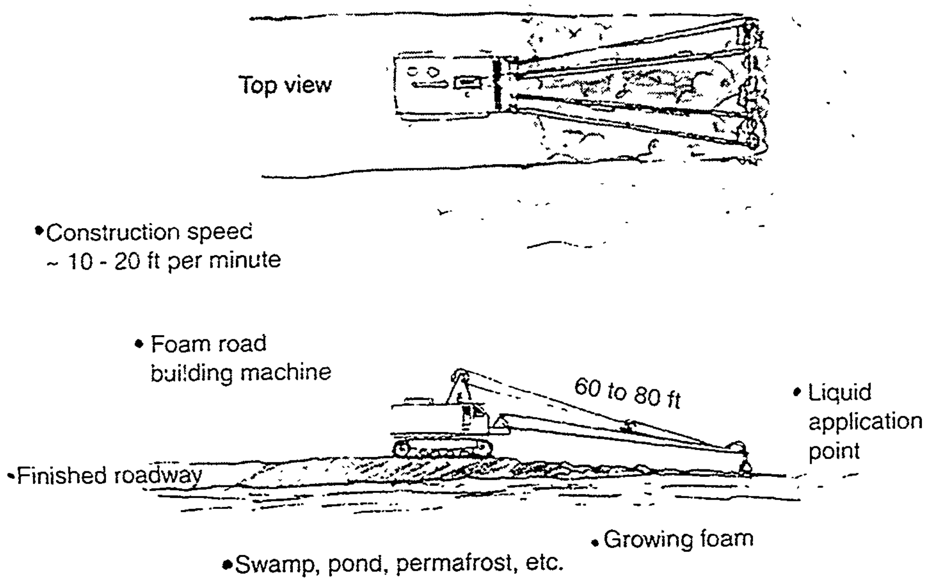

Figure 43. Foam Road Construction Concept

Foam could be used for filling in ditches, arroyos, or tank traps, thus enhancing the mobility of attacking troops. This concept is depicted in Figure 44.

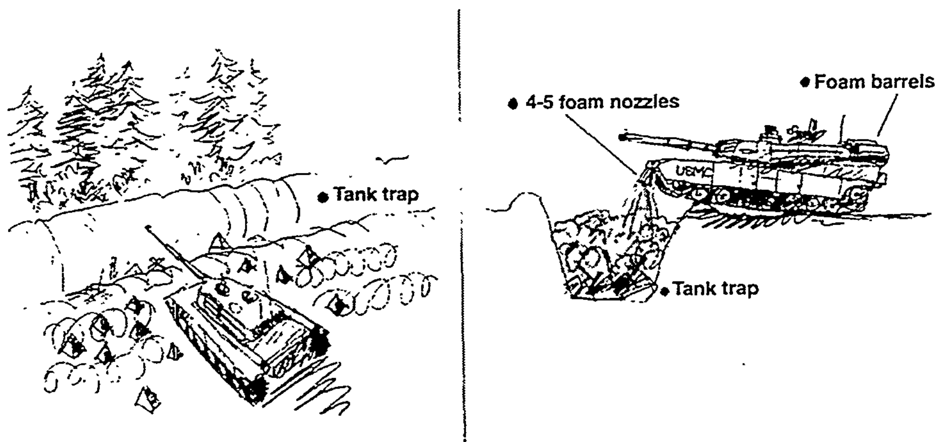

Figure 44. Tank Trap Filling Concept

Another concept being worked on is the use of foam pontoons for river crossing. Several fabric envelopes could be filled from a few barrels of foam to produce foam pontoons for a floating bridge. Light Forces could carry enough materials in one 5 ton truck to create a sizeable floating bridge. The bridge could be disassembled and brought forward for a subsequent crossing. Figure 45 shows this concept.

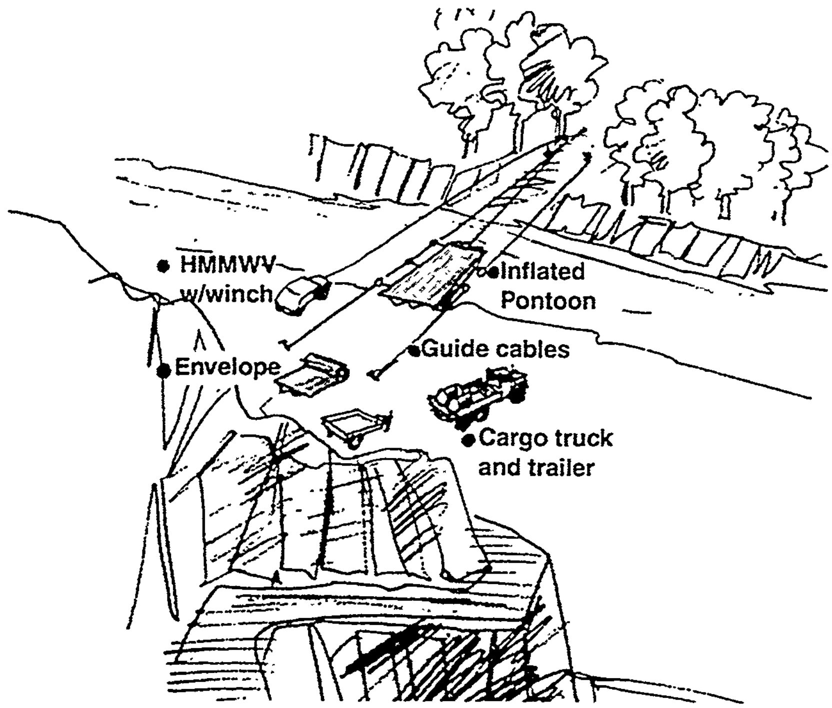

Figure 45. Foam Pontoons for River Crossing

Foam causeways for unloading in an austere harbor would allow troops to get their supplies and equipment ashore in an efficient manner. Foam can also be formed into large booms and anchored as a breakwater to allow lighterage in high sea states. Foam causeway sections might be equipped with large outboard motors and used as ferries or lighters to move equipment ashore. Figure 46 depicts the foam causeway concept.

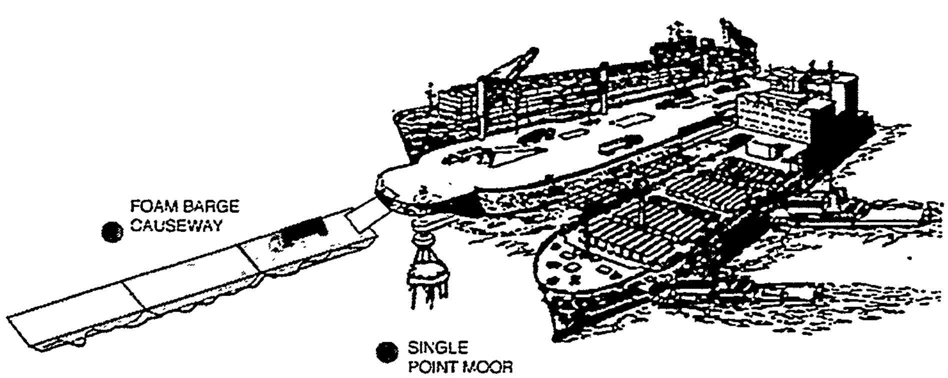

Figure 46. Rapidly Deployed Pier with Foam Causeway

In nearly every meeting held to explore RPF materials, someone comes up with another concept for their advantageous use. When these materials are provided to troops, such as an Engineer Company, they will find dozens of new and practical ways to use RPF.

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SECTION 4

Conclusions

After three full years of deploying the RPF material in a wide variety of hostile conditions, in ways it has not been used heretofore, and mistreating the finished product with vehicles, fire, explosions, and water, we have concluded that it can be a militarily useful material. It should be viewed as an alternate form of construction material which has significant advantages in transport and flexibility of use. The expansion ratio between the liquid components and the finished material means that the transport cube is greatly reduced, perhaps by as much as a factor of thirty. The ease with which we found it to be adaptable to new applications encourages us to believe that it will find more military uses than we have imagined.

This original concept of a bridge from the sea to the land, whether over obstacles in the surf, mines in the water or on the beach, or merely muddy tidal flats and soft sand beaches, can be realized for a variety of military scenarios, with a nominal development effort. It can certainly be done easily for follow-on echelons and resupply, but it appears possible to develop a system which could be placed sufficiently rapidly to enable the assault phase to use it as well.

These second phase experiments and analyses have demonstrated with substantial certainty that:

- RPF material can be deployed in moving surf to form a bridge capable of carrying military traffic
- RPF filled fabric pontoons can be prefabricated in a wide variety of sizes for on-site construction, and used for bridges, floats, boats and similar floating items
- RPF roadways can be made adequate to protect traffic from either anti-tank (AT) or anti-personnel (AP) mines on land
- RPF roadways can be laid, with almost no preparation, over soft sand, deep mud, or swampy ground sufficiently rapidly to enhance military operations
- RPF will absorb a substantial and predictable quantity of blast energy from an adjacent explosion
- RPF can be used to protect ship and/or craft structures from damage by underwater explosions
- RPF can be quickly formed from small kits for many auxiliary military uses including small foot bridges, tent floors, maintenance pads, helicopter landing or service pads, repair of shell craters in roads and runways, stabilization of loose terrain, habitability enhancement of tents in very hot or very cold conditions, and other uses not yet imagined

- The RPF industry in the US has the capability to produce appropriate dispensing equipment and chemical formulations for military applications

The exploratory work reported here should not be considered as sufficient to indicate that any specific military system has been designed or tested. Some detailed engineering work is still required before any military system can be fielded.

We are convinced by the experience gained here that the RPF material and the current dispensing processes are readily adaptable for use in a number of military situations, with consequent improvements in efficiency and effectiveness. It seems relatively straightforward to design systems for military use that will accomplish a variety of goals. As with any material, RPF is not a solution for all problems. Some past attempts by the services have tried to use RPF in ways inappropriate to its characteristics. Some considerations for its application are:

- The use should take advantage of the expansion ratio between the transported and finished products to reduce transport cube. Exploitation of this characteristic likely produces the greatest overall advantage.

- Unsinkable floating devices and systems fabricated near, or at the point of use, offer opportunities to expeditionary, light and special operations forces. This characteristic is intrinsic to the material; i.e. any shape or fragment will float and support non-buoyant objects. RPF can be formed in or on water at reasonable temperatures. (All the foams considered herein are of the closed cell form.)

- Load is better carried in shear and compression than in tension. RPF should be used structurally in a manner somewhat similar to concrete, in that tension-carrying reinforcement is needed for some applications. RPF efficiently spreads the pressure load so that applications of it over soft or unstable ground (or over mines), to distribute compressive loads, may be used to advantage. It would serve better as a road base material than as a floor spanning a cavity.

- RPF has moderate resistance to wear from traffic but would serve better for long-term use under a surface coating of some other material. This will also prevent UV degradation.

- RPF can be profitably used in situations where the local loading exceeds the material failure stress, if local damage is acceptable. The individual cell walls may break near the point of load while the load is quite adequately supported by the bulk of the RPF structure. This is because the load is rapidly, in a spatial sense, spread over a larger volume of the material.

- Concentrated puncture type loads or fasteners are not well supported by RPF of moderate densities if the dimensions of the loading device or fastener are such that only a few cells are loaded. The precise ratio of load area to cell "diameter" has not been determined in general. Higher density RPF has smaller cells and hence carries these loads and fasteners better.

- When using reinforcing for carrying tensile forces, or for connections, the concept of "development length" used in concrete design has a direct corollary in RPF design. This has not been precisely quantified.

- The elastic moduli are direct functions of density; hence the stiffness of a planned RPF block or pad may be increased by increasing its density, and conversely. A comprehensive tabulation of these data are not available in any known handbook since the material properties depend on the forming conditions. In general the mechanical properties will not be isotropic. Properties normally are obtained from the manufacturer or from direct measurements.

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REFERENCES

1. *Rigid Polyurethane Foam (RPF) Technology for Countermine (Sea) Program Phase 1*, SAND96-2841, R. L. Woodfin, Sandia National Laboratories, printed April 1996.

2. *Minutes of the Sea Mines Countermeasures Project Technology Coordination Group Meeting*, LATA, May 22, 1996.

3. *Minutes of the Sea Mines Countermeasures Project Technology Coordination Group Meeting*, LATA, February 19, 1997.

4. *Minutes of the Sea Mines Countermeasures Project Technology Coordination Group Meeting*, LATA, July 21, 1997.

5. *Minutes of the Sea Mines Countermeasures Project Technology Coordination Group Meeting*, LATA, January 29, 1998.

6. *Minutes of the Sandia National Laboratories' Industry Workshop on Rigid Polyurethane Foam (RPF) for Military Use*, LATA, May 12, 1998.

7. *Foam Bridge Feasibility Study Demo Plan,* Coastal Systems Station, September 15, 1998.

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Appendix A

Summary of Phase I Experiments

This appendix provides a very brief overview of Phase I work. Futher details are found in Reference 1

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A brief summary of the results of the Phase I experiments follows:

Small Arms: 2 pcf foam was fired into with 5.56 and 7.62 mm ball ammunition. Bullets completed perforated 12 feet 10 inches of foam without causing any damage other than the bullet hole.

Cannon Caliber: 2 and 4 pcf 54-inch blocks were impacted by a 30 mm high explosive (HE) incendiary projectile. The 2 pcf foam was completely perforated by the projectile that exited and detonated on the steel safety plate. In the 4 pcf foam, the projectile detonated after traveling 39 inches into the 54 inch block and blew a normal cavity out of the back of the block. The cavity could be easily repaired.

Flammability: Both standard and intumescent samples were burned. Neither experienced a flash fire. The intumescent foam did not survive any better than standard foam. When both 2 and 4 pcf foam walls were subjected to a diesel fuel fire, they burned like soft wood and self-extinguished as soon as the initiating fire went out.

Explosive Experiments: Explosive (C-4) charges ranging from 0.1 grams to 1 kg were fired as surface shots or embedded at the geometric center of both 2 and 4 pcf foam blocks. Both the surface and the embedded shots produced cavities of a diameter that corresponded very well with previous work done with RPF materials. Charge weights of 100 g and higher destroyed the 54-inch foam blocks because the blocks were not large enough to contain the generated pressure. The cavities formed could have been repaired if they had been formed in a large ramp.

POL Compatibility: Foam samples were soaked in lubricating oil, JP-8, and standard military alcohol antifreeze to determine their reaction to vehicle drips and leaks. No reaction was apparent after about a year of immersion in the POL products.

Foam Characterization: RPF materials from a number of sources were evaluated for their risetime, tack-free time, strength, and ability to perform in water. NCFI-811 was selected as the best of the candidates and was used throughout the Phase II experiments.

Trafficability: Four different vehicles ranging from 3 ½ tons to an M60 tank weighing 53 tons were driven over 54-inch cubes of 2 and 4 pcf foam. The ruts created were carefully measured and plotted. The conclusions from a lengthy series of traffic experiments were that 2 pcf foam was marginal for heavy tracked vehicles, but 4 pcf material stood up quite well. Figure 1 shows the number of passes required to rut the foam to a 12-inch depth where the vehicles begin scraping the foam surface.

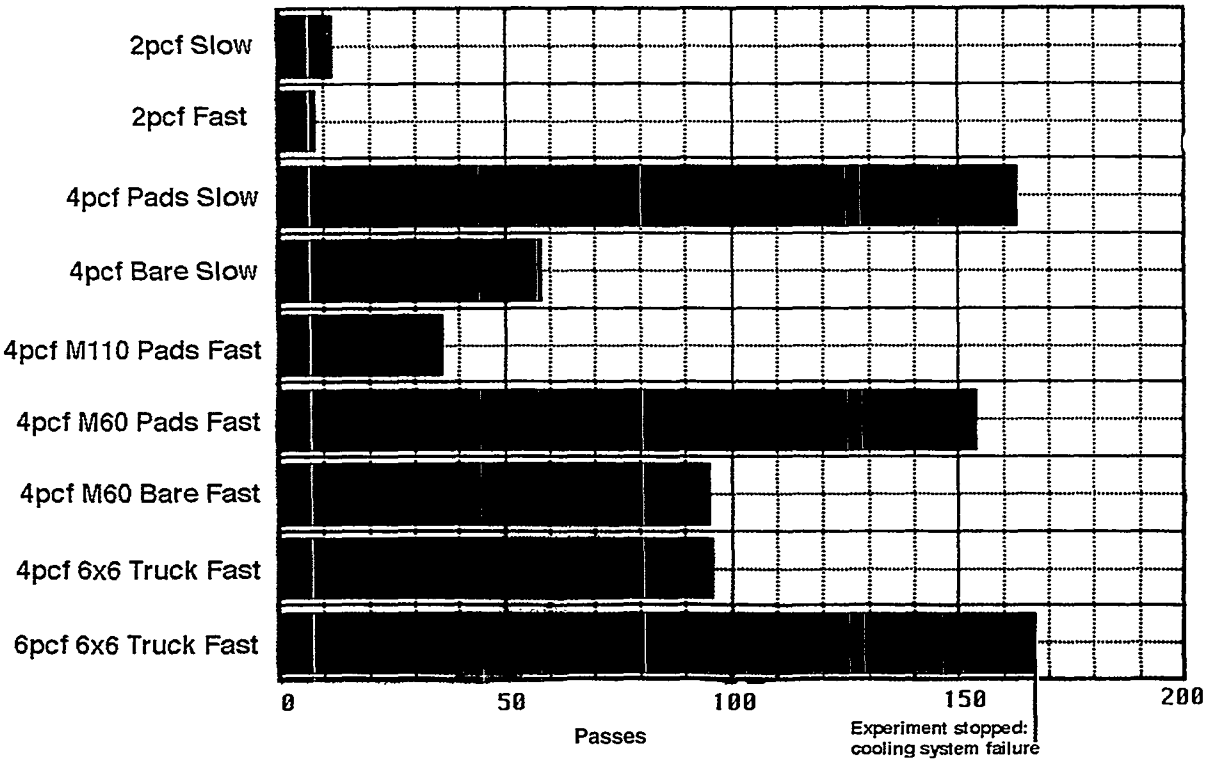

Figure 1. Number of Passes to Create 12 inch rut

Road Repair: Four blocks of 6 pcf foam were embedded in roadways at EMRTC and driven over daily. The foam withstood this moderate traffic for about six months.

Appendix B

Explosive Effects Experiments on Rigid Polyurethane Foam

CPT Al Alba, USA

This appendix outlines CPT Alba's plan for simulation of anti-personnel landmines under RPF slabs.

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Explosive Effects Experiments on Rigid Polyurethane Foam
Exploratory Sensors & Munitions Department
Sandia National Laboratories
Albuquerque, NM 87185-0860

1. Task: Evaluate the explosive effects of a simulated land or sea mine on a block of Rigid Polyurethane Foam (RPF).

2. Location: Field experiments will be conducted at the Energetic Materials Research and Testing Center (EMRTC) of the New Mexico Institute of Mining and Technology, Socorro, NM on 11-17 August 1997.

3. Concept of the Experiment: We will study the cavity formations that result from detonating simulated mines placed underneath blocks of foam located on both land and water. The following parameters will be varied in order to achieve sufficient data: depth of mine, thickness of foam, and charge size. Land experiments will be conducted before the water experiments.

4. Land Experiments: Figure 1 shows the set-up for the land experiments.

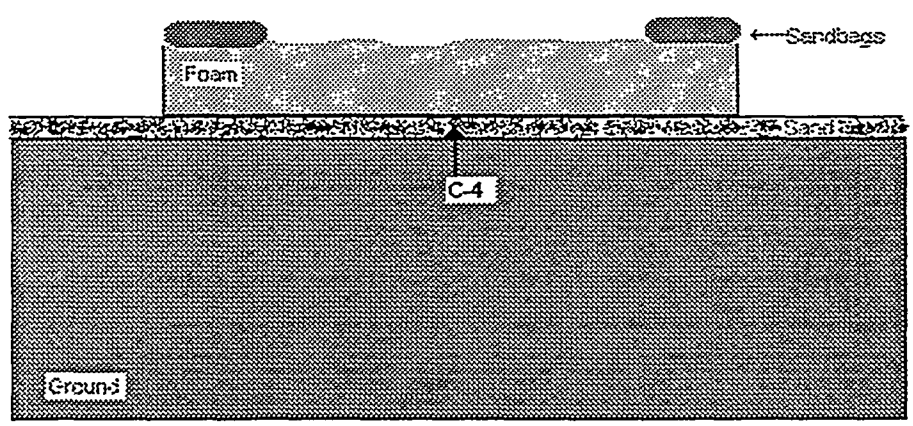

Figure 1. Set-up for Land Experiments

EXPERIMENT #L1

A 3.3 pcf block of foam with dimensions 65 X 65 X 6 inches will be placed directly on top of 2-3 inches of sand which will be uniformly spread over flat ground. A 20 gm C-4 explosive will be placed in the sand directly underneath the geometric center of the foam. The top portion of the explosive will maintain contact with the block of foam. Sand bags will be placed on top of the edges of the foam in order to keep the foam from entirely lifting off the ground after detonation. Video will cover frontal and top views. After detonation, we will conduct crater measurements and take video and still shots of the foam.

EXPERIMENTS #L2 - #L12

These experiments will be conducted using the parameters from the following matrix:

Expt #	Task #	Medium		Block Size (in)	Charge Size (gms)		Charge Depth (in)*	
		Land	Sea		10	30	0	6
L1	L610	X		65 X 65 X 6	X		X	
L2	L616	X		65 X 65 X 6	X			X
L3	L630	X		85 X 85 X 6		X	X	
L4	L636	X		85 X 85 X 6		X		X
L5	L1210	X		65 X 65 X 12	X		X	
L6	L1216	X		65 X 65 X 12	X			X
L7	L1230	X		85 X 85 X 12		X	X	
L8	L1236	X		85 X 85 X 12		X		X
L9	L1810	X		65 X 65 X 18	X		X	
L10	L1816	X		65 X 65 X 18	X			X
L11	L1830	X		85 X 85 X 18		X	X	
L12	L1836	X		85 X 85 X 18		X		X

Figure 2. Land Test Matrix

* The charge depth will be measured from the bottom layer of the foam.

5. Water Experiments: An artificial pond will be constructed with the following specifications:
   Dimensions: 15 X 15 X 6 (ft)
   Water Depth: 5 ft

Figure 3 shows the set-up for the water experiments.

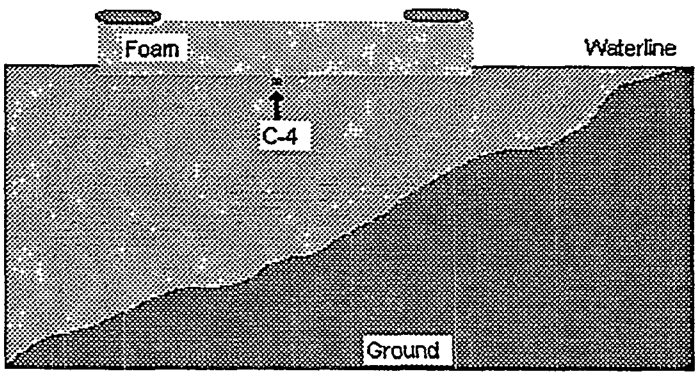

Figure 3. Water Set-up

EXPERIMENT # S1

A 3.3 pcf block of foam with dimensions 65 X 65 X 6 inches will be placed on the surface of the water. A 20 gm C-4 explosive will be placed directly underneath the geometric center of the foam. The top portion of the explosive will maintain contact with the block of foam. Wire guides or strings tied to the corners of the foam will keep the foam in place, and sand bags will be placed on top of the edges of the foam in order to keep the foam from entirely lifting off the ground after detonation. Video will cover bottom (underwater) and top views. After detonation, we will conduct crater measurements and take video and still shots of the foam.

EXPERIMENT # S2

Repeat S1 but change the charge depth to 12 inches. The charge will be suspended by string from the geometric center of the foam.

EXPERIMENTS #S3 - S12

These experiments will be conducted using the parameters from the following matrix:

Expt #	Task #	Medium		Block Size (in)	Charge Size (gms)		Charge Depth (in)	
		Land	Sea		10	30	0	12
S1	S610		X	65 X 65 X 6	X		X	
S2	S612		X	65 X 65 X 6	X			X
S3	S630		X	85 X 85 X 6		X	X	
S4	S632		X	85 X 85 X 6		X		X
S5	S1210		X	65 X 65 X 12	X		X	
S6	S1212		X	65 X 65 X 12	X			X
S7	S1230		X	85 X 85 X 12		X	X	
S8	S1232		X	85 X 85 X 12		X		X
S9	S1810		X	65 X 65 X 18	X		X	
S10	S1812		X	65 X 65 X 18	X			X
S11	S1830		X	85 X 85 X 18		X	X	
S12	S1832		X	85 X 85 X 18		X		X

Figure 4. Water Test Matrix

6. Point of Contact for this experiment is Dr. Ron Woodfin, 844-3111.

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Appendix C

Thesis Research on Rigid Polyurethane Foam: Phase II

This appendix details CPT Alba's experiments and findings at EMRTC and Waterways Experimental Station.

The traction experiments described represent an unfortunate misuse of the RPF materials. WES personnel, without much experience with RPF, and against Sandia's advice, configured the traction experiment in a manner that guaranteed failure. The RPF layer applied was too thin to carry the loads imposed by an M88 retriever when formed on water. The experiment could have suceeded had it been conducted properly.

RPF which is laid in water entrains liquid water in the cells until it floats enough to raise the freshly forming material above the surface. that RPF material which entrains the water is found to be very brittle and weak, sufficient only to form a base for a layer with normal structural characteristics. When laid thickly enough this process is automatic. In the unfortunate situation at WES sufficient material for only about two inches of finished RPF was laid in two inches of water. All this material was then of the inferior strength form. Had enough material been laid to form a finished layer about six inches thick, the traction experiment with the M-88 could have been made to succeed. This was done in the later experiment with the HMMWV, where the benefit was not expected to be as much, even with success.

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NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

THE USE OF RIGID POLYURETHANE FOAM AS A LANDMINE BREACHING TECHNIQUE

by

Albert L. Alba

December 1997

Thesis Advisor: X. K. Maruyama

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13. ABSTRACT *(maximum 200 words)*

The results of a feasibility test using Rigid Polyurethane Foam (RPF) as an operational anti-personnel mine counter-mine technique are presented. RPF, at a given density and thickness, can withstand the explosive effects of anti-personnel blast mines and mitigate or neutralize the effects of surface laid anti-vehicular mines. A 12-inch thick, 4 pound per cubic foot foam block completely contained a 10 gram explosive charge of PETN while a 30-inch foam block with the same density contained a 30 gram charge. A 24-inch thick pad supported 50 passes of an M88A2 Recovery Vehicle, crushing the foam no more than 2-3 inches throughout the length of a 56 foot foam roadway. Underneath this roadway, simulated land mines set at 14 psi were not detonated by the passage of an M88A2 and a HMMWV. Our experiments indicate that RPF can provide additional traction in muddy conditions and set-off explosives connected to trip wires. The pressure and trafficability experiments were conducted at the Waterways Experiment Station, Vicksburg, MS in July-August 1997, and the explosive experiments were conducted at the Energetic Materials Research and Testing Center (EMRTC) of the New Mexico Institute of Mining and Technology, Socorro, NM in August and October 1997.

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THE USE OF RIGID POLYURETHANE FOAM AS A LANDMINE BREACHING TECHNIQUE

Albert L. Alba
Captain, United States Army
B.S., United States Military Academy, 1989

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN APPLIED PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
December 1997

Author: ______________________
Albert L. Alba

Approved by: ______________________
X. K. Maruyama, Thesis Advisor

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R. Woodfin, Second Reader

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W. Maier, Chairman
Department of Physics

ABSTRACT

The results of a feasibility test using Rigid Polyurethane Foam (RPF) as an operational anti-personnel mine counter-mine technique are presented. RPF, at a given density and thickness, can withstand the explosive effects of anti-personnel blast mines and mitigate or neutralize the effects of surface laid anti-vehicular mines. A 12-inch thick, 4 pound per cubic foot foam block completely contained a 10-gram explosive charge of PETN while a 30-inch foam block with the same density contained a 30-gram charge. A 24-inch thick pad supported 50 passes of an M88A2 Recovery Vehicle, crushing the foam no more than 2-3 inches throughout the length of a 56 foot foam roadway. Underneath this roadway, simulated land mines set at 14 psi were not triggered by the passage of an M88A2 and a HMMWV. Our experiments indicate that RPF can provide additional traction in muddy conditions and set-off explosives connected to trip wires. The pressure and trafficability experiments were conducted at the Waterways Experiment Station, Vicksburg, MS in July-August 1997, and the explosive experiments were conducted at the Energetic Materials Research and Testing Center (EMRTC) of the New Mexico Institute of Mining and Technology, Socorro, NM in August and October 1997.

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LIST OF ACRONYMS AND ABBREVIATIONS

EMRTC	Energetic Materials and Research Center
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
MDI	Diphenylmethane Diisocyanate
MSDS	Material Safety Data Sheet
NCFI	North Carolina Foam Industry
RPF	Rigid Polyurethane Foam
SNL	Sandia National Laboratories
WES	Waterways Experiment Station

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I. INTRODUCTION

Mines, both anti-tank and anti-personnel, have been combat multipliers in past and present battlefields. When properly employed, mines can drastically reduce a unit's ability to maneuver its forces and synchronize its efforts on the battlefield. Currently, our land forces have breach in-stride techniques and countermine systems that can reduce a 300-meter long obstacle within ten minutes, but these techniques and weapon systems are slowly becoming obsolete against the rapidly evolving mine technology and techniques. Harry Hambric [Ref. 4] contends that the United States has made very little countermine progress since World War II, instead, the focus has been on developing fuzing, lethality, and emplacement technologies. This study presents new results using Rigid Polyurethane Foam (RPF) to improve current breaching techniques. The scope of this study is centered on anti-personnel mines, however this report also includes results of experiments that can be extended to anti-tank mines.

The purpose of this study is to determine if rigid polyurethane foam can be used to either neutralize or efficiently attenuate the explosive effects of surface or subsurface laid anti-personnel mines. It will also determine if the foam is a viable system for operational use on the modern day battlefield. Feasibility experiments in the areas of trafficability, traction effects, trip wire reduction, foam repair, and explosive cavity formations will provide information to determine the foam's applicability in military operations. One possible application is to spray the foam on a minefield and allow a combat unit to continue through the obstacle field with speed and avoid losses to the covering enemy unit. Rigid Polyurethane Foam could also be used as a temporary walkway as part of humanitarian efforts to protect civilian populations from mines left behind after a conflict.

Chapter I will introduce the purpose of this study. Chapter II will discuss the properties of Rigid Polyurethane Foam and discuss previous work that has been done by Sandia National Laboratories. Chapter III will describe the experimental set-up, conduct, and results of the feasibility experiments conducted by Waterways Experiment Station, MS, and Sandia National Laboratories. Chapter IV is dedicated to the analysis of the results from Chapter III, and Chapter V will discuss the conclusions of this study. Chapter VI will discuss other areas of consideration such as underwater explosive effects on foam, energy absorption properties of the foam, and logistical issues regarding the foam's delivery package and performance in all weather conditions.

II. BACKGROUND

A. RIGID POLYURETHANE FOAM (RPF)

The RPF chosen for these feasibility experiments, NCFI 811-91, is a two-part liquid which can expand up to 60 times its original volume. The amount of expansion will depend on the desired strength of the foam. Because of this considerable volume expansion, this foam can be transported in minimum bulk for possible military applications. The two chemicals are 1,1-Dichloro-1-flouroethane (CH_3CCl_2F or HCFC-141b) and Polymethylenepolyphenylisocyanate (Polymeric MDI). The first chemical is the Polyol resin and the second chemical is the isocyanate. The mix ratio of the chemicals by volume is one part resin to one part isocyanate. The mix ratio by weight is 100 parts resin to 106 parts isocyanate. It has a cream time of 55-65 seconds and a rise time of 3-4 minutes [Ref. 7, 8].

Polyurethanes are formed from the reaction of a polyol with an isocyanate. The polyol, which means multiple alcohols or multiple OH groups, reacts with isocyanate, which is the N-C-O combination of atoms. When these two monomers combine, a more stable molecular structure results from the molecular rearrangement. Figure 1 shows the basic reaction to form polyurethanes [Ref. 12:p. 232]. R is usually a multifunctional polyether but can also be a small organic group while R' is usually a large aromatic group. Diisocyanate is a type of chemical compound that has two isocyanate groups [Ref. 12:p. 232].

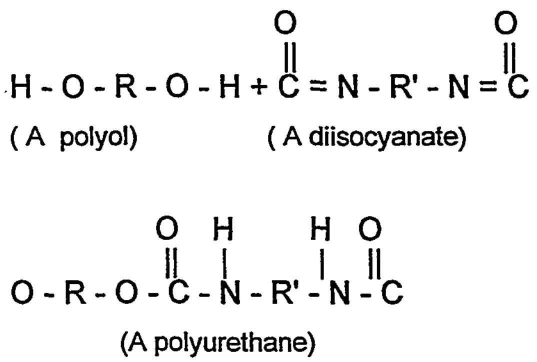

Figure 1. Basic formation of polyurethanes, polyol + diisocyanate from Ref. [12].

Rigid polyurethane foams are produced from the reaction of multifunctional polyols and multifunctional, polymeric isocyanates. RPF is highly crosslinked and has densities ranging from 5 to 15 lb/ft^3.

RPF has been used in a variety of applications, such as in the automotive and building industries, but it has been primarily used for thermal insulation, specifically for frozen containers fitted for trains, trucks, aircraft, and ships. In the automotive industry, RPF is used to fill longitudinal runners, motors, and trunk hoods in order to provide additional stiffening. The building industry uses RPF to fill gaps between door casings and walls [Ref. 5:p. 259].

B. PREVIOUS WORK DONE BY SANDIA NATIONAL LABORATORIES

1. General

Dr. Ronald Woodfin of the Exploratory Sensors and Fusing Department of Sandia National Laboratories conducted extensive experiments on RPF from November 1995 through February 1996. His results are contained in SAND96-2841. This Phase I report focuses on the "development of a foam that can neutralize mines and barriers and allow the safe passage of amphibious landing craft and vehicles" [Ref. 13: Abstract]. Phase I concentrated on the following areas:

- Laboratory characterization of foam properties
- Field experiments with prefabricated foam blocks in order to determine its capability to carry military traffic
- Flammability characteristics
- Response to bullet impact
- Toxicity
- Explosive cavity formation from surface and subsurface shots

2. Summary of Results

a. *Foam Properties*

Peter Rand [Ref. 10], a foam expert from Sandia National Laboratories, conducted the foam property tests and determined that the compressive strength of the foam selected for the Phase I experiments, NCFI 811-91, increases rapidly with increasing density. He also noted that the foam demonstrated lower strength in the perpendicular to rise direction, it would have higher properties in the parallel to rise direction [Ref. 10]. NCFI 811-91 was also selected for the experiments because of the good foam quality that was produced after water immersion. The other foam materials, such as PP 475-20 and Stathane 4802 W, either shrank, had poor quality cell structure, or were brittle [Ref. 9]. Sandia selected a foam that could be used to create a passageway over the obstacles in the shallow surf zone and the beach.

b. *Trafficability Experiments on Pre-fabricated Foam Blocks*

Trafficability experiments were conducted using 54-inch cube foam blocks with 2, 4, and 6 lb/ft^3 densities. An M60 Main Battle Tank, M110 8-inch self propelled Howitzer, 3.5 ton Light truck, and a 6 X 6 cargo truck were used to determine if the foam could adequately carry military traffic. The 2 pcf foam block had a 12-inch rut after 8 to 12 passes by a tracked vehicle while the 4 pcf foam carried 36 to 163 passes of a tracked vehicle before it suffered a 12-inch rut. Sandia concluded that moderate density RPF foams, 2.5 to 3.5 pcf for tracked vehicles, will adequately carry military traffic during the first days of an amphibious assault [Ref. 13:p. xi].

c. *Flammability Characteristics*

Experiments were conducted using 2 and 4 lb/ft^3 foam. In both cases, once the initiating heat was removed, the foam began to self-extinguish. The foam did not develop a flash fire and burned very much like light wood [Ref. 13:p. xi].

d. ***Response to Bullet Impact***

Experiments were conducted using rifle caliber small arms on 2 lb/ft^3 . The bullets slowed down and tumbled in the foam without causing considerable damage. High explosive/point detonating fuzed projectiles, such as the 30 mm Cannon caliber perforated the 2 lb/ft^3 foam, but the projectile did not detonate. The same type of projectile detonated in a 4 lb/ft^3 foam and caused moderate damage [Ref. 11:p. xii].

e. ***Toxicity***

Melecita Archuleta and William Stocum [Ref. 1] conducted the toxicity evaluation and hazard review for rigid foam and concluded that there is no significant health hazard expected during the normal use or deployment of the foam, but there is a possibility for thermal decomposition at temperatures below ignition, which would result in the generation of toxic isocyanate vapors and other toxic vapors such as Freon-12. These vapors would only be significant to individuals operating near the foam during the foaming process. The deployment of foam in well ventilated areas prevents any asphyxiation hazard due to oxygen depletion.

Archuleta and Stocum also contend that a hazardous situation can occur in the event of a partial deployment of the foam in which only the isocyanate component of RPF is released. This component consists of toxic polymeric isocyanates which can severely irritate the tissues of the mucous membranes and upper respiratory tract. The resin component by itself does not pose a hazardous situation [Ref. 1].

f. ***Explosive Cavity Formation from Surface and Subsurface shots***

Explosive experiments were conducted using 10, 100, and 1,000 gram C-4 charges in both 2 and 4 lb/ft^3 foam. Charges were either placed on the top surface or interior of the foam blocks. The results of these explosive experiments were accurately predicted by the work of Cooper and Kurowski in 1975.

Figure 2 , [Ref. 13:p. 43], shows the data of Cooper and Kurowski as well as the new data points from the Sandia experiments conducted in 1995. The original work by Cooper and Kurowski is denoted by the X for the 2 lb/ft^3 foam and the Δ for the 14 lb/ft^3 foam.

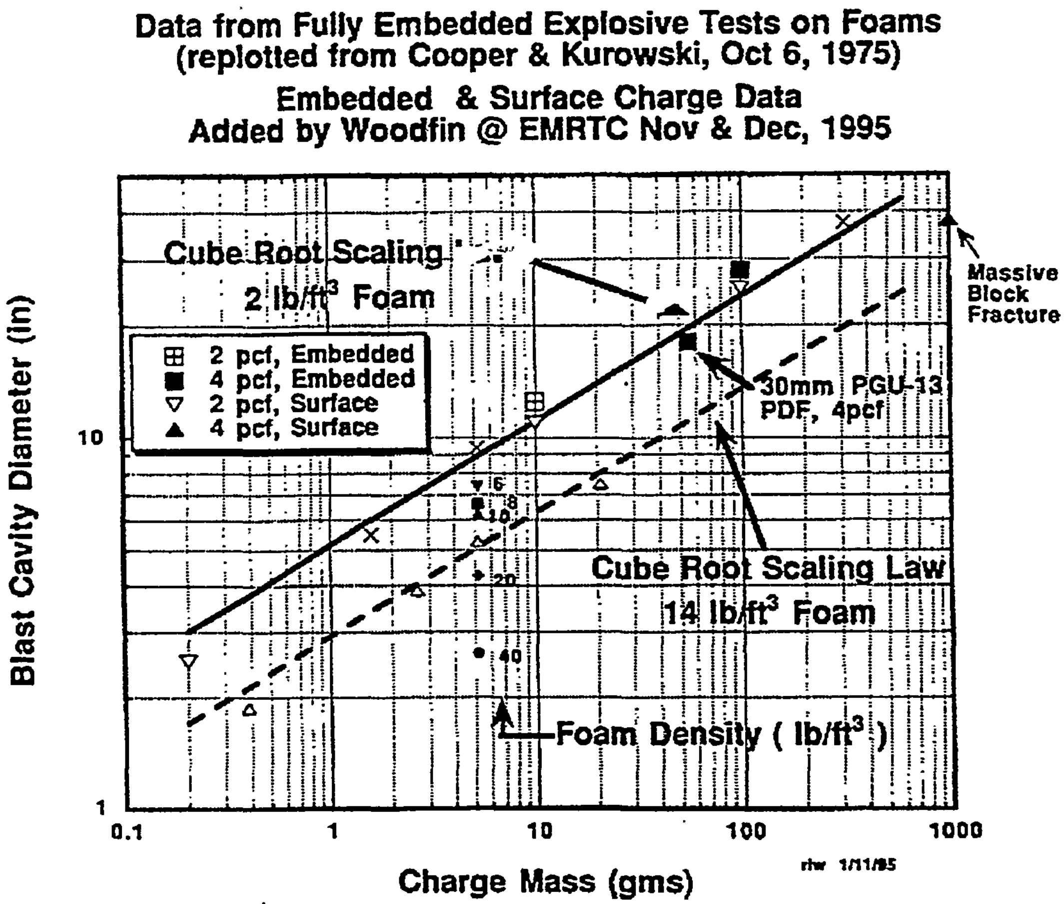

Figure 2. Blast cavity diameters from surface and embedded shots from Ref. [11] conducted by Cooper, Kurowski, and Woodfin. The solid line depicts the 2 lb/ft^3 foam while the dashed line depicts the 14 lb/ft^3. The prediction of the foam densities (6, 8 ,10 , 20, and 40 lb/ft^3) were predicted by Cooper and Kurowski in 1976.

∞

III. EXPERIMENTS

A. GENERAL

The feasibility experiments were conducted at two locations. The initial experiments were conducted with the Waterways Experiment Station, Vicksburg, MS at Duckport, LA while the explosive tests were conducted with Sandia National Laboratories, Albuquerque, NM, at EMRTC, Socorro, NM.

1. Waterways Experiment Station

Waterways conducted a Concept Evaluation Program in order to determine the trafficability of a foam roadway, the ability of the foam to distribute the load of a static and moving vehicle, the effects of laying foam on trip wires, and finally the effects on sub-surface laid mines.

2. Energetic Materials Research and Training Center

The Sandia experiments concentrated on the explosive effects on Rigid Polyurethane Foam blocks. Failure criteria of the foam based on density, explosive charge, and foam thickness were explored. The final experiments were conducted to determine the possibility and efficiency of repairing damaged blocks.

Both experiments were part of an integrated plan with Sandia National Laboratories playing the lead role. Because these were operational feasibility tests, mixed English and metric units are reported.

B. TRAFFICABILITY AND PRESSURE EXPERIMENTS

All trafficability and pressure experiments were conducted at Duckport, LA. These experiments took place between 25 July - 07 August 1997.

1. Trafficability Tests

These experiments were conducted in order to investigate the foam's ability to carry military traffic. A tracked vehicle, M88A2 Hercules Tank Retriever, and a wheeled vehicle, M998 High Mobility Multi-purpose Wheeled Vehicle (HMMWV), were used for these tests. The M88A2 weighed 138,000 lb and was fitted with an M60 track which produced a contact pressure against the road bed of 17.4 psi. The HMMWV weighed 9,490 lb with a front tire pressure of 25 psi and a rear tire pressure of 35 psi. The contact pressures on the ground were 20 psi and 26 psi respectively.

a. Set-up

An RPF roadway with dimensions, 51' X 26' X 2' was constructed on a flat plastic clay soil surface. Figure 3 is a picture of the final configuration of the foam roadway. The top surface does not have a flat surface because of operational limitations of the foam dispensing machine. The foam dispensing machine was a Decker Industries commercial model applicable to the building industry. The machine can only dispense foam at a maximum rate of 90 lb/min, which is not quick enough to dispense large quantities of foam in the required time for an in-stride breach. In order to construct the 24-inch thick roadway, the foam had to be dispensed in approximately four layers with each layer no more than 6 inches thick. When the layers were poured larger than six inches thick, the internal temperature in the foam increased. This heat buildup caused the foam to split.

Figure 4 shows a schematic of the instrumentation layout and respective paths of the M88A2 and HMMWV. In order to use the roadway for both vehicles, the M88A2's right track traversed over the HMMWV's right wheel path. This method left two clear lanes for the vehicles.

Figure 3. Set-up for Trafficability Tests. Note that the roadway does not have a flat upper surface. The undulations were caused by the uneven rising of the foam. This 24" thick roadway was poured in four separate layers. Each layer was between 5-7 inches thick.

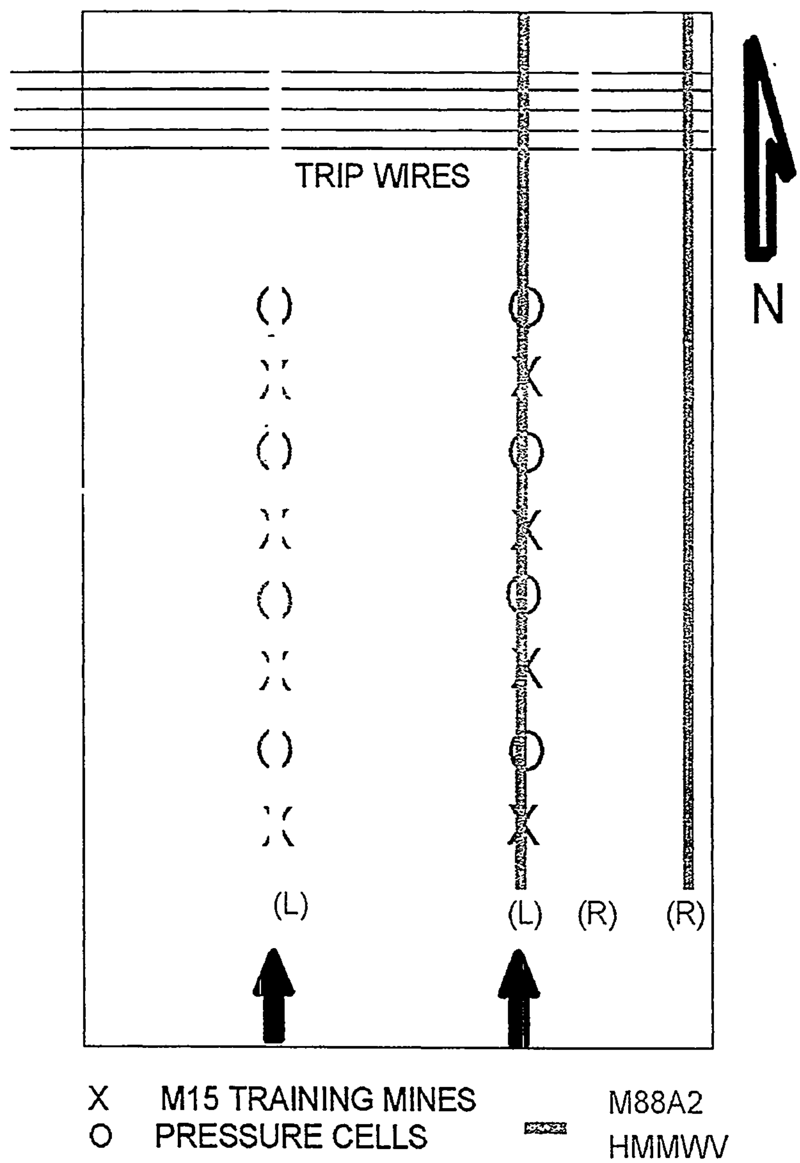

Figure 4. Mine and Pressure Cell Layout. The M15 training mines were employed to simulate anti-tank mines. The pressure cells were located close enough to the mines in order to provide pressure readings after each vehicular pass.

Figure 5 shows the paths taken by the two vehicles. The large ruts were made by the M88A2 while the HMMWV's left wheels crossed over the foam in between the M88A2's path.

Figure 5. Set-up for Roadway Experiments.

b. Experiment

The M998 HMMWV and M88A2 Tank Retriever were driven over the 24-inch deep, 4 lb/ft^3 foam roadway for a total of 50 passes each. The HMMWV initially made 5 passes over its predetermined path. Indentation measurements of the foam were taken after each pass, which was one length of the roadway in the forward direction. The M88A2 then made its first 10 passes, which consisted of 5 forward and 5 reverse passes over the roadway. Indentation measurements were taken after the first five passes followed by measurements after every fifth pass. The HMMWV completed its remaining 45 passes followed by 40 more passes of the M88A2 .

c. Results

After the first five passes, the HMMWV vehicle barely indented the foam. In some areas where the foam was slightly higher, small cracks developed. After 50 passes, the foam was indented no more than 1 inch. These indentations were measured on the left track which was not affected by the M88A2. Figure 6 shows the indentation marks of the HMMWV on the upper right foam path.

The M88A2's first pass created an indentation up to an inch in depth in some portions of foam. After the second pass, the M88A2 began to pack the foam underneath the tracks and the debris began to settle on top of the worn surface. After 50 passes, the M88A2 crushed the foam between 2-3 inches throughout the length of the roadway. Figure 6 shows the rut created by the M88A2 and the slight indentation created by the HMMWV. Figure 7 shows another view of the damaged roadway as well as the chunks of debris that are compacted in the path.

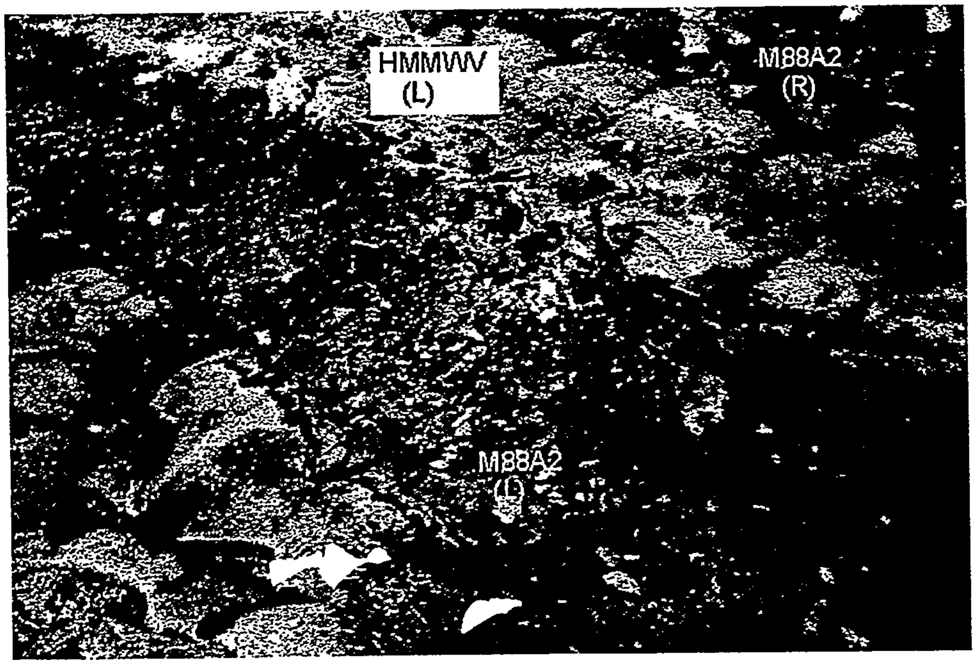

Figure 6. Foam wear from the M88A2 and HMMWV. Note that the HMMWV barely indented the foam while the M88A2 created two large ruts.

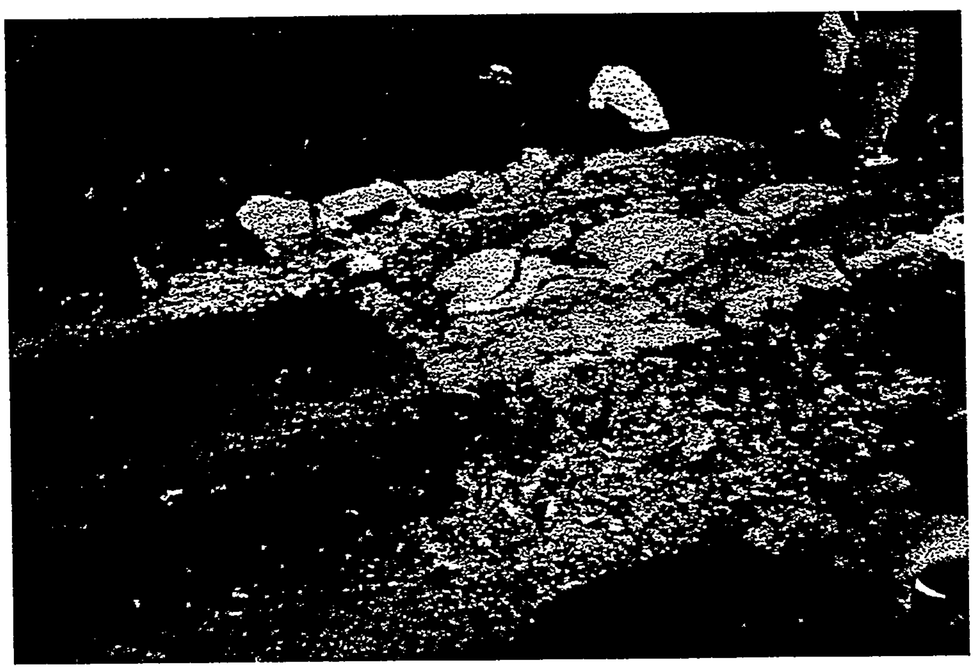

Figure 7. Results of Roadway Experiments. The deep ruts were created by the left and right tracks of the M88A2. The HMMWV left the discoloration in the center of the roadway.

2. Trip Wire Experiments

a. Set-up

Figure 3 shows the set-up of the trip wires on the northern end of the roadway. Three of the trip-wires were M-1, 7 lb pull devices while the remaining two were string tension potentiometers. Each wire was anchored on one end to a wooden stake while the other end was attached to a tripping mechanism set at 7 lb. The wires were approximately two inches above the ground.

b. Experiments

The foam was poured into the trip wire area with a west to east fill pattern. The goal was to achieve a total foam depth of 24 inches. Due to limitations of the foam machine, this depth had to be achieved in multiple layers. An initial layer of 6 inches was followed by three more 6-inch layers. Additional layers were applied only after the bottom layer became tack-free. Dirt berms about 18 inches in height were constructed along the edges of the minefield in order to help confine the flow of the foam.

c. Results

At the front end, the wire remained embedded in the foam. The expansion of the foam caused the wires to rise. The expansion continued to the very end of the pour. Initial results indicated that the foam stretched the wire 8-10 inches.

These results were not very conclusive because of the manner at which the foam was applied. The foam started to expand from the western edge, but the flow of the rising foam was towards the eastern edge. This created a gradual slope wherein the eastern edge was approximately 6 inches thicker than the western edge.

3. Traction Experiments

a. Set-up

An M88A2 is configured to pull another M88A2 located 20 meters to its rear. A bulldozer was used as the brake vehicle.

b. Experiments

Initial traction tests (drawbar pull experiments) for the M88A2 and HMMWV were conducted on dry surface. These experiments were then repeated on a watered down surface which simulated 2 inches of rain. The final traction tests involved spraying 5 - 8 inches of foam in the watered down ruts. After allowing the foam to cure for one hour, the lead M88A2 ran over the foam with the other M88A2 in tow. Figures 8, 9, and 10 show the set-up for the traction tests. Measurements were taken to determine if the foam provided any additional traction for the pulling vehicle.

Similar traction experiments were conducted with the HMMWV. The HMMWV pulled a water truck with a 5-ton truck as a break vehicle. Instead of ju[illegible]g in the rut created by the repeated passes of the HMMWV, 3-5 inches of foam was sprayed over the entire roadway. This procedure was modified for the HMMWV in order to ensure that the wheels would maintain contact with the foam throughout the entire length of the road. Figure 11 shows the HMMWV pulling the water truck while driving on the foamed roadway.

Figure 8. Set-up for M88A2 drawbar-pull experiments.

Figure 9. Dispensing foam into water logged M88A2 ruts to investigate traction effects.

Figure 10. Foam-filled ruts for M88A2 traction test. The foam was allowed to cure for one hour before the experiments were conducted.

Figure 11. HMMWV drawbar pull experiments. This HMMWV is pulling a water truck located 20 meters to its rear.

c. Results

The M88A2 initially crushed the foam before it completely churned up the entire foam in the ruts, Figure 11 and 12. The foam was not as hard as the foam placed on dry land. It was easier to compress because of its lower density. The foam also had a much lower measured internal temperature, 174 ° F, because of the presence of water in the rut. Without water, the measured internal temperature in the foam is greater than 400° F. The drawbar pull experiments determined that the foam did not provide any additional traction for the pulling vehicle.

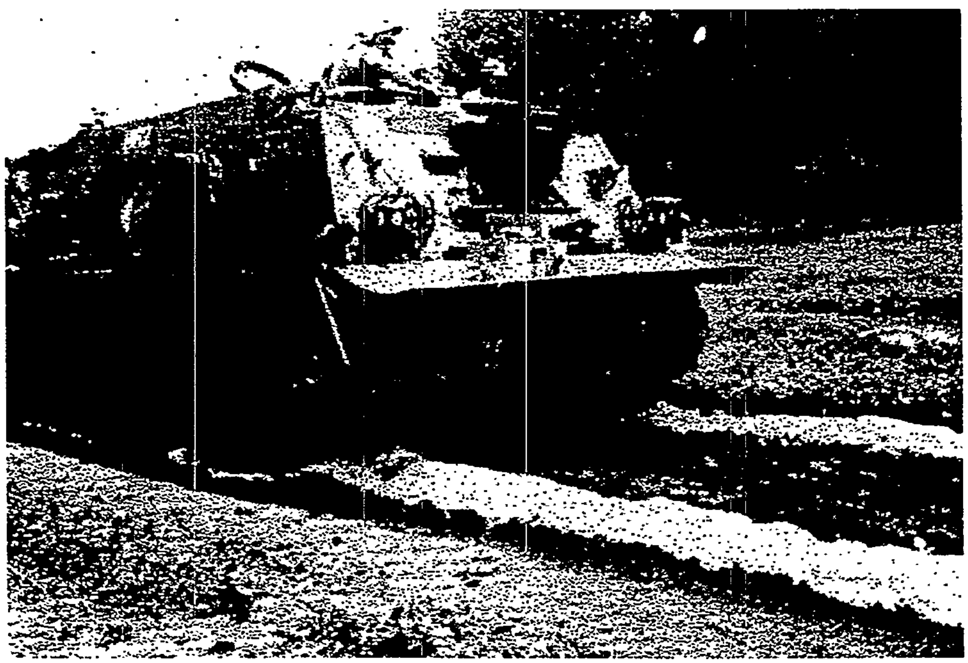

Figure 12. M88A2 conducting traction tests. The foam immediately began to buckle under the weight of the vehicle.

Figure 13. Foam damage during traction tests. This lower density foam did not provide additional traction for the M88A2.

The foam employed for the HMMWV traction tests had the same consistency as that for the M88A2 tests. The results of the drawbar pull tests indicate that the foam provided additional traction for the HMMWV that was towing the disabled water truck.

4. Effects on Sub-surface laid Mines

a. Set-up

Eight M15 training mines and eight pressure cells were employed under the same roadway used for the trafficability tests. Four of the pressure cells were rated at 50 psi and used for the HMMWV lane while the remaining four cells were rated at 100 psi and used for the M88A2 lane. The mines were buried approximately 2 inches deep and were set to be tripped after experiencing a load of 14 psi. The pressure cells were buried approximately 3 inches in depth and placed adjacent to the M15 mines in order to provide the loading data for each pass of a vehicle. Figure 3 shows the actual layout of each mine and pressure cell. The data for this experiment was taken concurrently with the trafficability data.

b. Experiments

Load sensor data was taken for each of the 50 passes of the M88A2 and HMMWV.

c. Results

Without the use of the foam, the M88 was calculated to have a surface contact pressure of 17.4 psi while the HMMWV had a contact pressure of 20 psi for the front tires and 26 psi for the rear tires. The load sensors indicated an average load of 5.4 psi for the M88A2 and 0.34 psi for the HMMWV. The Phase I report by SNL calculated similar values, 5.0 psi for the M88A2 and 0.5 psi for the HMMWV [Ref. 11:p. 109]. None of the simulated mines were triggered by any of the 100 passes over the foam roadway.

C. EXPLOSIVE EXPERIMENTS

All explosive experiments were conducted at the Energetic Materials Research and Testing Center (EMRTC), Socorro, NM.

1. Explosive Effects on RPF

a. Set-up

Figure 14 shows the experimental set-up for the explosive experiments conducted at EMRTC, Socorro, NM. A twelve-inch thick layer of fine sand was placed on top of solid ground. Sand was chosen in order to provide a level surface for the foam blocks. Sand bags were placed on top of the foam blocks to ensure that the foam remained on top of the sand during the explosion. The smaller foam blocks will tend to elevate, thus causing a considerable air gap during the propagation of the explosive shock.

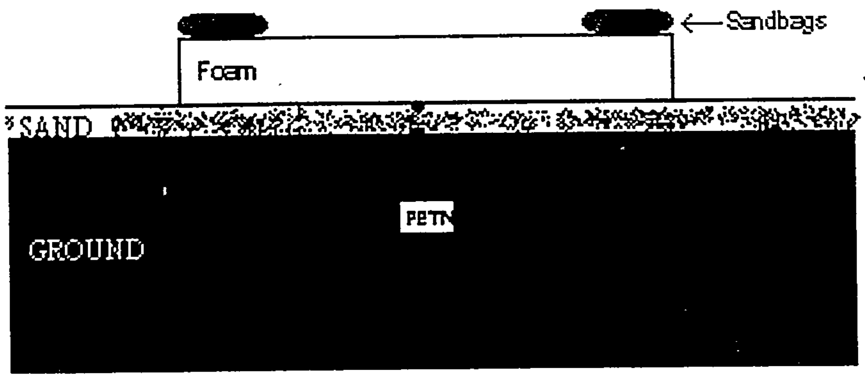

Figure 14. Schematic for Land Experiments. The sandbags are placed on the foam block in order to ensure that the foam remains on top of the sand during the explosion.

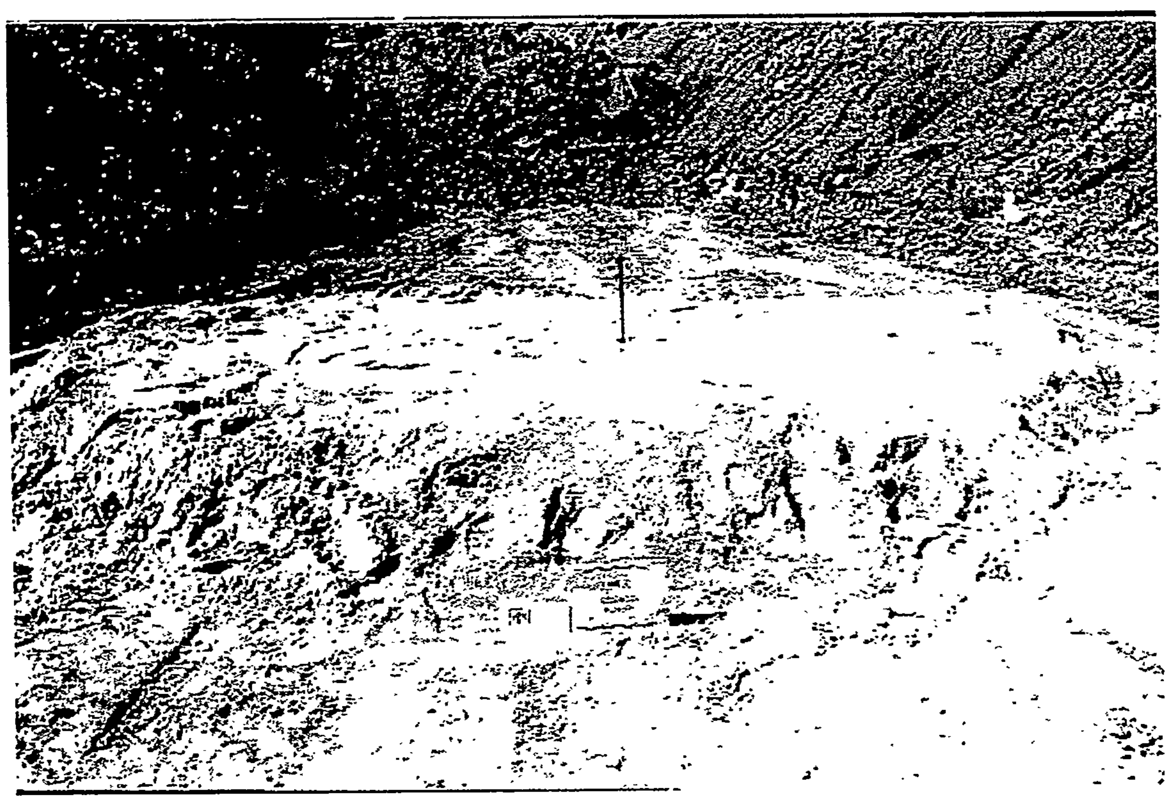

Figure 15. Ground set-up for experiments.

The explosive used for these experiments was PETN, pentaerythritol tetranitrate, which is commonly used in grenades, small caliber projectiles, and demolition devices [Ref. 3:p. 6.13]. PETN has a conversion factor of 1.45 when scaled to TNT, i.e. 10 g PETN has the explosive effect of 14.5 g TNT. Figure 16 shows how PETN was molded to approximate the shape of a typical blast anti-personnel mine. A patty-shaped explosive was chosen over a spherical shape in order to closely replicate the explosive geometry in an anti-personnel mine.

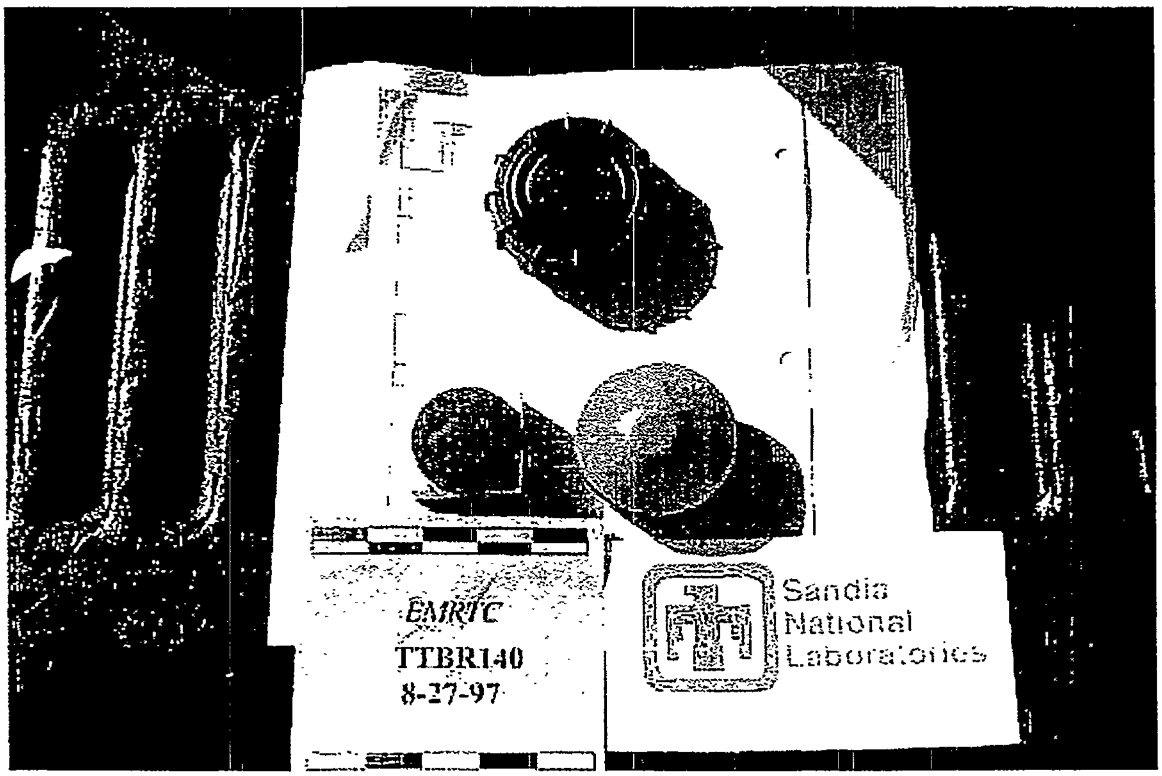

Figure 16. PETN explosives used in experiments. The mine on the top of the figure is a VS-MK2 training AP pressure mine. The 10 g PETN were formed like the charge on the bottom left while the 30-g charge looks like the patty-shaped figure on the bottom right.

The foam blocks were poured in two different frames, 65 X 65 X 24 and 85 X 85 X 24 inches. Figure 17 shows the set-up of one frame. The frames were lined with plastic to prevent the foam from sticking to the wood. Handles were constructed to provide easy handling of the foam block after sufficient hardening.

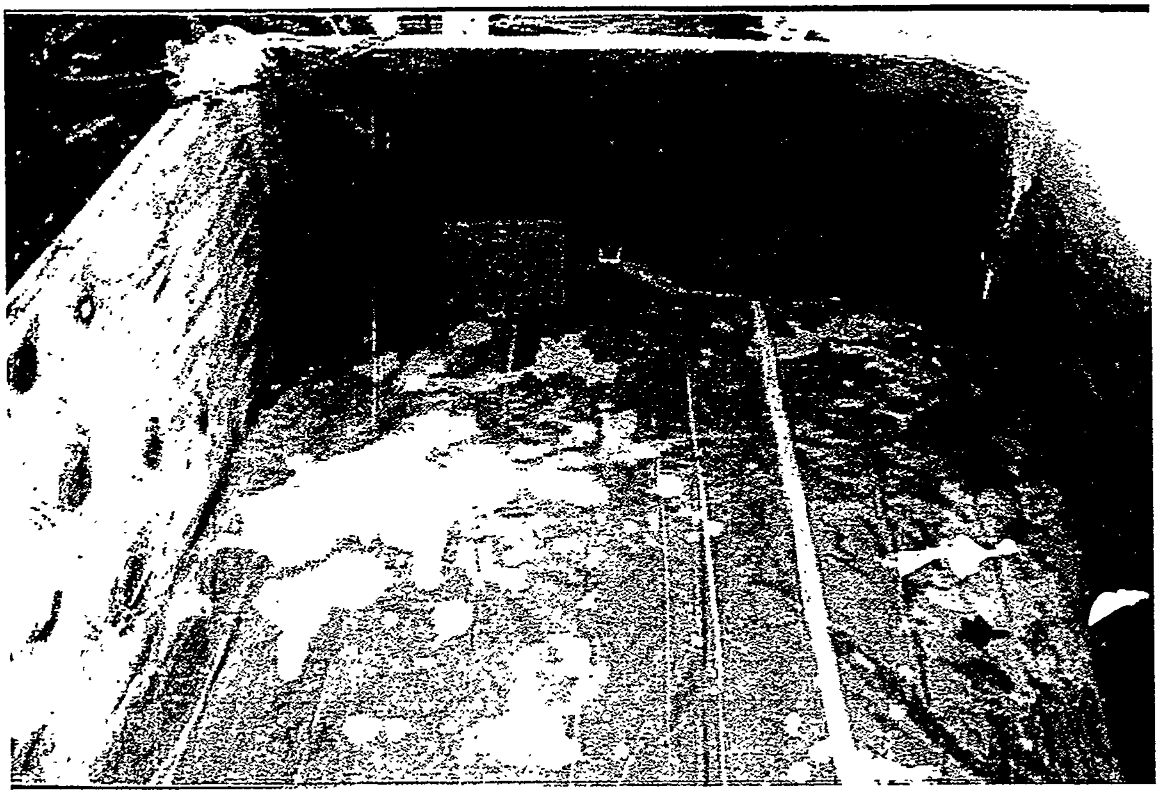

Figure 17. Frame used to mold foam blocks. The plastic was used in order to prevent the foam from adhering to the wooden frame. The handles were used to extract the foam block from the frame.

A two-part polyurethane dispensing machine made by Decker Industries, Florida, was used to make the 15 foam blocks for this experiment. This was also the same machine used to create the foam roadway for the trafficability experiments. The machine was dispensing 3.5-4.0 lb/ft^3 foam at an average rate of 55 lb/min. Cream time, which is the amount of time elapsed before the mixture reached a cream-like consistency, took place after 55-65 seconds. The foam reached its maximum expansion after a rise time of 3-4 minutes. Figure 18 shows the Decker foam machine used for these experiments.

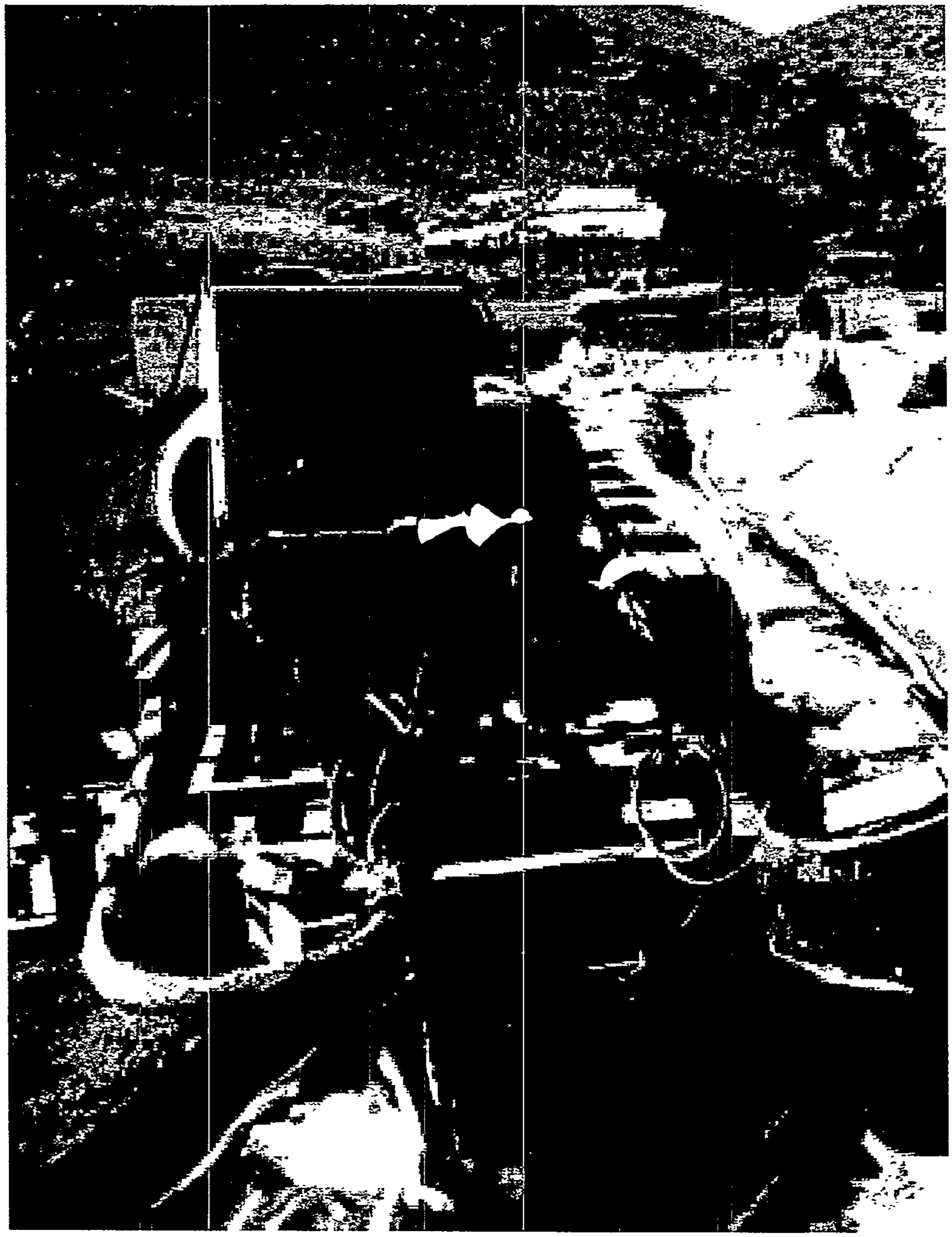

Figure 18. Decker Foam Machine. The resin and isocyanate are in separate barrels located directly behind the machines control panel. The two parts are mixed in the dispensing gun just before the mixture is sprayed out of the gun.

Table 1. Matrix for Explosive Cavity Formation Experiments

TEST / Expt #	***Medium***		***Block Size***	***Charge Size***			***Charge Depth***	
			(cu. in)	(grams)			(inches)	
	Land	Sea		10	30	50	0	2
L1	X		65X65X6	X			X	
L2	X		65X65X6		X		X	
L3	X		85X85X6	X			X	
L4	X		85X85X6		X		X	
L5	X		65X65X12	X			X	
L6	X		65X65X12		X		X	
L7	X		85X85X12	X			X	
L8	X		85X85X12		X		X	
L9	X		65X65X18	X			X	
L10	X		65X65X18		X		X	
L11	Y		85X85X18	X			X	
L12	,		85X85X18		X		X	
MOD1	X		85X85X30		X		X	
L13	X		85X85X30		X		X	
L14	X		85X85X18			X	X	
L15	X		85X85X30			X	X	

b. Experiment

Table 2 is the matrix used for the explosive cavity formation experiments. Two different block sizes, 65" X 65" and 85" X 85", were used in order to investigate edge effects. The PETN explosive was positioned directly underneath the geometric center of each foam block. The top of the explosive was made flush with the sand surface in order maintain direct contact with the block. Nonel Primadet chord, a non-electric blasting device, was used to detonate the charge. The chord made contact with the bottom of the PETN and was routed underneath the sand towards the triggering mechanism. After each shot, measurements were taken of the ground crater, entrance cavity, exit cavity, and depth of penetration in the foam. Figure 19 and 20 show the set-up for Experiment L1.

Figure 19. PETN set-up for explosive cavity experiments. Note that the PETN is shaped to simulate an anti-personnel mine.

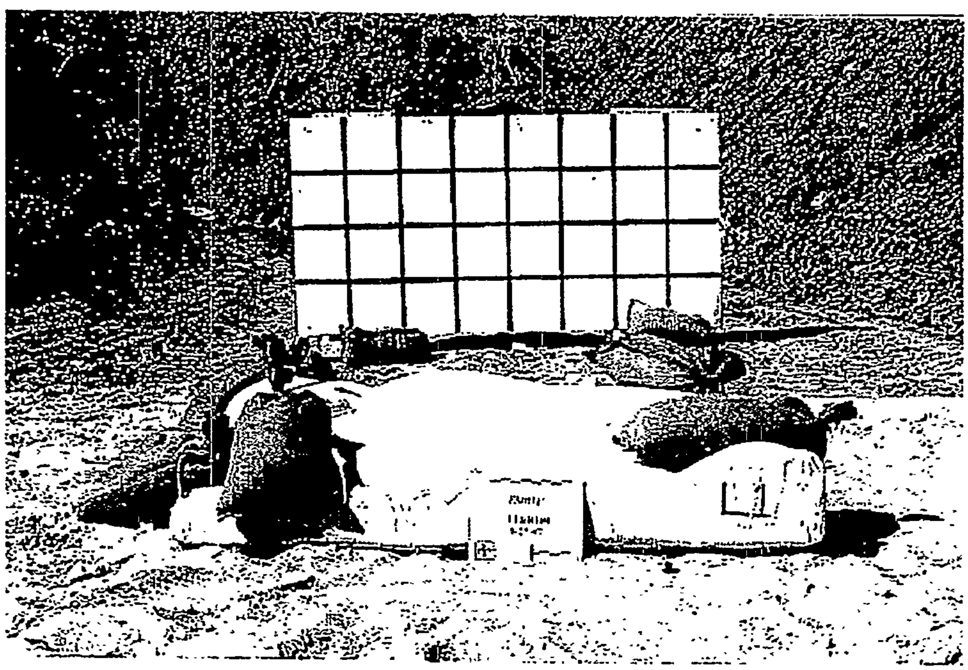

Figure 20. Set-up of Experiment L1. The sand bags kept the foam pad in contact with the ground during the blast. The grid in the background has an interline spacing of 1 foot.

Experiments L4 and L12 were conducted with a 3,000 pound metal plate, 72 X 72 X 2 inches placed directly on top of the foam. This metal plate simulated an external static load, such as a vehicle directly on top of a mine. The concept was to determine if damping would enhance the performance of the foam against an exploding anti-personnel mine.

c. ***Results***

Table 2 shows the cavity diameter from all fifteen experiments. The 30-gram explosive perforated through all but the thickest foam block, MOD 1, and the 10-gram explosive was contained by foam blocks thicker than 12 inches, L5, L9, and L11. L5, 18 inches thick, which was loaded with the metal plate, was able to contain the 30-gram charge. MOD 1 was an addition to the initial matrix. It was the thickest foam block, 30 inches, and the only block without additional damping to contain the 30-gram charge.

Figures 21 ,22, and 23 show the effects of a 10-gram charge on a 6 inch block of foam. The explosive created an exit cavity (top) almost twice the size as the entry cavity (bottom) and a ground crater 21 inches in diameter. The failure of the foam block was contained to the cavity, and there were no cracks observed laterally to either side of the foam. Two modes of failure were observed on the blocks that were perforated. The direct blast failure results in the crushing of the foam cells near the entry point of the explosive while the foam's mechanical failure results in a shear plug. The shear plug creates an exit cavity significantly larger than the entry cavity. Figure 21 shows a generic sketch of the explosive effects on an RPF block.

Table 2. Results from Explosive Cavity Experiments.

				Cavity Diameter			
EXPT #	***L X W (inches)***	***Thickness (inches)***	***Charge (grams)***	***Entry (inches)***	***Exit (inches)***	***Depth (inches)***	
L1	65 X 65	6.00	10.00	5.75	11.00	6.00	*
L5	65 X 65	12.00	[illegible]	8.50	0.00	7.00	
L9	65 X 65	18.00	10.00	6.00	0.00	6.00	
L2	65 X 65	6.00	30.00	8.50	18.50	6.00	*
L6	65 X 65	12.00	30.00	11.50	18.25	12.00	*
L10	65 X 65	18.00	30.00	9.75	15.50	18.00	*
L3	85 X 85	6.00	10.00	4.75	13.75	6.00	*
L7	85 X 85	12.00	10.00	4.50	10.25	12.00	*
L11	85 X 85	18.00	10.00	5.75	0.00	6.50	
L4	85 X 85	6.00	30.00	8.25	14.25	6.00	*, **
L8	85 X 85	12.00	30.00	7.75	19.25	12.00	*
L12	85 X 85	18.00	30.00	8.50	12.50	18.00	*, **
L13	85 X 85	18.00	30.00	11.20	0.00	11.20	
Mod 1	85 X 85	30.00	30.00	5.75	0.00	11.85	
L14	85 X 85	18.00	50.00	7.20	10.80	18.00	
L15	85 X 85	30.00	50.00	10.70	0.00	12.80	

* failure
** loaded

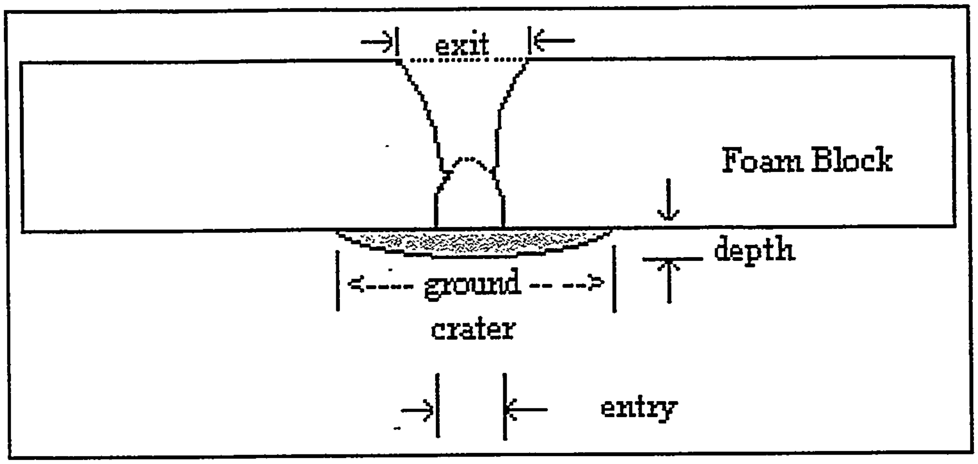

Figure 21. Sketch of the explosive effects on an RPF block. Note that the ground crater is significantly larger than both entry and exit craters. This is a sketch of the cross section of foam block L10, 18" thick, 30-gram PETN charge (not drawn to scale). L10 was perforated by the explosive. The bottom section of the foam cavity (dark yellow) is the result of the direct blast while the upper portion (shear plug) results from mechanical failure.

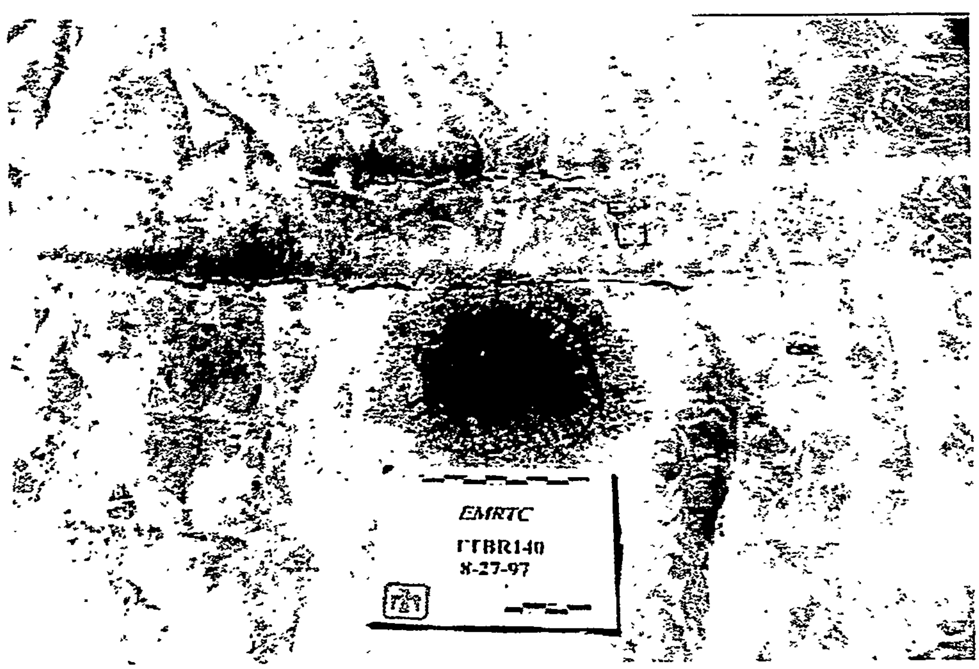

Figure 22. Entry cavity for Experiment L1, 6" thick, 10-gram charge.

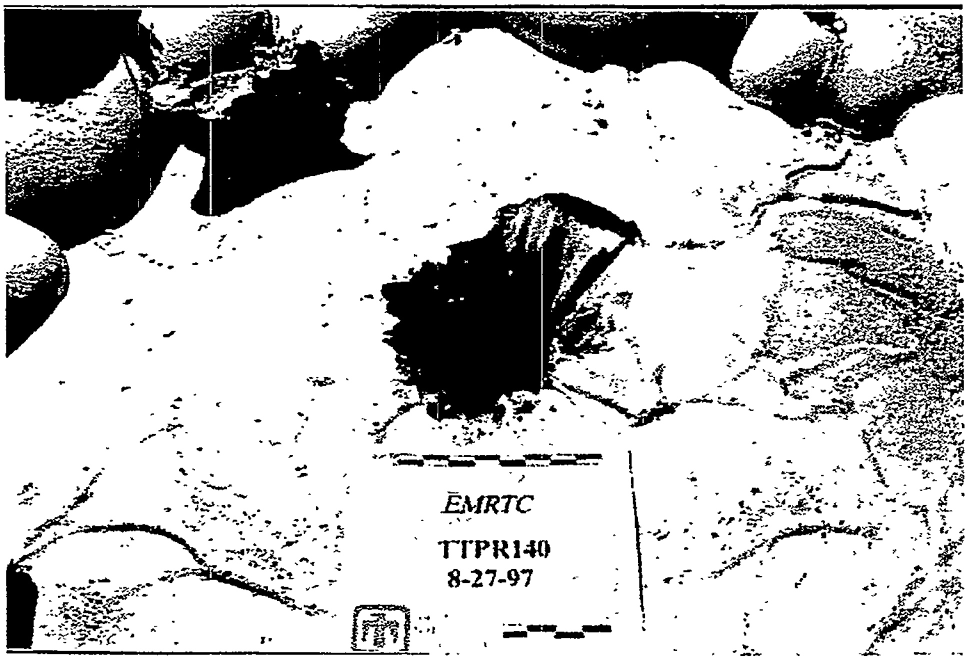

Figure 23. Exit cavity for Experiment L1, 6" thick, 10-gram charge

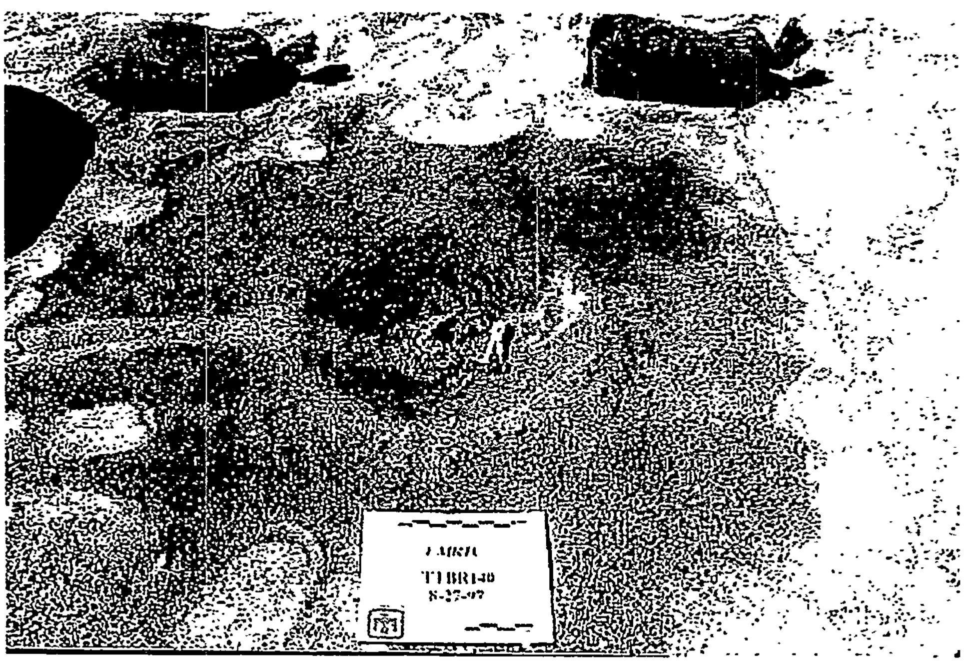
Figure 24. Ground crater from Experiment L1, 6" thick, 10-gram charge.

Figure 25, 26 and 27 show the results of a 10 gram PETN charge on an 18-inch thick foam block, L9. L9 completely contained the effects of the 10 gram charge. The entry cavity diameter and the depth of penetration were both 6 inches. The top surface (exit) of the foam block had no cracks or fissures. The ground crater was measured to be 18.5 inches in diameter and 2.9 inches deep.

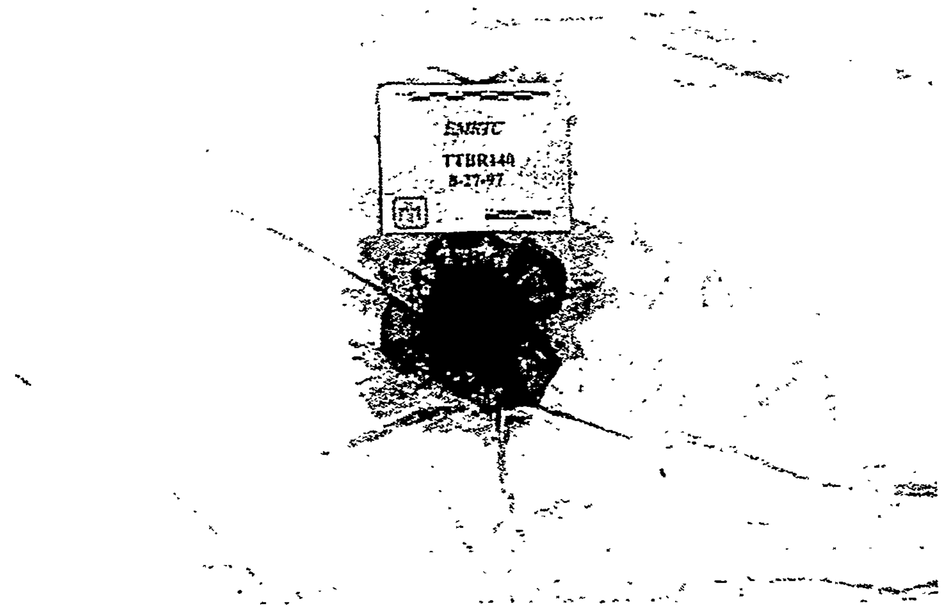

Figure 25. Entry Cavity for Experiment L9, 18 " thick, 10-gram charge.

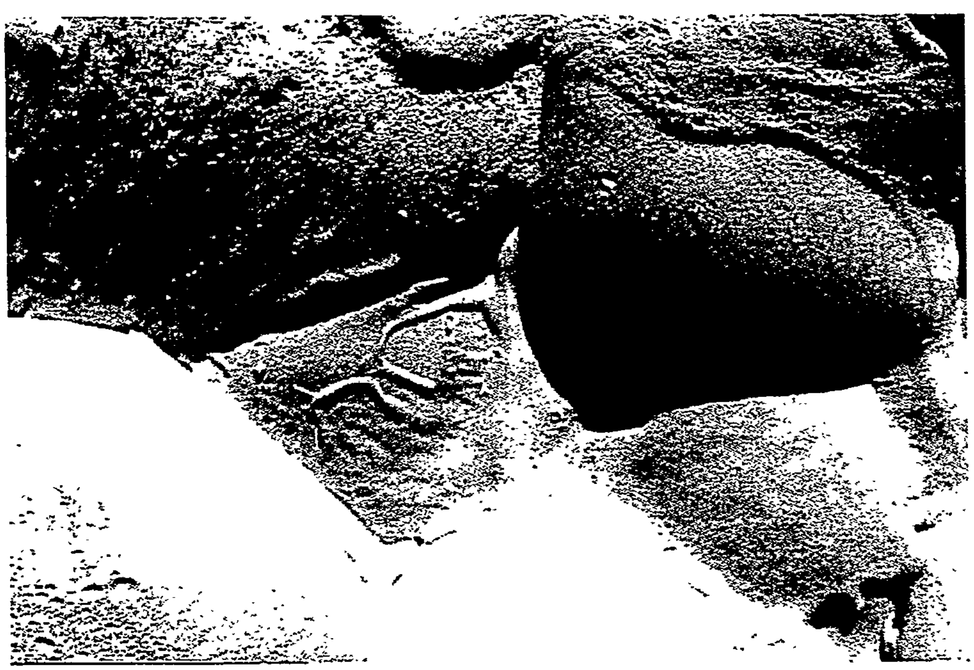

Figure 26. Exit Cavity for Experiment L9 (No perforation), 18 " thick, 10-gram charge.

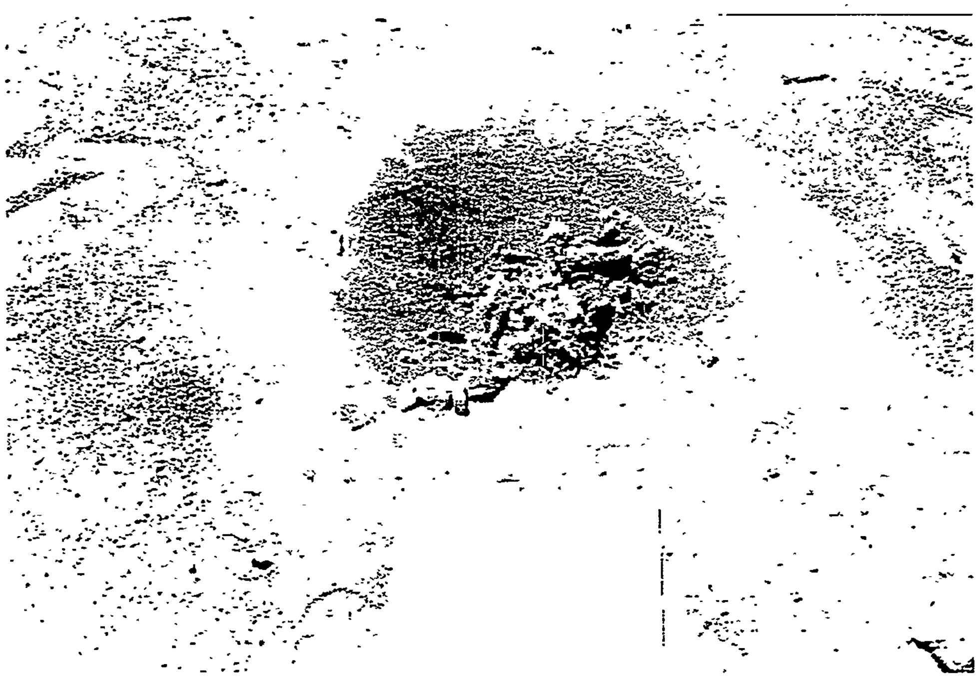

Figure 27. Ground Crater from Experiment L9, 18 " thick, 10-gram charge.

2. Repair of Damaged RPF Blocks

a. Set-up

The damaged foam blocks used for these experiments were the blocks used for the cavity formation experiments. The damaged blocks were placed on a flat surface with the exit cavities facing up. Figure 27 shows the initial set-up for the repair experiments.

b. Experiments

These experiments were conducted to determine the most efficient method of repairing a damaged foam block and its subsequent strength. Figures 28, 29, and 30 show how the damaged foam was repaired. By pouring the foam directly into the damaged cavity, some of the foam escaped through the bottom. Once the foam began to rise, it quickly adhered to the interior of the block.

c. ***Results***

Figure 29 shows a cross-section of the repaired foam block. It is evident that the foam not only filled the cavity, but it also seeped through the smaller cracks in the interior wall. Cold joints were formed at the boundary between the new and old joints. Follow-on experiments will determine the resulting strength of these repaired foam blocks. Figure 31 shows a schematic of a repaired foam block.

Figure 28. Dispensing Foam into damaged section

Figure 29. Top surface of a repaired block of foam

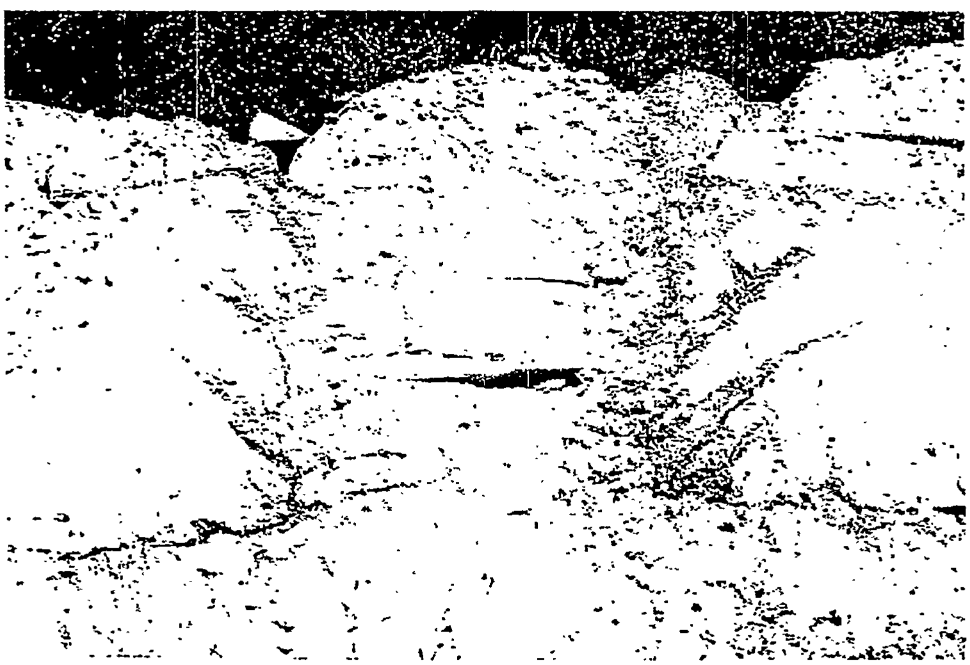

Figure 30. Cross section of repaired block of foam. Notice the cold joints that are formed between the new and original foam.

IV. ANALYSES

A. WATERWAYS EXPERIMENTS

1. Trafficability

These trafficability experiments were conducted to determine if RPF, at a given thickness and density, can provide a durable lane for multiple passes of track and wheel vehicles. The 24-inch thick, 4 lb/ft^3 roadway successfully withstood 50 passes of the M88A2 and HMMWV with a maximum rut depth of 3 inches throughout the length of the roadway. An M1A1 tank battalion consists of four tank companies. The battalion would have a total of 58 M1A1 tanks, 10 M88A2 Recovery vehicles, and an assortment of trucks, and Armored Personnel Carriers (APC). The M88A2 is the heaviest vehicle in the unit and it would inflict the most damage to the foam roadway. The minimal damage created by 50 passes of the M88A2 would suggest that the foam roadway will be able to carry the passage of at least an entire battalion before repairs would have to made on the foam.

2. Traction Tests

Results of the drawbar-pull experiments indicate that the foam did not increase the pulling capability of the M88A2. Instead, the foam decreased the traction of the M88A2 by 7 percent of the vehicle weight. On the other hand, the HMMWV's pulling capability was increased by 20 percent of the vehicle weight [Ref. 6:p. v]. It was observed that when the foam was dispensed on the watered down rut, the foam expanded into a less dense and porous material. Even several hours after the experiments were conducted, the foam retained its spongy consistency. The amount of foam poured into the water logged ruts of the M88A2 was only 3 - 5 inches in depth. Since a lower foam density was predicted because of the presence of water, more foam should have been poured for the M88A2 experiments. Additional experiments will have to be conducted in order to determine the amount of foam needed to increase the drawbar-pull capability of the M88A2 by more than 10 percent of its weight in poor conditions [Ref. 6:p. 36].

Figure 31 shows the initial drawbar-pull coefficient, slip percentage, and work index from the M88A2 test on dry surface [Ref. 6:p. 14]. The optimum drawbar-pull coefficient of 0.69 occurs at a slip of 22%. This slip percentage is taken at the maximum work index of 0.55. The drawbar-pull coefficent is a measurement of the load being pulled by the lead vehicle with respect to a certain slip condition. The coefficient is obtained by normalizing the load to the weight of the vehicle. The work index for each slip value is calculated by multiplying the load by the distance represented by 1 - slip %.

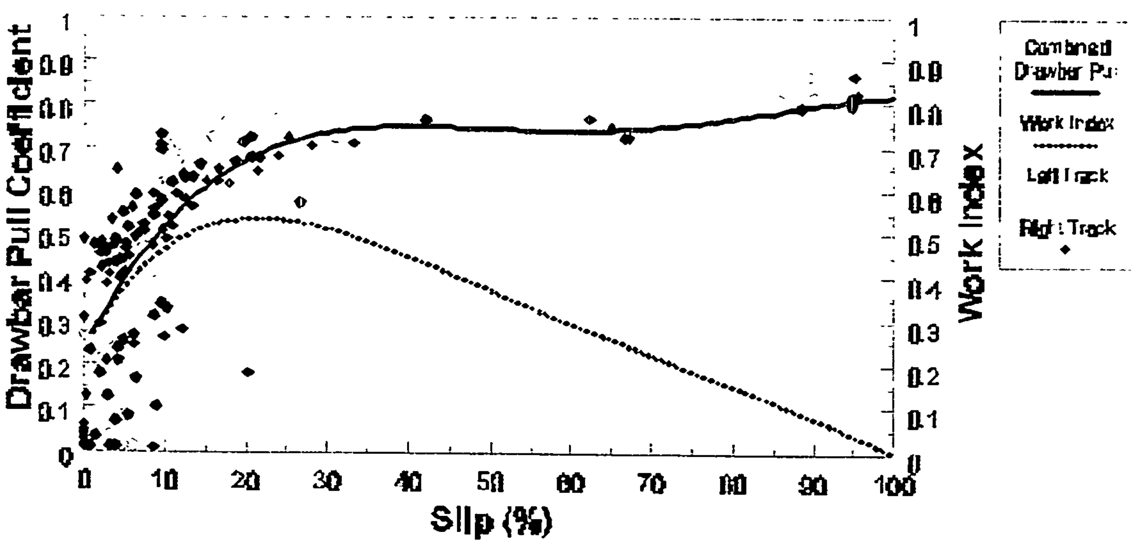

Figure 31. From Ref. [6], Dry Surface drawbar-pull test on M88A2

When the track ruts were filled in with 1-2 inches of water, the M88A2 recorded a decrease in the drawbar-pull coefficient from 0.69 to 0.20. The work index decreased from 0.55 to 0.15. Figure 32 shows these parameters for the wet surface, drawbar-pull tests for the M88A2 [Ref. 6:p. 15]. It is also evident from the data that there was no significant difference in the left and right track.

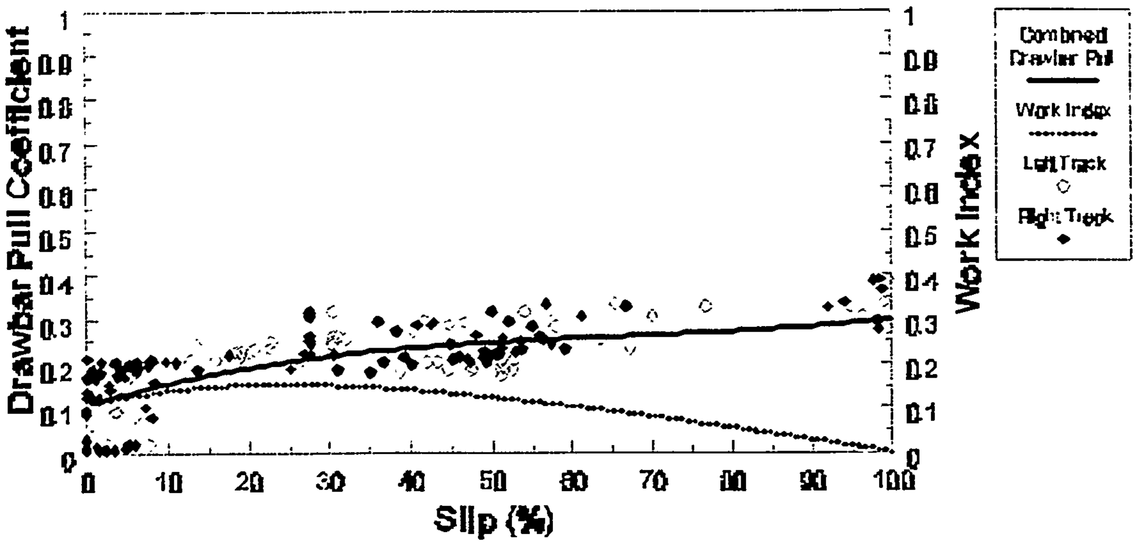

Figure 32. From Ref. [5], Wet surface drawbar-pull test on M88A2.

After the foam was dispensed into the wet track rut, the optimum drawbar-pull coefficient decreased to 0.14 at 22 percent slip. The maximum work index was 0.1. Figure 33 shows the results of the experiments on the foam-filled ruts [Ref. 6:p. 15].

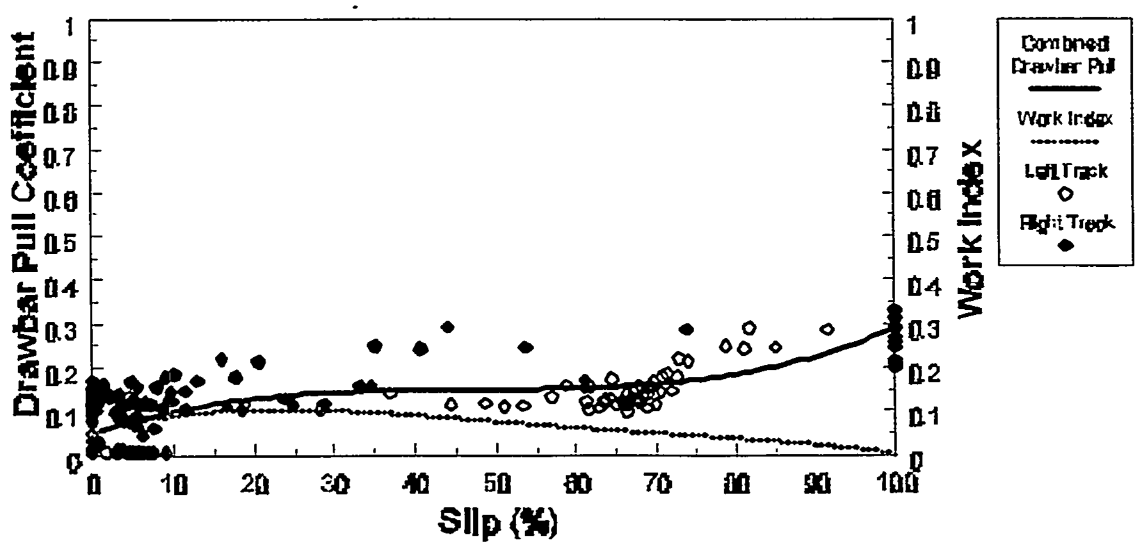

Figure 33. From Ref. [5], Foam surface drawbar-pull test on M88A2

Figures 34, 35, and 36 show the corresponding output for the HMMWV experiments [Ref. 6:p.16-17]. On dry surface, the optimum drawbar-pull coefficient was 0.75 at a slip of 25 percent. The drawbar-pull coefficient decreased to 0.30 at 30 percent slip during wet surface tests, but increased to 0.50 at 33 percent slip when the HMMWV was tested on the foam.

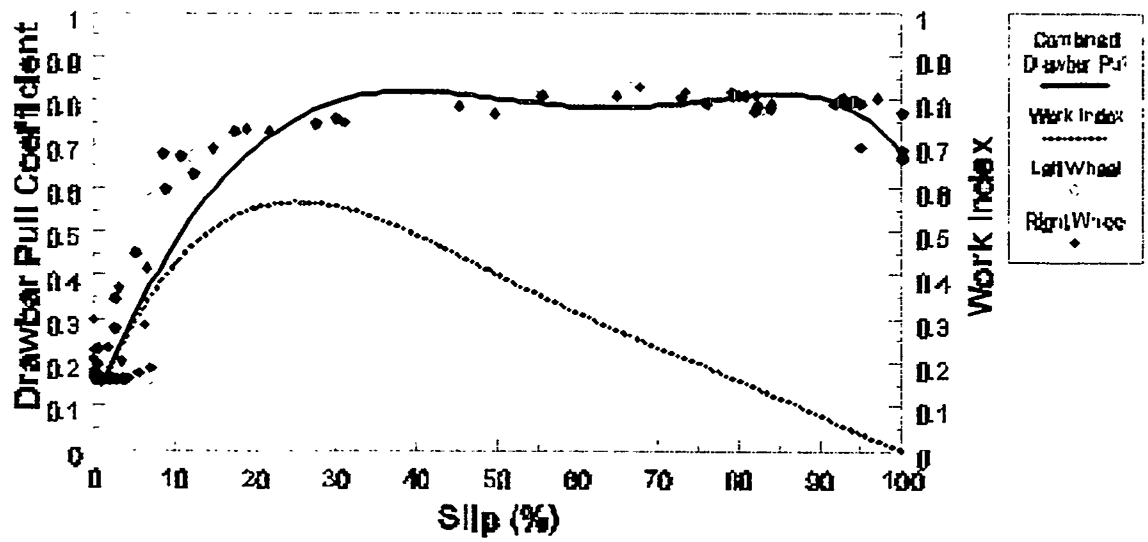

Figure 34. From Ref. [5], Dry Surface drawbar-pull test on HMMWV

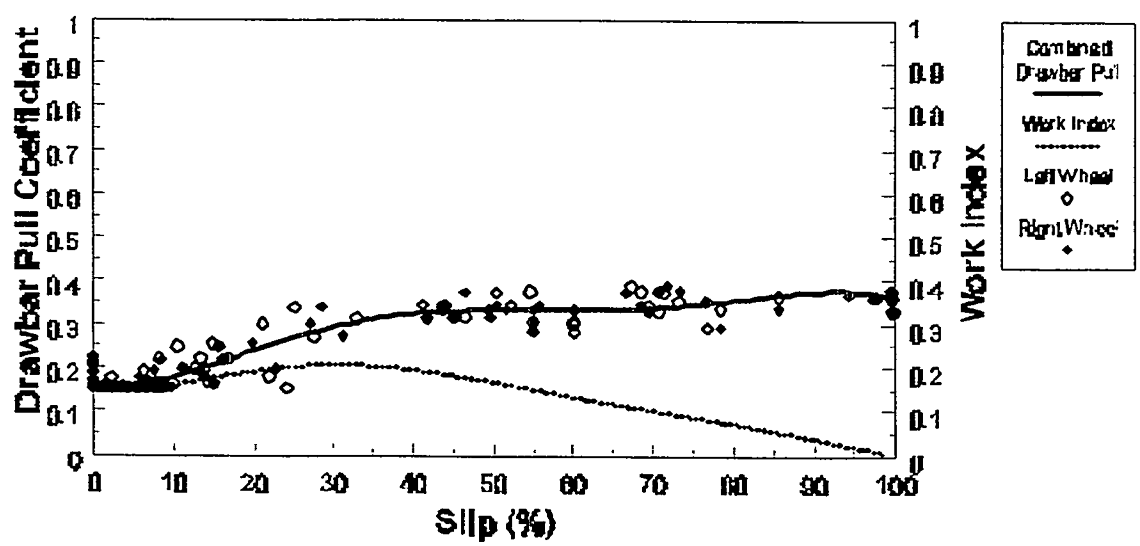

Figure 35. From Ref. [5], Wet Surface drawbar-pull test on HMMWV

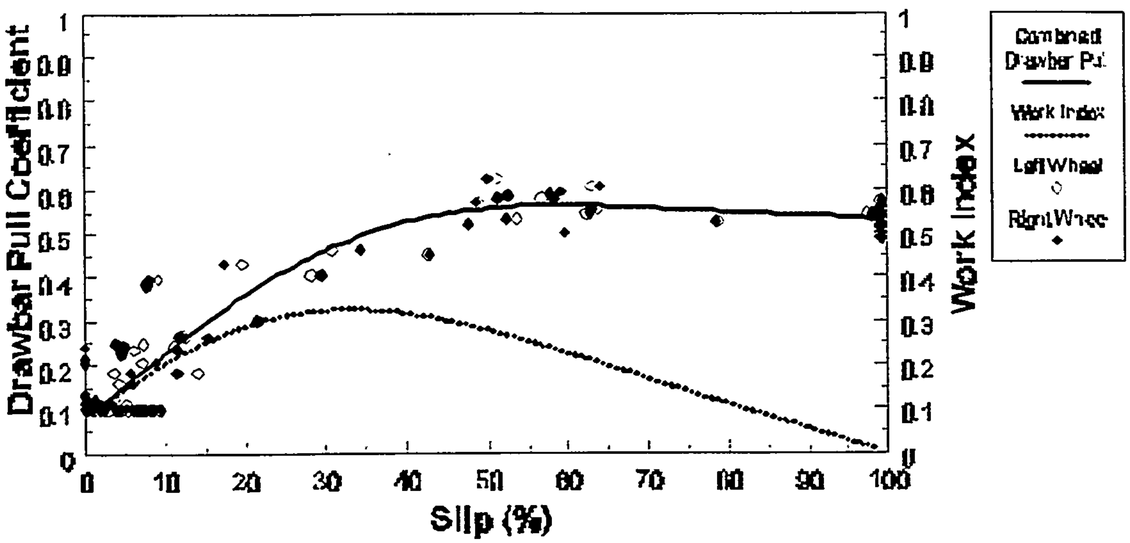

Figure 36. From Ref. [5], Foam Surface Drawbar-pull test on HMMWV.

The decrease in traction for the M88A2 can be attributed to the less dense foam that resulted from the mixture of water with the resin and isocyanate. Unlike the M88A2 which completely destroyed the foam in the rut, the HMMWV merely crushed the top layer of the foam. Despite the lower density foam, the intact foam provided a 66 percent increase in drawbar-pull coefficient.

3. Foam Effects on Subsurface laid Mines

The average pressure exerted by the M88A2 on the foam roadway was 5.40 psi while the HMMWV had an average of 0.34 psi. Table 3 shows a summary of the effects of a 24 inch foam roadway on selected anti-tank mines. Only 2 of the 13 anti-tank mines would be activated by the load of a dynamic load of a M88A2. The HMMWV would not activate any of these anti-tank mines under similar test conditions. Even for the activated mines, the foam should mitigate the blast effects of the anti-tank mines.

Tables 4 and 5 [Ref. 6: p 9] lists some typical pressure and trip-wire fused anti-personnel mines and their corresponding activation pressures. If theses mines were encapsulated by RPF under similar test conditions, the M88A2 would activate 7 of the 8 anti-personnel pressure fused mines. The HMMWV would not activate any of the listed mines. These measurements imply that foot traffic would not activate any of these anti-personnel mines.

Table 3. Summary of anti-tank mines neutralized due to 60 cm application of foam, After Ref. [5].

Mine Type	***Origin***	***Activation Pressure***	***M88A2 Activated***	***HMMWV Activated***
MK-7	UK	4.21	*	
SH-5TC-65	Italian	5.19	*	
TM-46	Italian/Egyptian	10.31		
TM-57	Russian	6.24		
TM-62	Russian	6.93		
VS-2.2	Russian	11.59		
TC/2.4	Italian/Egyptian	10.31		
SBB/81	Italian	8.59		
VS-1.6	Italian	10.88		
M15	US	7.92		
M19	US	6		
[illegible]	US	5.77		

* Based on average pressur

Average M88A2 Pressure @ 50 passes = 5.40 psi

Maximum M88A2 Pressure @ 50 passes = 7.0 psi

Average HMMWV Pressure @ 50 passes = 0.34 psi

Maximum HMMWV Pressure @ 50 passes = 0.54 psi

Table 4. Effects of M88A2 and HMMWV on Anti-personnel (Pressure Fuzed) mines, After Ref. [5].

Mine Type	***Origin***	***Fuse Type***	***Activation Pressure*** (psi)	***M88A2 Activated***	***HMMWV Activated***
PMN	Russian	Pressure	0.92	*	
PMN-02	Russian	Pressure	0.58	*	
PMD-6	Russian	Pressure	0.47	*	
VAL 69	Italian	Pressure	1.08	*	
SB-33	Italian	Pressure	7.7		
VS-MK2	Italian	Pressure	2.29	*	
PFM-1	Russian	Pressure	2.24	*	
M14	US	Pressure	2.86	*	

Table 5. Effects of M88A2 and HMMWV on Anti-personnel (Tripwire Fuzed) mines, After Ref. [5].

Mine Type	Origin	Fuse Type	Activation Pressure (psi)	M88A2 Activated	HMMWV Activated
POMZ-2	Russian	Trip-wire	7		
MON-50	Russian	Trip-wire	7		
MON-100	Russian	Trip-wire	7		
MON-200	Russian	Trip-wire	7		
OZM-3	Russian	Trip-wire	7		
OZM-4	Russian	Trip-wire	7		
OZM-72	Russian	Trip-wire	7		
P-40	Italian	Trip-wire	11		
VAL 69	Italian	Trip-wire	13.2		
M16A1	US	Trip-wire	6.5		
M1 Fuse	US	Trip-wire	4		
M1A1 Fuse	US	Trip-wire	10		
M3	US	Trip-wire	6		

Waterways Experiment Station plotted the maximum pressure of each vehicle pass for the M88A2, Figure 37 [Ref. 6:p. 10]. The graph indicates that the vehicle exerted higher pressures when the passes were conducted in the reverse direction as opposed to the forward direction. The M88A2 's maximum pressure was 7 psi on the second reverse pass and a minimum of 3 psi on the fourth forward pass. After the 44th pass, the pressures for both directions converge to about 6 psi. These numbers suggest that as the rut became deeper, the foam became stronger. As the debris in the rut became compacted, the crushed layer efficiently cushioned the impact of the vehicles [Ref. 6: p 9-10].

Figure 37 also shows that the M88A2 recorded higher pressures in the reverse direction. This can be explained by the manner in which the track advances in the reverse direction. In the reverse direction, the track exerts its maximum load directly underneath the final roadwheel. In the forward direction, track bridging takes place. This allows the weight to be distributed over a larger piece of track.

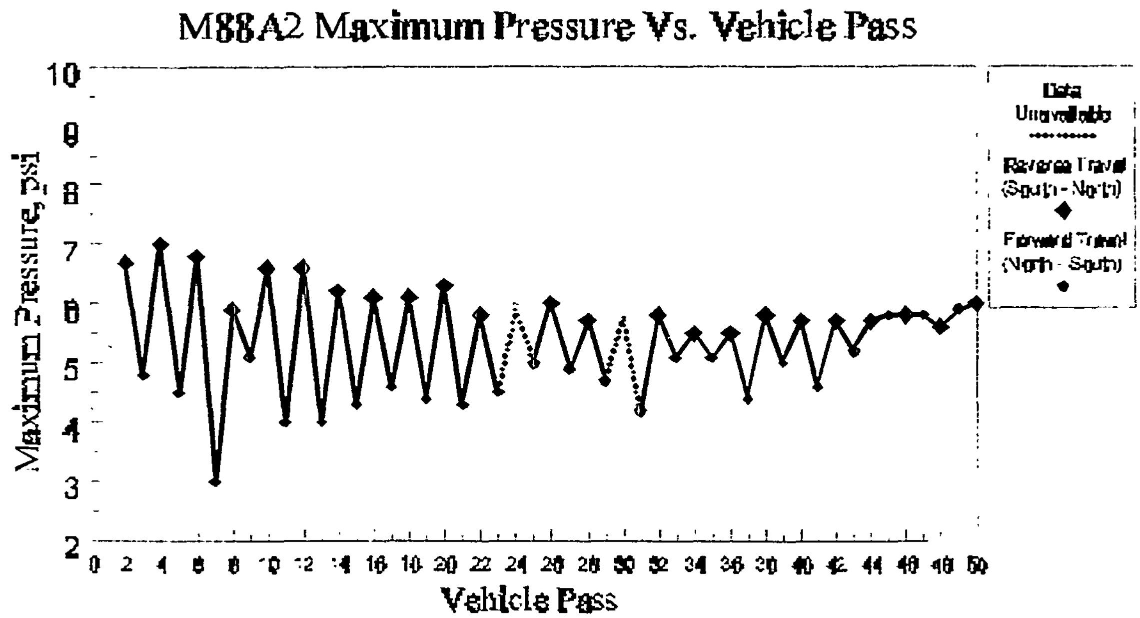

Figure 37. Change in maximum pressure versus pass number, After Ref. [5]

4. Foam Effects on Trip Wire

All of the trip wire devices placed in the proposed foam roadway were tripped by the expansion of the foam. The activation of trip-wire detonated mines within or adjacent to the roadway further decreases the threat posed to vehicular and foot traffic.

B. EXPLOSIVE EXPERIMENTS

1. Explosive Cavity Formations in RPF.

Based on the experimental results taken by Cooper and Kurowski, and Woodfin [Ref 12:p.43], predictions were made of the cavity sizes resulting from 10, 30, and 50 gram PETN explosives. Table 6 presents measured cavity diameters compared to the predictions based on earlier work.

Table 6. Predicted and Actual Cavity Results for 4 lb/ft^3 foam

Cavity (inches)	Explosive Charge PETN (Grams)		
	10	30	50
Predicted	12.00	17.00	19.00
Actual	5.30	10.00	10.70

The earlier works were based on C-4 and the present measurements were made with PETN. The experiments conducted by Cooper and Kurowski, and by Woodfin used C-4 as the explosive charge. C-4 has a TNT equivalent of 1.30 while PETN has an equivalent of 1.45 [Ref. 3:p. 76]. These results indicate that explosive charges placed between the ground and a foam block interface resulted in cavities which were smaller than the cavities formed from surface and embedded shots. The difference in cavity diameters for the three charges are 56%, 41%, and 47% for 10, 30, and 50 grams respectively.

Figure 38 shows the predicted plot for the 4 lb/ft^3 foam (blue). The 2 lb/ft^3 and 14 lb/ft^3 foam are depicted in red and green respectively. The experimental matrix for the PETN shots were based on the surface and embedded empirical data.

Figure 39 shows how the cavity data from the ground shots compares with the surface and embedded shots. The blast cavity diameters created by the ground shots were significantly smaller than the surface and embedded shots. The present experiment suggests that when the explosive lies between the ground and foam pad, more energy is absorbed by the ground, lessening the impact on the foam. Additionally, the ground shots exhibit the same charge scaling as the surface and embedded shots.

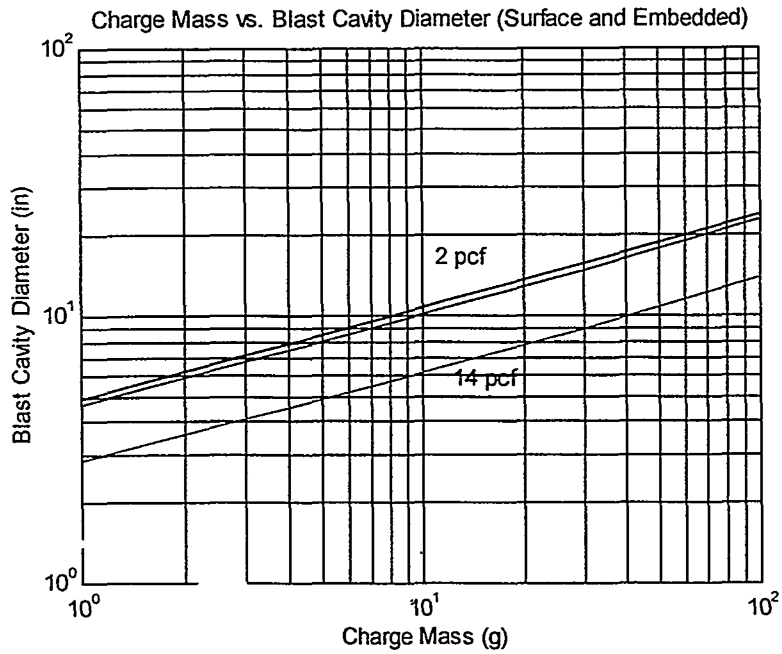

Figure 38. Cavity Prediction for 4 lb/ft^3 based on Surface and Embedded Data (C-4). The red and green lines depict the 2 lb/ft^3 and 14 lb/ft^3 Surface and Embedded data respectively.

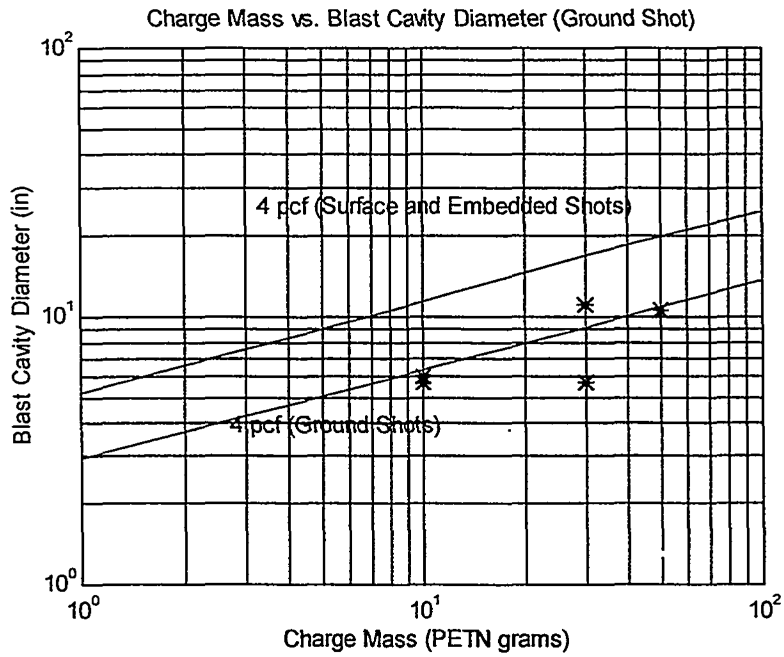

Figure 39. Comparison between Ground Shots and Surface and Embedded Shots. Note that the ground shots created smaller cavity diameters.

Table 7 shows a comparison of the cavity results for the two different block sizes to investigate the effect of edges. The data shows that the cavity sizes are very similar regardless of whether the foam block contained the explosive blast or was perforated by the blast. The 10 gram charge showed a 10% difference in cavity size while the 30 gram charge showed a 16% difference between the two different thickness. These numbers indicate that edge effects were not significant.

Table 7 also shows an approximate threshold charge before perforation occurs. The 10 gram charge can be completely contained by a block thickness of 18 inches while the 30 gram can be contained by a 30-inch block. A 50 gram charge was also completely contained by a 30-inch block. Additional experiments have to be conducted in order to determine a more precise failure criteria for a given charge and foam block thickness. Table 6 provides a graphical means to predict the cavity depth created by larger yields. Figures 39 and 40 are generated by using cube-root scaling on the measured cavity depth and cavity diameters. Using the cube-root scaling equation,

$$D = AW^{1/3}, \qquad (1)$$

where D is the cavity depth in inches, A is a constant with units in/g$^{1/3}$, and W is the yield in grams, we can calculate the constant, A, in order to predict cavity depths from larger yields. For the 4 lb/ft^3 foam, A has a value of 3.26 in/g$^{1/3}$. This constant yields the cavity depth and cavity diameter predictions in Table 8. Using these predictions for the 4 lb/ft^3 foam, a VS - 1.6 anti-tank mine, which has 1.7 kg of TNT, would create a 31-inch cavity diameter with a cavity depth of 35 inches. Similarly, the M19 anti-tank mine, which has 9.5 kg of Comp B, would create a 61-inch cavity diameter with a cavity depth of 67 inches. These numbers suggest that in order to completely contain an anti-tank mine similar to the M19, the foam roadway would have to be much larger than 67 inches thick. Additional experiments will have to be conducted in order to obtain a foam density that can provide an operationally capable foam roadway.

Table 7. Comparison of Cavity Diameters and possible Edge Effects.

EXPT #	***L X W***	***Thickness***	***Charge***	***Cavity***	***Diameter***		
	(inches)	***(inches)***	***(grams)***	***Entry***	***Exit***	***Depth***	
				(inches)	(inches)	(inches)	
L1	65 X 65	6	10	5.75	11.00	6.00	*
L3	85 X 85	6	10	4.75	13.75	6.00	*
L5	65 X 65	12	10	8.50	0.00	7.00	
L7	85 X 85	12	10	4.50	10.25	12.00	*
L9	65 X 65	18	10	6.00	0.00	6.00	
L11	85 X 85	18	10	5.75	0.00	6.50	
L2	65 X 65	6	30	8.50	18.50	6.00	*
L4	85 X 85	6	30	8.25	14.25	6.00	*, **
L6	65 X 65	12	30	11.50	18.25	12.00	*
L8	85 X 85	12	30	7.75	19.25	12.00	*
L10	65 X 65	18	30	9.75	15.50	18.00	*
L12	85 X 85	18	30	8.50	12.50	18.00	**
L13	85 X 85	18	30	11.20	0.00	11.20	
Mod 1	85 X 85	30	30	5.75	0.00	11.85	
L14	85 X 85	18	50	7.20	10.80	18.00	*
L15	85 X 85	30	50	10.70	0.00	12.80	

* failure
** loaded

Table 8. Predicted values for Cavity Depth and Cavity Diameter for 4 lb/ft^3 foam.

Cavity (in)	***Yield (grams)***					
	100	300	500	1000	3000	5000
Depth	15.10	21.80	25.90	32.60	47.00	55.80
Diameter	13.70	19.80	23.50	29.60	42.70	50.60

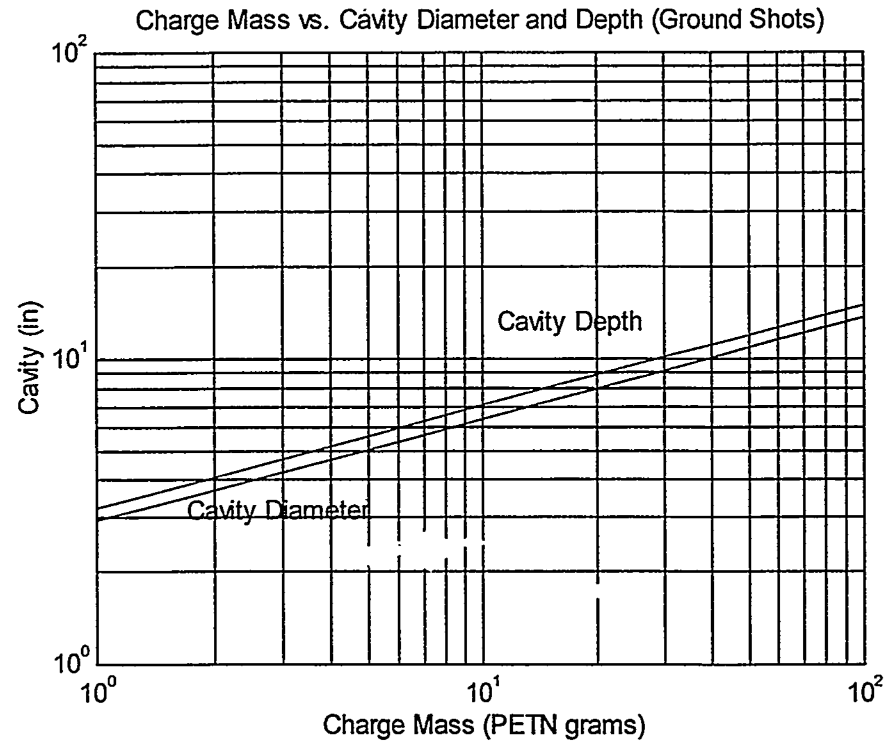

Figure 40. Charge Mass vs. Blast Cavity Diameter and Depth. Note that the cavity depth and diameters are only slightly different. This suggests that the blast cavity is semi-elliptical in shape. The red line represents the cavity depth while the blue represents the cavity diamter.

2. Repair of RPF explosive cavities.

The cavities of the damaged foam blocks were easily repaired by simply pouring foam into the damaged areas. During the foaming process, the foam would creep into all of the empty voids in the block. This process results in a repaired foam block that can be used to perform its original function, such as a roadway or an airport runway. Follow-on experiments will have to be conducted in order to compare the repaired block's initial and final properties. Figure 42 shows a sketch of the repaired foam block.

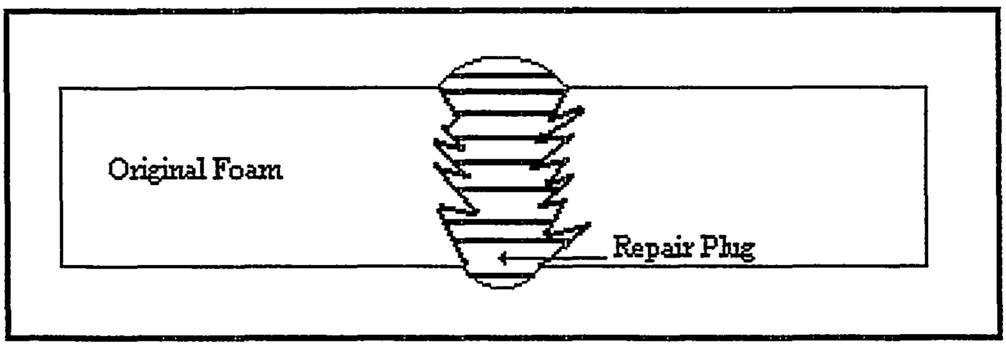

Figure 41. Sketch of a repaired foam block. Note that the new foam completely fills the cavity formed by the explosive blast. A cold joint is formed at the interface between the new and old foam.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The test results gathered from the Waterways Experiment Station indicate that a 24-inch thick, 4 lb/ft^3 Rigid Polyurethane Foam roadway adequately supported multiple passes of a track and wheeled vehicle. More importantly, the foam roadway was able to neutralize the mines buried underneath the foam and activate all trip wire detonated devices in the breach lane. Traction tests revealed that the foam did not improve traction for the M88A2 and only slightly increased the traction of the HMMWV. As for its use as a breaching technique for anti-personnel mines, the foam roadway itself serves as a very efficient breach lane, but it currently can not be employed in the timely manner needed for breaching exercises. The current dispensing machine can not dispense large enough quantities of foam in the required time for a in-stride breach.

The explosive cavity formation tests by Sandia National Laboratories indicate that a blast anti-personnel mine with 30 grams of PETN can be adequately contained by a 16-inch thick, 4 lb/ft^3 foam block. A 10 gram PETN charge can be contained by a 14-inch thick, 4 lb/ft^3 foam block This thickness is reduced when the foam is statically loaded.

The combined results of the two test sites indicate that the same 24-inch thick foam roadway constructed by Waterways should be able to withstand the explosive effects of a 30-gram PETN charge. Based on cube root scaling laws, the 24-inch foam roadway should be able to completely contain a 10-gram PETN charge, and the 30-gram data suggests that the foam roadway could contain a significantly larger charge. Energy absorption experiments are currently being conducted by Sandia National Laboratories in order to determine the amount of energy that is mitigated by the foam. The amount of foam needed to contain a specific explosive can be determined from the energy absorption properties of the foam.

These feasibility experiments indicate that Rigid Polyurethane Foam, at a given density and thickness, can withstand the explosive effects of anti-personnel blast mines and mitigate or neutralize the effects of surface laid anti-tank mines.

B. RECOMMENDATIONS

1. Conduct larger scaled explosive tests in order to determine the foam's performance against anti-tank mines. These test matrix should also include different foam densities. Peter Rand, a foam specialist at Sandia National Laboratories, suggested that foam densities between 8-10 lb/ft^3 would drastically increase the foam's ability to contain larger explosives.

2. Design or purchase a foam dispensing system that can dispense large volumes of foam from a considerable stand-off distance from a mine obstacle.

3. Conduct scaled explosive experiments to determine the structural effects of a mine detonated underneath an RPF block.

4. Evaluate other foam materials that may result in higher densities after water immersion.

5. Conduct experiments to determine the amount of explosive energy that is attenuated by RPF at a given density and thickness.

VI. OTHER CONSIDERATIONS AND APPLICATIONS

A. UNDERWATER EXPLOSIVE CAVITY FORMATIONS

Underwater explosive cavity formation experiments have also been conducted on RPF blocks in order to determine the effects of detonating underwater mines from varying depths. Figure 42 depicts the experimental set-up for the underwater explosive experiments. These experiments were conducted at the Energetic Materials and Research Training Center at Socorro, NM.

Figure 42. This is the set-up for the Underwater Explosive Experiments. This foam block is 6" thick and the explosive, PETN, is placed directly underneath the foam block. The PETN charge will also be located 12" and 24" underneath the foam.

B. ENERGY ABSORPTION PROPERTIES OF RPF

Experiments will be conducted by Sandia National Laboratories in November 1997 in order to determine how much energy is absorbed by an RPF foam block. These experiments will investigate the velocity of foam fragment particles impacting on a witness plate to determine how much foam will be required in order to contain the blast of a small scale explosive. The results from these experiments will be used to predict the foam's energy absorption properties against larger explosives such as anti-tank mines. Eventually, a real anti-tank mine will be detonated underneath a tank statically loaded on an RPF foam block to investigate the structural effects on the tank.

C. LOGISTICAL CONSIDERATIONS

A variety of logistical considerations will need to be investigated in order to determine if RPF can be operationally employed on the battlefield. Currently, the foam can not be dispensed in the large quantities required for breaching operations. This technology would also have to be employed in a timely manner under all weather conditions. Since the component temperature is crucial to final outcome of the foam, the dispensing mechanism may need an intricate heating system that will keep the two components at operating temperature, especially when used in cold environments. A Stockpile to Target Sequence (STS) study will have to be conducted in order to evaluate the foam's performance in known and assumed threat environments.

LIST OF REFERENCES

1. Archulete, M. and W. Stocum, *Toxicity Evaluation and Hazard Review for Rigid Foam*, Sandia National Laboratories, 1994.

2. Bailey, A and S. Murray, *Explosives, Propellants & Pyrotechnics*, Brassey's (UK), Ltd., 1989.

3. Coppens A. and R. Reinhardt, *Explosives and Explosions*, Naval Postgraduate School, 1995.

4. Hambric, H. and W. Schneck, *The Anti-personnel Mine Threat*, Night Vision Electronic Sensors Directorate, 1994.

5. Hespe, H., *Guide to Engineering Plastic Families: Thermosetting Resins*, Mobay Corporation, 1983.

6. Mason, G. and K. Hall, *Rigid Polyurethane Foam Countermine and Traction Concept Evaluation Program*, Waterways Experiment Station, 1997.

7. North Carolina Foam Industries, *MSDS: Aromatic Isocyanate*, NCFI, 1996.

8. North Carolina Foam Industries, *MSDS: Polyol Resin System*, NCFI, 1996.

9. Rand P. and B. Hance, *Foam for Barrier Crossing: Initial Properties*, Sandia National Laboatories, 1995.

10. Rand P. and B. Hance, *Foam for Barrier Crossing: Mechanical Properties as a Function of Density, Temperature, and Time After Pour*, Sandia National Laboratories, 1995.

11. Rand P., Interview with Peter Rand on September 11, 1997, SNL.

12. Strong, B., Plastics, *Materials and Processing*, Prentice-Hall Inc., 1996.

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

BIBLIOGRAPHY

Bailey, A. and S. Murray, *Explosives, Propellants and Pyrotechnics,* Brasseys, Inc, 1989.

Bening, R. and M. Kurtz Jr, *The Formation of a Crater as Observed in a Series of Laboratory-scale cratering experiments,* U.S. Army Engineer Nuclear Cratering Group, 1967.

Bowen, J., Manson, N., Oppneheim,A., and R. Soloukhin, *Shock Waves, Explosions, and Detonations*, American Institute of Aeronautics and Astronautics, Inc., 1983.

Chew, T., Rooke, A. Jr., and L. Pitman, A *Small-scale Study of Craters Resulting from Repeated Explosions along a Common Vertical Axis*, Waterways Experiment Station, [illegible]6.

Cooper, P. and S. Kurowski, *Introduction to the Technology of Explosives*, VCH Publishers, Inc, 1966.

Dobratz,M., *LLNL Explosives Handbook: Properties of Chemical Explosives and Explosive Simulants*, Lawrence Livermore Laboratory, University of California, 1981.

Enhamre, Z., *Effects of Underwater Explosions on Elastic Structures in Water*, Bulletin No. 42, Transactions of the Royal Institute of Technology, 1954.

Kuhl, A., Leyer, J., Borisov, A., and W. Sirignano, *Dynamic Aspects of Detonations. Volume 153, Progress in Astronautics and Aernautics*, American Institute of Aeronautics and Astronautics, Inc., 1993.

Gibbs, T. and A. Popolato, *LASL Explosive Property Data*, University of California Press, 1980.

Graham, R., *Solids under High Pressure Shock Compression,* Springer-Verlag, N.Y. 1992.

Rooke, A. Jr, Carnes, B., and L. Davis, *Cratering by Explosions: A compendum and an Analysis*, Waterways Experiment Station, 1974.

Rooke, A. Jr. and T. Chew, *Crater and Ejecta Measurements for a full-scale Missile Detonation in an Underground cell*, Waterways Experiment Station, 1966.

Rooke A. Jr. and J. Strange. *Techniques for Determining the Cratering Effects of Surface and Underground Explosions*, Waterways Experiment Station, 1966.

Snell, C., *One-dimensional analysis: Shock Wave Propagation from Underwater Cratering Detonations*, Waterways Experiment Station, 1975.

Spyrakos, C., *Finite Element Modeling in Engineering Practice*, West Virginia University Press, 1994.

Wolsky, S. and A. Czanderna, *Ballistic Materials and Penetration Mechanics*, Elsevier Scientific Publishing Company, 1980.

Zukas, J., Nicholas, T., Swift, H., Greszczuk, L., and D. Curran, *Impact Dynamics*, Wiley-Interscience Publication, 1982.

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Appendix D

Explosive Experiments — RPF / EMRTC

C. O. Schmidt / LATA 622

This appendix provides details of the initial anti-personnel landmine simulations in water.

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MEMORANDUM FOR THE RECORD

1 November 1997

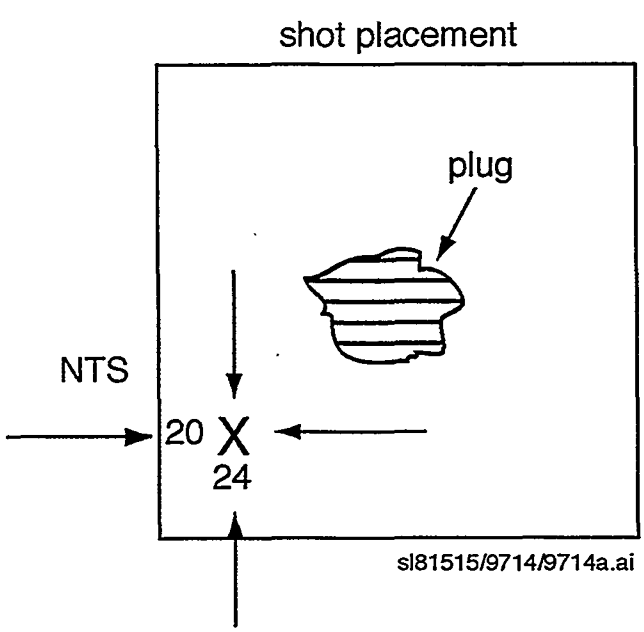
C. O. Schmidt / LATA 621

Subject: Explosive Experiments - RPF / EMRTC, 28 - 30 October 97

28 October: Negotiated and finalized test plan with EMRTC engineers. Woodfin finalized statement of work and got funding documents in order.

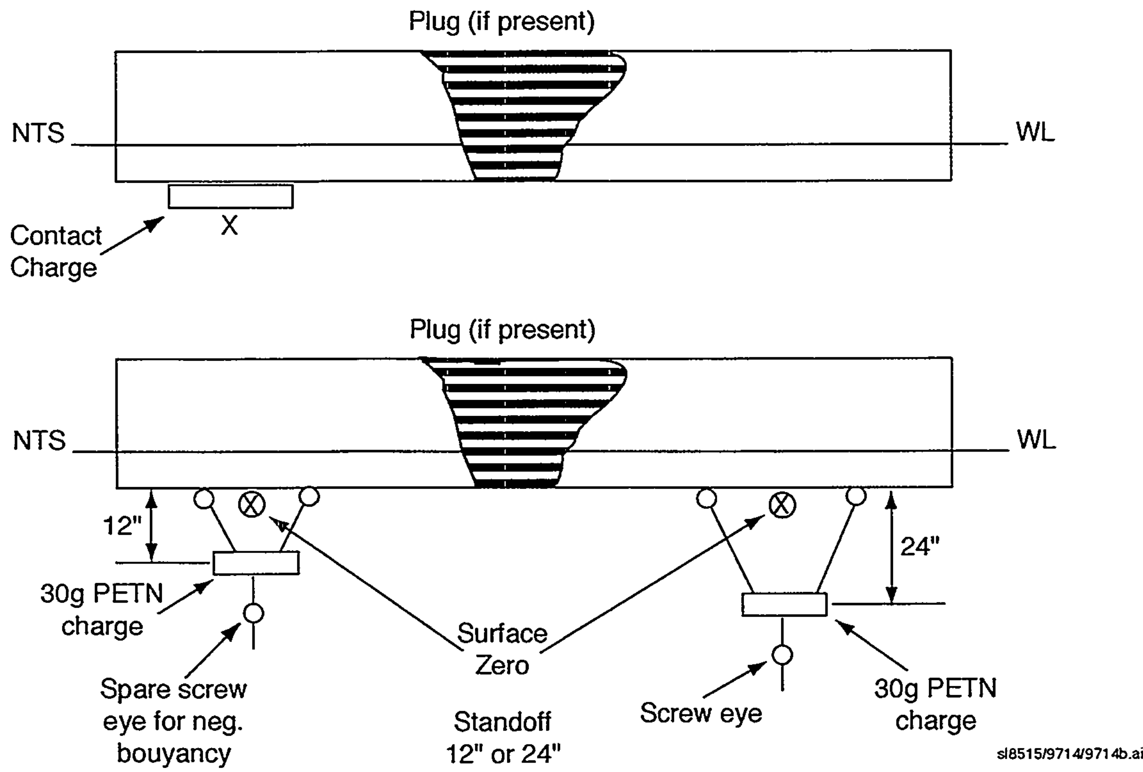
29 October: Considerable unnecessary flail in the field getting "beaver pond" ready for experiments and all required material in place. Ed Jones and Dave Faucett casting 6, 12, and 18 inch foam blocks for experiments. Transported already cast and patched blocks to beaver pond. Patched several more (5?) blocks for underwater (UW) experiments. Finally got in two shots in beaver pond:

Shot a: Block W1/L1: 85 x 85 x 6 in, contact shot, 30 g PETN with RP80 det.
Charge located away from previous plugged shot hole at ~ 20" & 24" in from one corner.
Result: tapered shear hole with complete perforation.
entry side: 15 1/2 / 13 1/2 / 15 1/2 = avg 14.8" diam
exit side: 17 1/2 / 22 1/2 = 20" avg diam
hole shows both smoke & "frag" paths (H_2O)



Block destroyed by structural sheer loads - ~10 larger pieces - much small debris - plug patch separated nearly intact.

Shot configuration - All UW Experiments



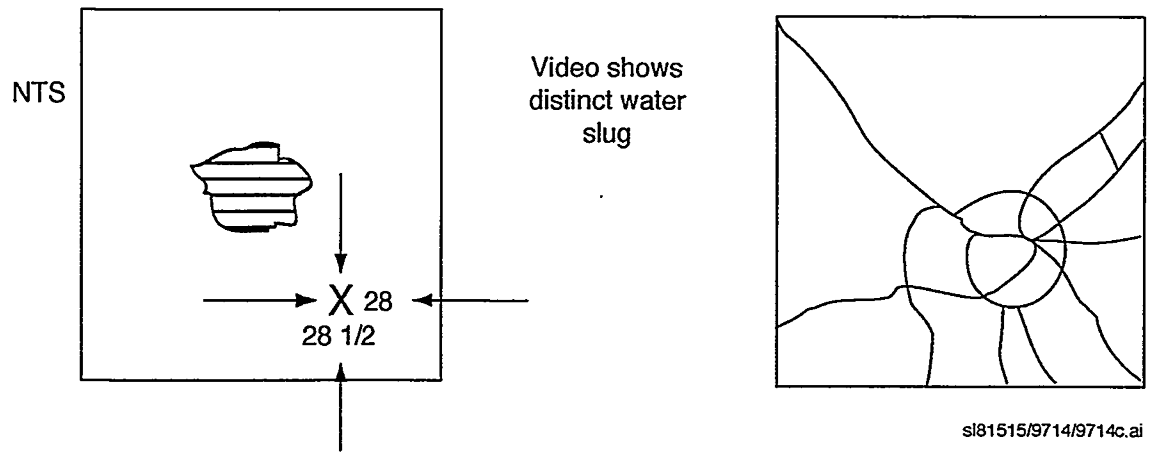
<u>Suspension</u>: light nylon cord to either 2 (12") or 4 (24") 5/16(?) screw eyes into foam - lowest screw eye added to assure negative buoyancy.

<u>Water depth</u>: variable between ~3 and 4 ft.

<u>Block</u>: suspended from light crane by ropes through all four corners - hoisting ropes slack for all shots.

Shots were centered for "virgin" blocks W7, 8, and 9.

<u>Shot b</u>: Block W2/L3: 85 x 85 x 6 in. - patched.
12 in standoff, 30g PETN with RP80 det.
Charge located away from plug patch at 28" and 28 1/2" from corner.
Result: Fracture into many pieces - circular pattern - no burn marks - radially punched hole ~35 in diameter, 7 radial cracks - glasslike fracture - ~18 large pieces

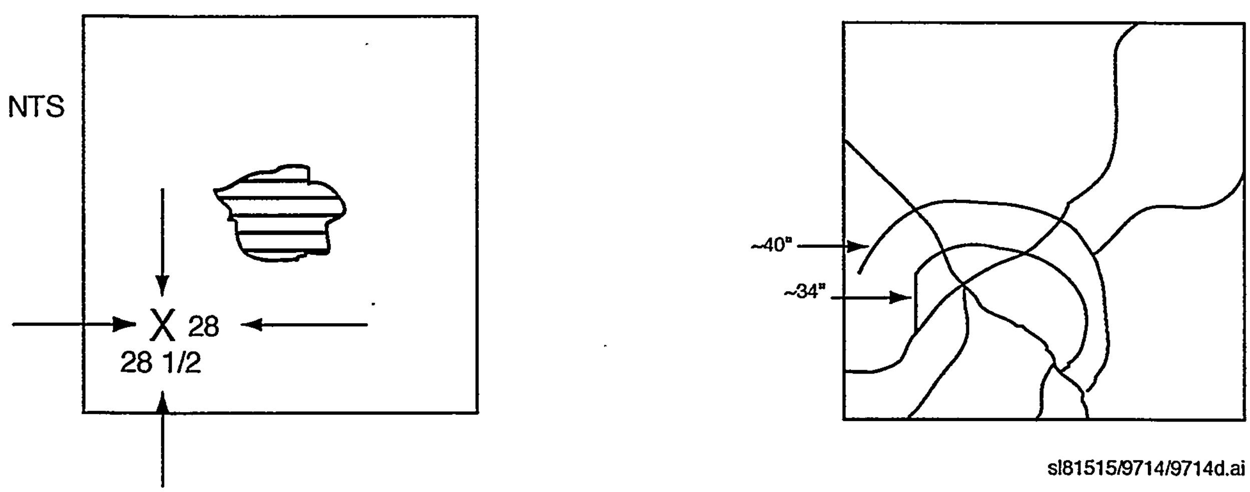


sl81515/9714/9714c.ai

Scoped out Little Eagle test site for next week.

30 Oct: Better coordination of support people. Got off 5 UW shots at beaver pond. Ed and Dave casting last 3 - 4 blocks.

Shot c: Block W5/L7: 85 x 85 x 12 in. - patched.
12 in. standoff, 30g PETN with RP80 det.
Charge located similarly - 28 in and 27 in from corner
Result: Glasslike radial fracture - many pieces. Two circular separations, ~34 in inner circle and ~40 in outer circle (incomplete - ~200°) - 6 radial cracks. Video shows two water slugs - one clean water - second with much mud from pond bottom.



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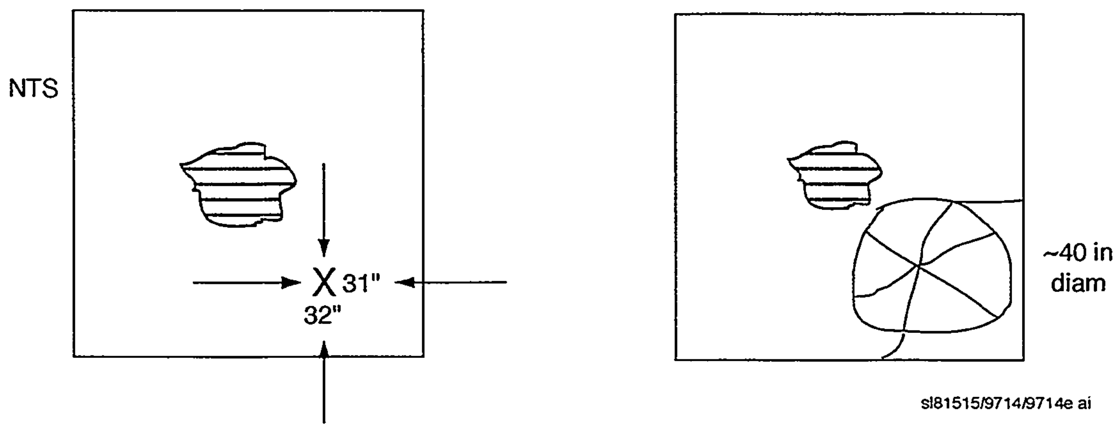
Shot d: Block W6/L8: 85 x 85 x 12 in - patched
24 in standoff, 30g PETN with RP80 det.
Charge located similarly - 31 and 32 in from corner
Result: Blew out 39 - 40 in center plug - less fracturing - 6 radial cracks - larger pieces.



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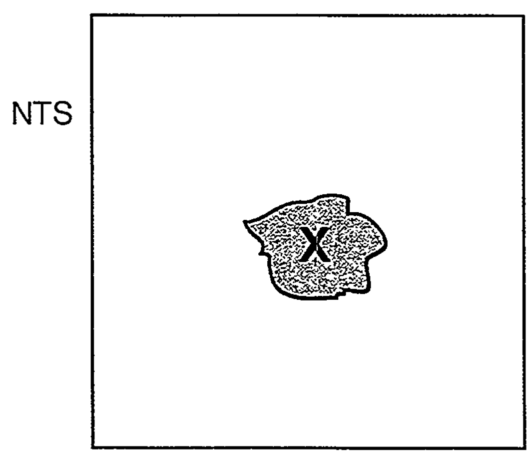
<u>Shot e</u>: New cast block W7: 85 x 85 x 6 in ~24 hrs old. Contact shot in Center - 10g PETN with RP80 det.

Result: Tapered punched hole similar to shot (a) but no fragmenting.

Entry hole: 9 1/2 / 9 / 7 1/2 in avg ~8.66 in

Exit hole: ??

Edges smoked and show "frag" paths from water wash.



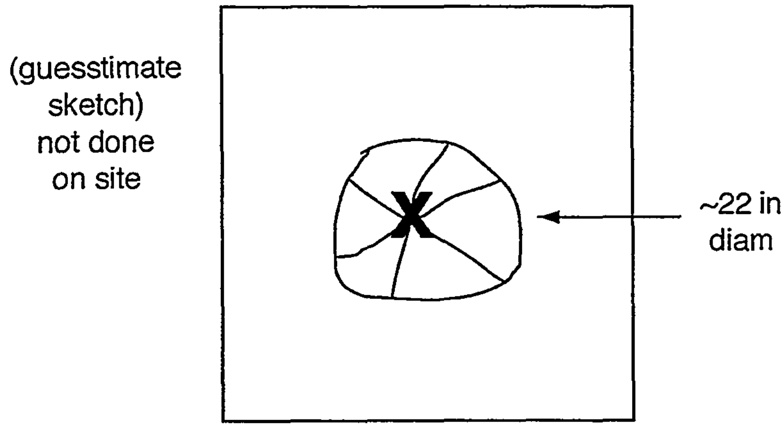
sl81515/9714/9714f.ai

<u>Shot f</u>: New cast block W8: 85 x 85 x 6 in

~24 hrs old. 12 in standoff, centered shot - 10g PETN with RP80 det.

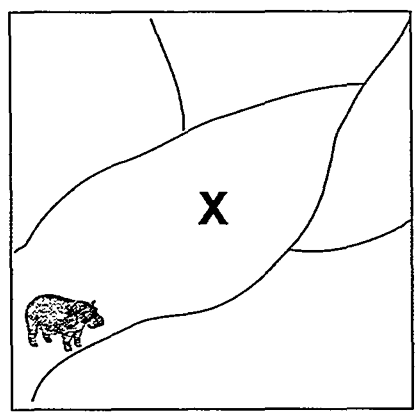
Result: Round plug fracture - glasslike - 21/23 in

avg 22 in diam. -5 radial cracks - <u>No</u> secondary circle crack



sl81515/9714/9714g.ai

Shot g: New cast block W9: 85 x 85 x 6 in
~24 hrs old. 24 in standoff, centered shot - 10g PETN with RP80 det.
Result: <u>No hole</u> - 5 very large pieces. Structural failure.



Finished up about 1630 and secured. Alba to continue Friday with 3 -4 more UW shots plus 3 dry shots @ 50 g.

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Appendix E

Timing of Application of Second Layer Of RPU Foam on Foam Formed in Water

Brad Hance, Sandia

This appendix provides details of pour interval timing experiments done in Sandia's laboratory to provide accurate timing of the second layer pour.

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Sandia National Laboratories

Albuquerque, New Mexico 87185-0860

date: December 9, 1997

to: Ron Woodfin, Org. 02522 MS0860

from: Brad Hance, Org. 02522 MS0860

subject: Timing of Application of Second Layer of RPU Foam on Foam Formed in Water

Motivation and Approach:

When RPU foam is applied in water, it is necessary to know how long the foam needs to cure before a second layer of foam can be applied without having it break through the initial foam layer. To address this issue, a series of laboratory scale experiments was conducted.

The time after mixing at which a given depth of liquid foam material could be supported by the initial layer of foam on water was the measured response in these experiments. The force (pressure) exerted by a 0.75 inch and a 3.0 inch layer of liquid foam was calculated and test weights of appropriate weight and bearing area were fabricated. The foam was mixed, poured in the water, and at appropriate time intervals, the test weights were carefully placed on the foam surface to determine it they would be supported without tearing through the foam. The time at which each load was adequately supported was then recorded.

Experimental Details:

All experiments were conducted in an inflatable wading pool approximately three feet in diameter. A thin layer of sand was placed on the bottom and four inches of water added. Wave motion was not incorporated into this series of tests. The pool was large enough such that, with the foam batch sizes used, the foam was not constrained in its horizontal expansion.

The foam used was NCFI 811-91-3.3 Lot#933. The foam was prepared using batch mixing with a rotary blade mixer for 25 seconds. Tests were conducted with batch sizes of 100 grams and 300 grams of material.

The test weights were constructed of lead fishing weights embedded in paraffin wax. The wax was cast around the lead weights in a mold with a bottom bearing area of 3.15 square inches. Two test weights were used, one that exerted a pressure of 0.03 psi (47.3 g / 3.15 sq. in.) and the other that exerted a pressure of 0.13 psi (183.22 g / 3.15 sq. in.). These pressures correspond to 0.75 inches and 3.0 inches of liquid foam head.

Results:

The experiments shown in the table below were conducted at a water temperature of 70°F.

Batch Size (g)	Pour Delay (sec)	Load (psi)	Time (min) to Support Load
100	0	0.03	6.5
100	0	0.13	9.5
100	30	0.03	6.33
100	30	0.13	9.0
300	0	0.03	6.15
300	0	0.13	8.0
300	30	0.03	6.25
300	30	0.13	8.5

Following analysis of the above experiments, two additional experiments were conducted at a water temperature of 60°F. This results are shown below.

Batch Size (g)	Pour Delay (sec)	Load (psi)	Time (min) to Support Load
300	0	0.03	6.5
300	0	0.13	9.5

Discussion:

Several assumptions were made to simplify and expedite this test series:

- The measured response (time to support load) is linear over the experimental range for each variable.
- Foam reaction kinetics scale linearly in general.
- Motion of water (waves) doesn't effect initial foam strength development.
- Batch mixing represents machine mixing.
- Carefully placed static loads represent dispensing of liquid foam from machine.

Some of these assumptions are not strictly correct, but given the time available for experimentation, could not easily be adjusted to reflect the situation in the test pond.

From these experiments, it appears that pour delay is an insignificant factor in the development of load bearing capacity of foam poured on water. It may be important in other aspects of foam formation and may warrant further study.

Temperature is always a major factor in chemical kinetics. Two factors in these experiments probe the role of temperature in the development of load bearing capacity; water temperature and batch size.

It was expected that batch size would have an effect on time to support a load, but over the limited range studied, it appeared to have only a minor effect. Furthermore, upon analysis of the data, it became apparent that the linear relationship between time to support a load and batch size, as determined from the experimental data, could not be used to exptrapolate effects on a much larger batch (27Kg) because the resulting extrapolated time was negative! Batch size does matter however, because a larger reacting mass will generate a greater internal heat of reaction and therefore speed up the reaction. It would be a good idea to conduct some experiments similar to those above on "pond scale" foam pours to better understand the role of batch size on initial strength development.

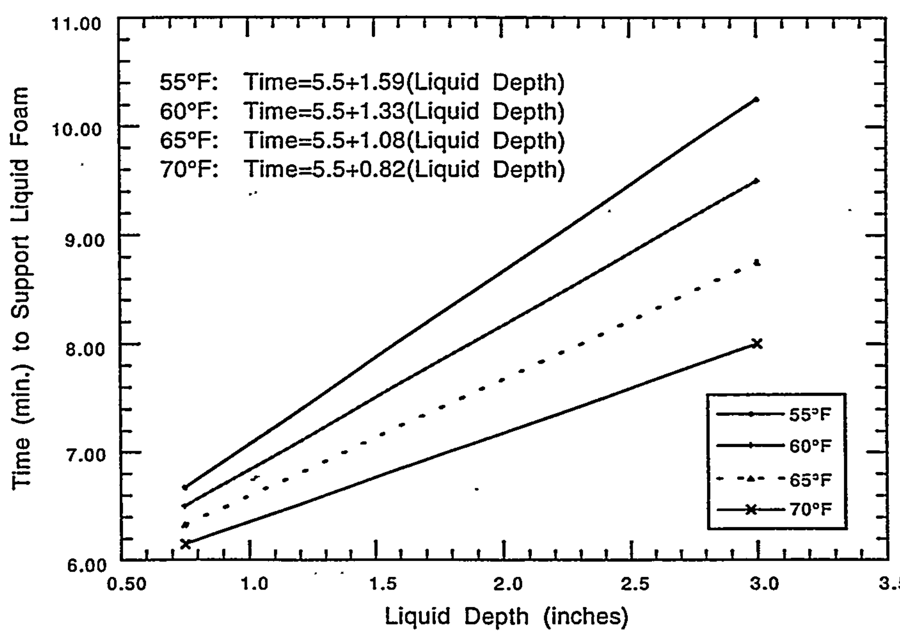
Previous studies have shown that water temperature is a major factor in foam reaction rates. There is evidence of a linear relationship between tack-free time and water temperature (Fig. B-3 on page B-8 of SAND96-2841). This suggests that other properties that are dependent on reaction kinetics may scale linearly with respect to water temperature.

The load applied is the main factor and should fall between the values used in the experiements. Previous studies of penetration resistance as a function of cure time for foam formed in air have shown that load bearing capacity increases linearly with cure time up to about 30 minutes (refer to Fig. B-14 on page B-19 of SAND96-2841). Although foam formation in water differs somewhat from that in air, it is still reasonable to assume that the load bearing capacity dependence on cure time follows a linear relationship. This allows us to interpolate time values from the experimental data with confidence.

Conclusions/Predictions:

The graph shown below summarizes the results of these experiments.

Time at which a Layer of Liquid Foam of a Given Depth can be Supported by the Initial Foam Layer



Timing of application of the second layer of foam becomes more critical as water temperature decreases, particularly if the initial layer of foam has a high degree of topographic relief. In this instance, localized areas of deep liquid pockets may exert enough pressure to break through the foam if care is not taken to regulate the amount of liquid foam dispensed into these areas. Alternatively, more time could be allowed for development of initial foam layer strength.

Although there is not any hard data regarding the timing of crack formation in foam placed in moving water, my recommendation is to dispense a second layer of foam about 8 minutes after the initial foam layer is dispensed. This should prevent the second layer from breaking through the first while avoiding wave-induced crack formation.

Appendix F

Explosive Velocity Attenuation Experiment

C. O. Schmidt, LATA / 621

This appendix provides details of flyer-plate velocity attenuation experiments with 2 and 4 pcf foam blocks.

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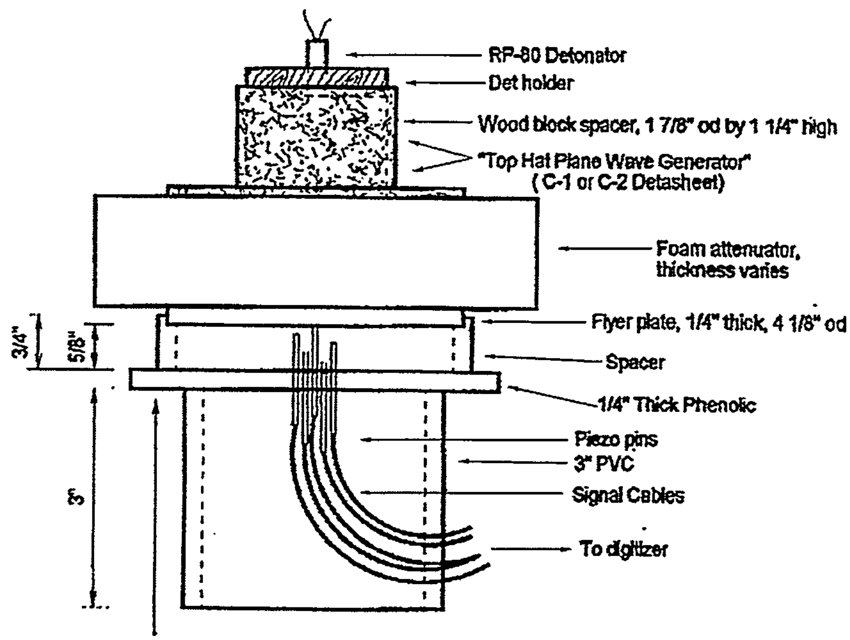
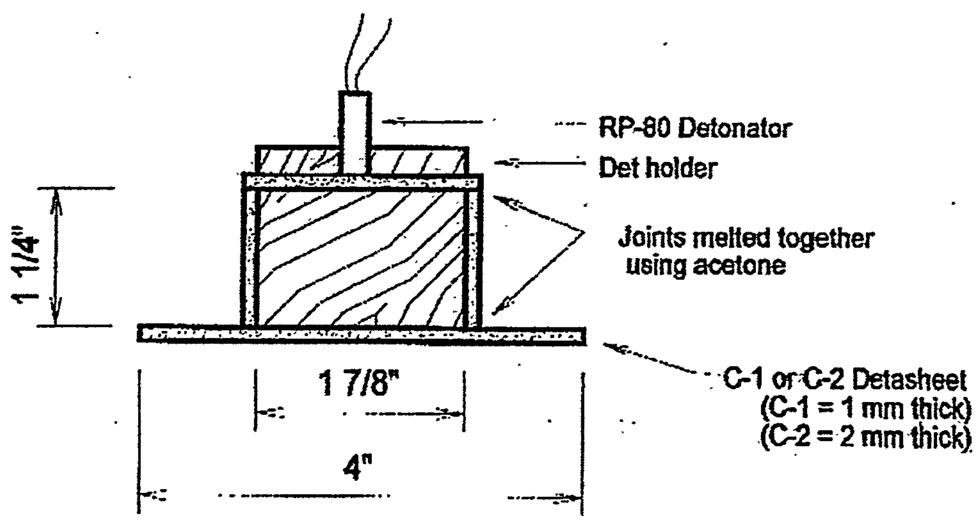
MEMORANDUM FOR THE RECORD
7 November 1997
C.O. Schmidt/LATA 621

Subject: Explosive Velocity Attenuation Experiment 6-7 November 97

Thurs 6 Nov: Began velocity attenuation experiment series using 1 and 2 mm Detasheet "top hat" plane wave charges. Detasheet has detonation velocity (D) of ~7.03 km/s and density (p) of 1.48. Charges assembled as follows.





Witness pins (7) were direct wired to a time interval recorder in control room. (Pin distances: .000, .050, .100, .130, .160, .250, .350 inches.) All shots were fired remotely inside Little Eagle steel blast cell from Capacitance Discharge Unit (CDU) fire set in control room. Matrix and experimental data recorded follows. Data marked "(?)" is questionable.

Experimental Matrix

	Charge		
	2 mm (45.4g)	**1 mm (27.5g)**	
FOAM 0 in	X	X (bad) 0	reshoot
12 in	X	X	
9 in	0	X	
6 in	0	0	
4 in	0	X	
2 in	0	0	
Cavity (bags)	0	X	

X = Thurs 11/6/97
0 = Fri 11/7/97

__Shot 1__: Calibration shot, 2mm Detasheet charge, (45.4g NEW) plus RP-80 detonator, no foam.

Channel
1 15.569μs
2 20.166
3 23.777
4 31.230
5 39.608
6 48.286
7 41.863 (?)

Quick look calculation (Banks) V ≅ 905 ft/s.

__Shot 2__: Foam 15" diam X 12" high; 2mm charge (45.4g) plus RP-80 det.

Channel
1 83.773 μs
2 748.494
3 no reading (?)
4 no reading (?)
5 3578.184
6 no reading
7 no reading

Changed to 1mm Detasheet in an attempt to get cavity data simultaneously– (didn't work).

__Shot 3__: Foam 15"d x 12"h' 1mm charge (27.5g) with RP-80 det.

__No__ velocity data; cavity: entry avg 11" (top) exit avg 8.5 in diameter. 8.5 in. cavity plus shear plug blown out. Saved.

__Shot 4:__ Foam 12"d x 9"h; 1mm charge (27.5g) with RP-80 det.
Channel 1 1481.733 μs.
No other velocity numbers. Foam block disintegrated into fist-size pieces.
1415: half hour break to make up more 1mm charges.

Shot 5: Foam 15"d x 4"h;' 1mm charge (27.5g) with RP-80 det.

Channel		
	1 89.660μs	5 385.766
	2 160.993	6 473.061
	3 202.354	7 533.118
	4 255.410	

Straight-through shear hole avg 11 in. diameter.
Quick look calculation (Banks) V ≅ 59 ft/s.

Shot 6: Calibration shot: No foam; 1mm charge (27.5g) Pin #2 appears loose.

Channel		
	1 16.150μs	5 45.401 (?)
	2 16.039 (?)	6 85.710
	3 43.970	7 94.622
	4 53.960	

Flyer plate is bent – pin marks show - small (1/16 in) spall hole in center.
Data looks flaky – will shoot over.

Shot 7: Cavity shot with foam in plastic bag: 23"h x oval 20 x 22" centered 2mm (27.5g) shot on 8-10 in meplat at top of bag.

Entry hole avg. 8.58 in, circular, roughly cylindrical cavity with nearly flat bottom. Depth avg. 10.83 in. block and outer bag intact. Saved.

Friday 7 Nov 97.
Shot 8: Foam 12"d x 9"h; 2mm charge (45.4g) with RP-80 det.

Channel		
	1 no reading	5 1542.523
	2 313.100 μs	6 no reading
	3 458.199	7 no reading
	4 no reading	

Foam destroyed – quarter-size chunks.

Shot 9: Foam 12"d x 6"h; 2mm charge (45.4g) with RP-80.

Channel		
	1 119.781 μs	5 398.024
	2 172.696	6 535.838
	3 217.682	7 668.161
	4 273.625	

Foam destroyed.

Shot 10: Foam 15"d x 4"h; 2mm charge (45.4g) with RP-80 det.

Channel	1 70.836 μs	5 169.468
	2 102.988	6 207.373
	3 120.143	7 235.768
	4 139.717	

Data leads installed backwards – readout Channel 7 → 1. Foam destroyed.

Shot 11: Foam 12"d x 2"h; 2mm charge (45.4g) with RP-80 det.

Channel	1 56.417 μs	5 110.228
	2 66.766	6 118.138
	3 78.522	7 118.156
	4 93.928	

Data leads installed backwards – readout was Channel 7 → 1. Foam destroyed.

Shot 12: Cavity Shot: Foam in plastic bag: 25"h x oval 19-1/2 x 23". Centered 2mm (45.4g) shot on 8-10 in. meplat cut in top of foam.

Cavity: Average 11.17 in diameter; avg. 14.83 in. deep – roughly cylindrical but rounded bottom. Foam broke into two large pieces with some smaller debris – reassembled and saved.

Shot 13: Foam 12"d x 6"h, 1mm charge (27.5g) with RP-80 det.

Channel	1 150.055 μs	5 no reading
	2 309.224	6 no reading
	3 434.717	7 no reading
	4 878.481	

Foam destroyed.

Shot 14: Foam 12"d x 2"h; 1mm charge (27.5g) with RP-80 det.

Channel	1 40.126 μs	5 133.242
	2 70.560	6 173.505
	3 85.312	7 206.242
	4 104.206	

Data leads reversed – readout channel 7 → 1. Foam destroyed.

Shot 15: Calibration shot – reshoot shot #6. No foam; 1mm charge (27.5g) with RP-80 det.

Channel	1 15.548 μs	5 67.159
	2 23.977	6 83.238
	3 37.873	7 89.515
	4 51.146	

Much better data.

NOTES:

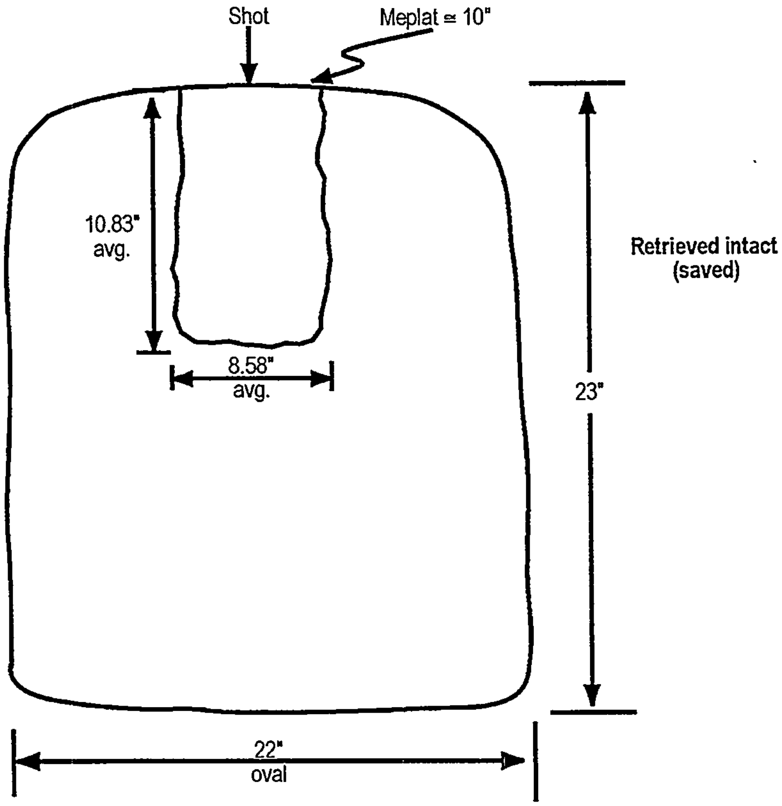
(1) All 15 inch foam circles were poured in heavy cardboard barrel and had cardboard outer layer still attached. All 12 inch diameter circles were taped with nylon reinforced strapping tape in one to four places, dependant on thickness.

(2) Photographs taken of calibration and foam shot setup; cavity shots and some remaining debris.

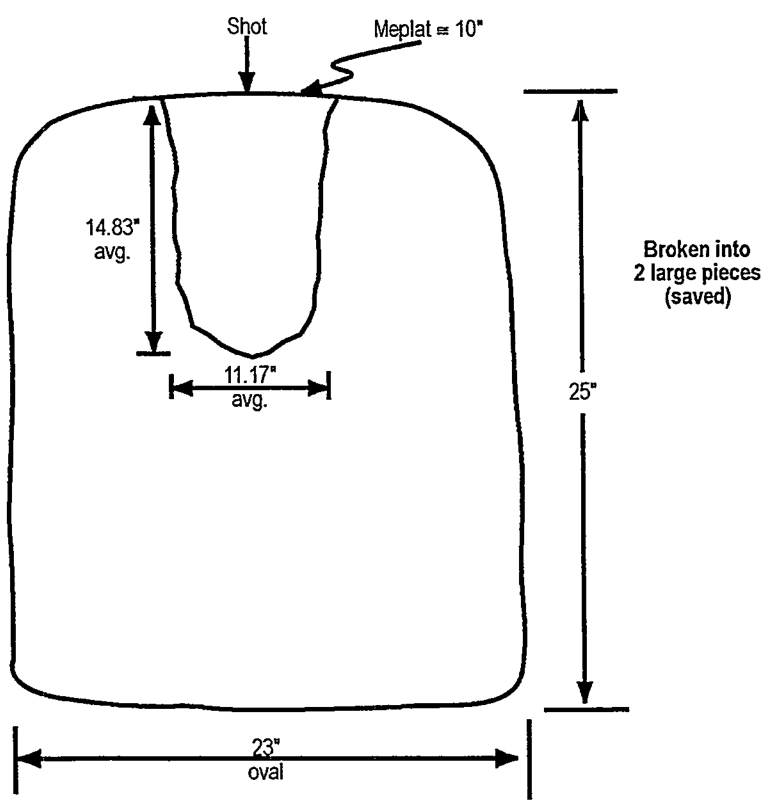
(3) Debris from shots 3, 7, and 12 saved for "show and tell."

(4) All flyer plates and representative pin boards saved

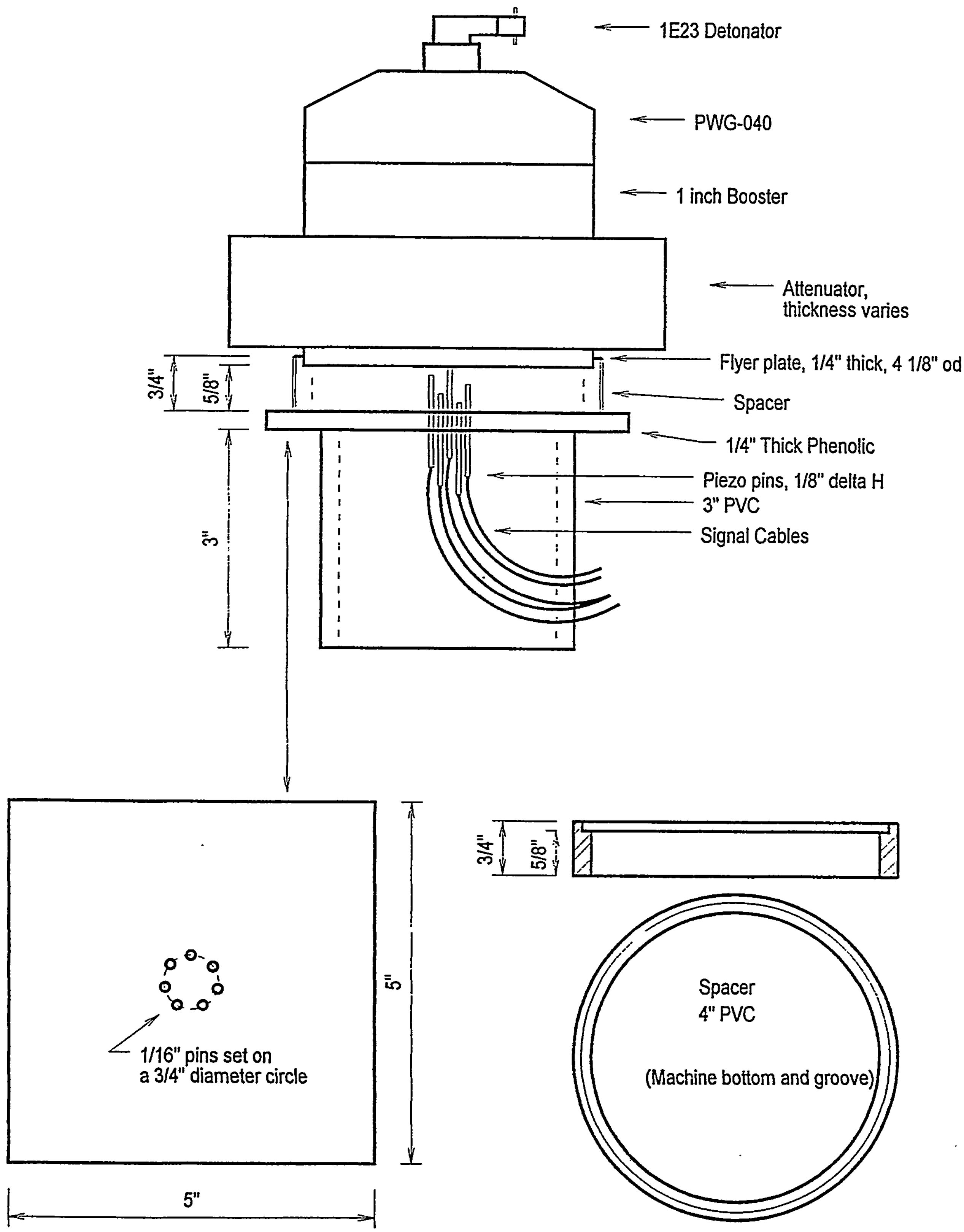
Shot 7:

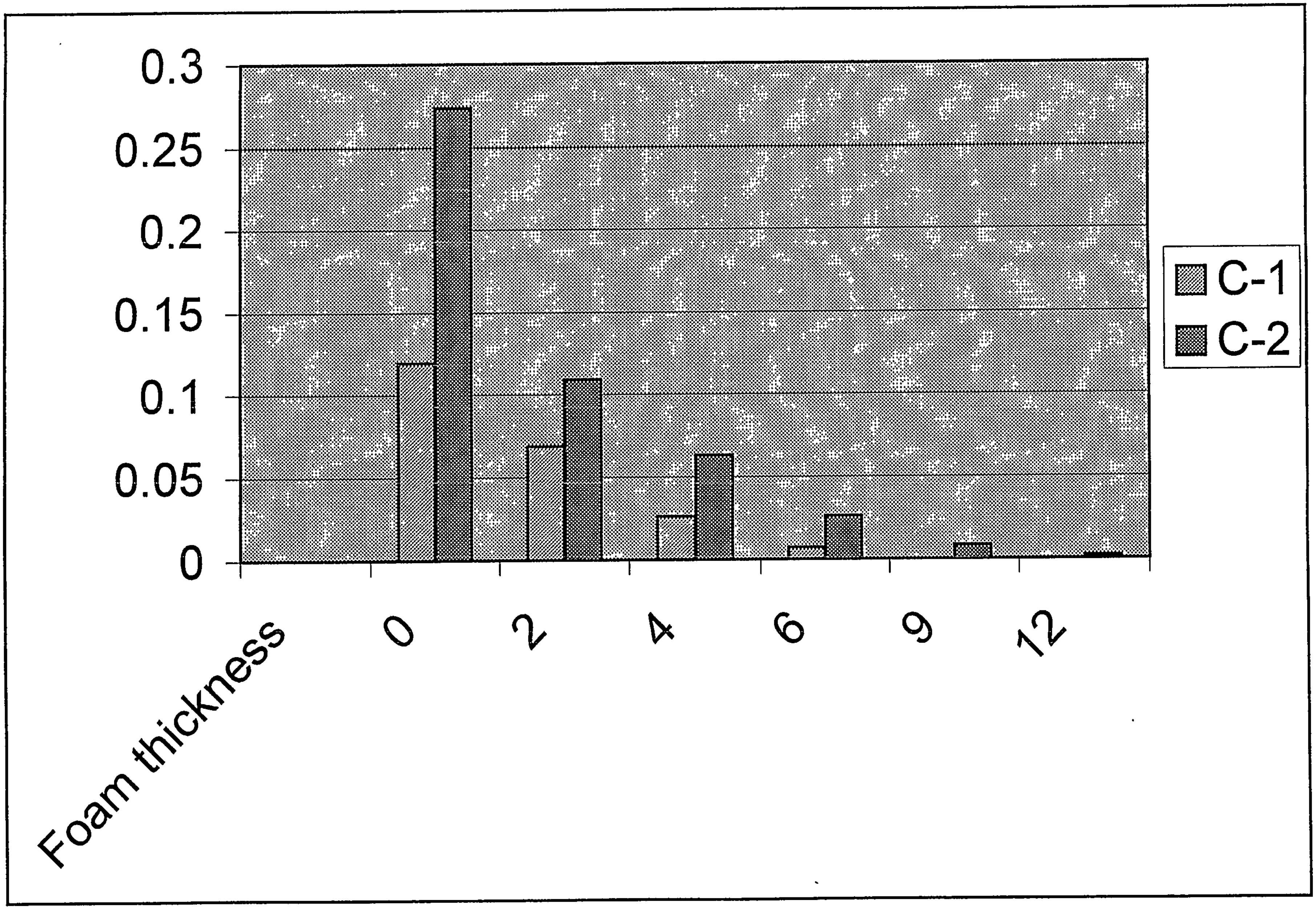


Shot 12:



SNL Attenuation Tests




0.3
0.25
0.2
0.15
0.1
0.05
0
Foam thickness
0
2
4
6
9
12
C-1
C-2

Appendix G

Explosive Velocity Attenuation Experiment

C. O. Schmidt, LATA / 621

This appendix provides details of explsoive velocity attenuation experiments using nominal 8 pcf foam.

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MEMO for Record

22 December 1997

C. O. Schmidt, LATA/621

Subject: Explosive Velocity Attenuation Experiments

Wednesday, 17 December 1997, we began a second series of explosive experiments using nominal 8 pounds per cubic foot (pcf) polyurethane foam. Shots were all fired in the test cell at Little Eagle site, EMRTC, Socorro. Explosive charges were made up of Detasheet ranging from 1 to 6 mm (C-1 to C-6) constructed per Figure 1.

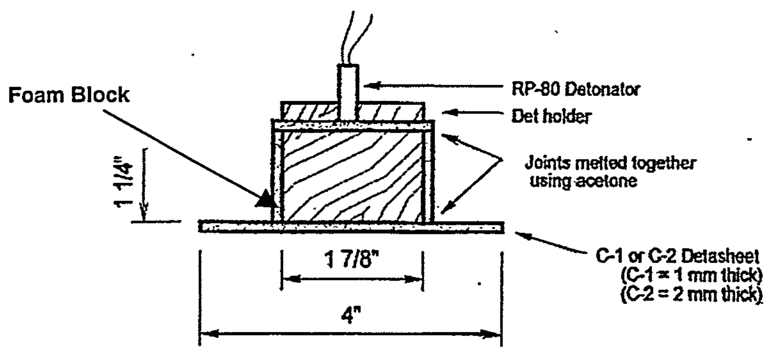

Figure 1. Detasheet "top hat" assembly

Detasheet has a detonation velocity (D) of ~ 7.03 km/sec and a density (p) of 1.48 g/cc.

The series of experiments was begun with four shots into a 6-inch foam block to determine what size charge would produce the best data. All shots were fired using a flyer plate assembly as shown in Figure 2 connected to a digital time interval recorder in the control room.

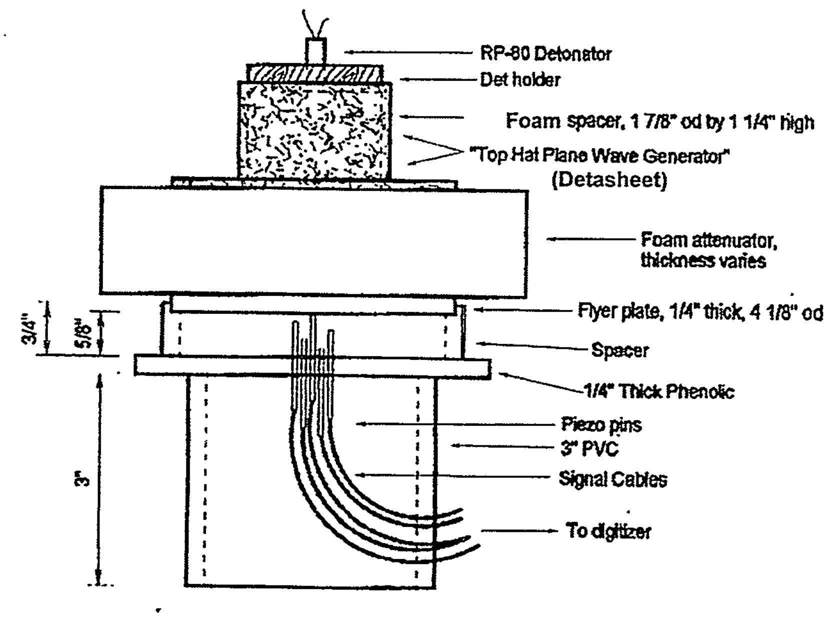

Figure 2. Flyer plate assembly

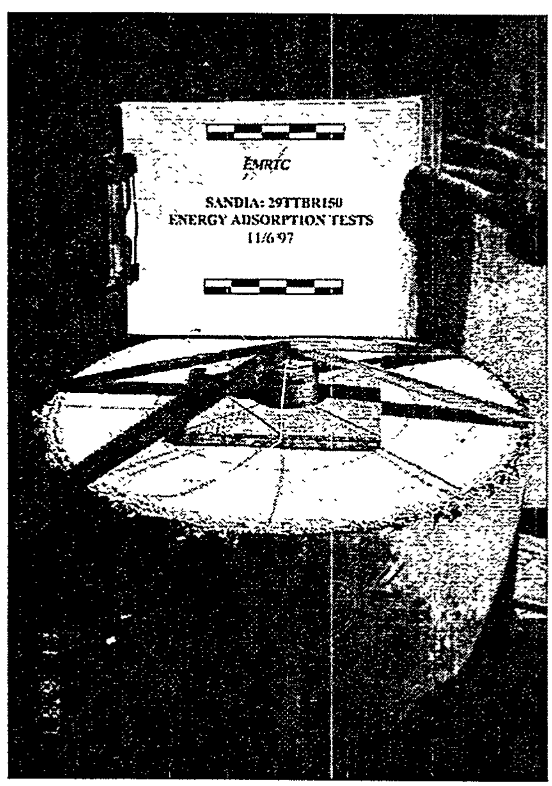

Figure 3. Assembled top hat charge

The four preliminary "locator" shots were fired as follows: (all times in microseconds)

Shot 1: 6-inch foam block no. 14; C-1 charge; flyer plate no. 1

Channel 1	no data	4	no data
Channel 2	511.597	5	no data
Channel 3	no data	6	no data

Shot 2: 6-inch foam block no. 10; C-4 charge; flyer plate no. 2

Channel 1	132.458	4	187.816
Channel 2	155.140	5	203.182
Channel 3	175.445	6	227.283

Shot 3: 6-inch foam block no. 8; C-2 charge; flyer plate no. 3

Channel 1	no data	4	no data
Channel 2	259.438	5	no data
Channel 3	324.884	6	no data

Shot 4: 6-inch foam block no. 9; C-6 charge; flyer plate no. 4

Channel 1	106.243	4	144.128
Channel 2	120.556	5	156.792
Channel 3	132.026	6	167.685

A decision was made to drop the C-1 charges and fire the experimental shots with 2, 4, and 6 mm detasheet. The experimental matrix was set up as follows:

Table 1. Experimental Matrix

	Shot Size (mm)		
0	2	4	6
2	2	4	6
4	2	4	6
6	2	4	6
9	2	4	6
12	2	4	6
Cavity bag	2	4	6

Charge weights varied somewhat but were nominally:

C-1/1 mm	27.5 grams	C-4/4 mm	95.5 grams
C-2/2 mm	45.7 grams	C-6/6 mm	153 grams

*the last 4 shots averaged more ≅ 165 g

Foam blocks were weighed and density calculated (Woodfin) as shown in Table 2.

Table 2. Foam Block Density

No.	Thickness	Density	No.	Thickness	Density
1	9 in	5.4 pcf	15	4 in	5.6
2	9	5.6	16	4	5.6
3	9	5.7	17	4	5.6
4	12	5.3	18	4	5.6
5	12	5.7	19	4	5.5
6	12	5.4	20	4	5.4
7	6	5.8	21	2	6.0
8	6	5.3	22	2	6.1
9	6	5.8	23	2	6.0
10	6	5.8	24	2	6.2
11	6.25	5.6	25	2	5.9
12	6	5.6	26	2	6.0
13	6	5.7	27	2	5.9
14	6	6.0			

Flyer plates were weighed and numbered as follows:

Table 3. Flyer Plate Weights

No.	g	No.	g	No.	g	No.	g
1	419.5	7	415.2	12	420.9	17	420.9
2	420.5	8	421.5	13	420.5	18	421.3
3	415.4	9	418.2	14	417.0	19	417.5
4	419.2	10	417.2	15	415.7	20	416.0
5	420.6	11	418.9	16	416.1	21	420.2
6	420.2						

Execution of the matrix began with shot no. 5 and data were recorded for each shot.

Shot 5: 9-inch foam block no. 2; C-2 charge; flyer plate 5.

Channel 1	no data	4	no data
Channel 2	no data	5	no data
Channel 3	no data	6	no data

Shot 6: 4-inch foam block no. 20; C-2 charge; flyer plate 6.

Channel 1	99.085	4	192.302
Channel 2	136.334	5	217.446
Channel 3	161.965	6	238.707

Shot 7: 2-inch foam block no. 26; C-2 charge; flyer plate 7.

Channel 1	46.696	4	88.370
Channel 2	67.738	5	95.062
Channel 3	79.710	6	101.775

Shot 8: no foam block; C-2 charge; flyer plate 8.

Channel 1	14.755	4	26.714
Channel 2	18.470	5	31.129
Channel 3	22.890	6	32.574

Shot 9: cavity experiment: plastic bag of foam 20" x 23" oval x 25" high

Cavity diameter: 9/9¼/9¼ avg. 9.166 in.
Cavity depth: 8½/8/9 avg. 8.5 in.

Cavity was about half full of crushed foam

Shot 10: no foam block; C-4 charge; flyer plate 9

Channel 1	15.153	4	23.020
Channel 2	17.282	5	25.332
Channel 3	20.332	6	27.974

Shot 11: 2-inch foam block no. 27; C-4 charge; flyer plate 10.

Channel 1	35.856	4	57.686
Channel 2	48.267	5	61.546
Channel 3	53.827	6	67.328

Shot 12: 4-inch foam block no. 15; C-4 charge; flyer plate 11.

Channel 1	69.785	4	111.097
Channel 2	123.260	5	104.505
Channel 3	115.881	6	91.168

Shot 13: 9-inch foam block no. 3; C-4 charge; flyer plate 12.

Channel 1	no data	4	723.047
Channel 2	345.386	5	no data
Channel 3	375.769	6	2471.386 (?)

Shot 14: 12-inch foam block no. 6; C-4 charge; flyer plate 13.

Channel 1	no data	4	no data
Channel 2	no data	5	no data
Channel 3	no data	6	no data

Shot 15: no foam block; C-6 charge; flyer plate 14.

Channel 1	15.267	4	21.358
Channel 2	17.026	5	22.502
Channel 3	19.250	6	24.948

Shot 16: 12-inch foam block no. 4; C-6 charge; flyer plate 15.

Channel 1	802.767	4	no data
Channel 2	559.730	5	no data
Channel 3	no data	6	2868.564 (?)

Shot 17: 9-inch foam block no. 1; C-6 charge; flyer plate 18.

Channel 1	404.238	4	274.649
Channel 2	342.850	5	308.776
Channel 3	248.863	6	2455.294 (?)

Very loud shot – 165g charge?

Shot 18: 4-inch foam block no. 17; C-6 charge-155.7 g; flyer plate 17.

Channel 1	61.572	4	91.504
Channel 2	75.997	5	98.256
Channel 3	84.679	6	103.583

Shot 19: 2-inch foam block no. 24; C-6 charge – 166.1 g; flyer plate 16.

Channel 1	34.477	4	46.111
Channel 2	42.344	5	49.114
Channel 3	45.041	6	53.864

Shot 20: cavity shot in used foam barrel,

C-6 charge, 166.9g, 23" inch diam x 23" in-high.

Cavity diameter:	17/17/16	avg 16.66 in.
Cavity depth:	23/23/22	avg 22.66 in.

Pressure wave appeared to be different – foam very broken up around edges and barrel about half full of crushed foam.

Shot 21: cavity shot in foamed plastic bag 23" in. diam x 24" in. high; C-4 charge

Foam came all apart and needed to be reassembled to measure resulting cavity

diameter 13/14 ~ 13.5 in.
depth 22/26 ~ 24 in.

A summary of the shots is provided in Table 4.

Shot	Foam (in.)	Foam No.	Charge Size	Flyer Plate	Time	Remarks
12/17 1	6	14	C-1	1	1410	data pin 2 only
2	6	10	C-4	2		OK
3	6	8	C-2	3	1441	data pins 2/3 only
4	6	9	C-6	4		OK
5	9	2	C-2	5	1513	no data
6	4	20	C-2	6		OK
12/18 7	2	26	C-2	7	0929	OK
8	0 (cal)	-	C-2	8	0944	OK
9	bag	-	C-2	-	1000	20x23 oval x 25 h: Cavity avg 9.16 dia x 8.5 h
10	0 (cal)	-	C-4	9	1015	OK
11	2	27	C-4	10	1030	OK
12	4	15	C-4	11	1043	OK pin 3?
13	9	3	C-4	12	1059	no pin 1/5
14	12	6	C-4	13	-	no data
15	0 (cal)	-	C-6	14	-	OK
16	12	4	C-6	15	1200	no pin 3/4/5 pin 6?
17	9	1	C-6	18	1440	OK 1/2/6?
18	4	17	C-6	17	1455	OK
19	2	24	C-6	16	1507	OK
20	bag	-	C-6	-	-	barrel: 23 dia x 23 h: Cavity 22.6 h x 16.6 diam pressure wave changed
21	bag	-	C-4	-	1537	23 dia x 24 h: fragments – needs reassembled & measured

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Appendix H

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

R. L. Woodfin, Sandia
C. O. Schmidt, LATA
M. Banks, EMRTC

This paper summarizes and analyses the results of the explosive velocity attenuation experiments in appendixes F and G. It was originally briefed and published at the Mine Warfare Symposium at Naval Postgraduate School, Monterrey, CA in February 1998.

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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.

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

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)	Charge (mm) 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)	Charge (mm) 4 mm (95.5 g)	Charge (mm) 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.

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.

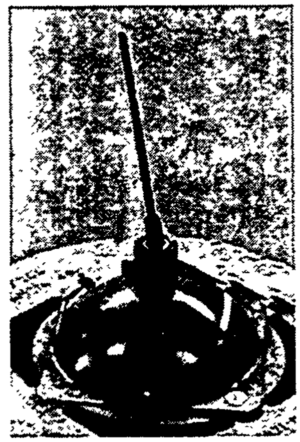


FIGURE 1
PDM-1M Anti-Craft Mine

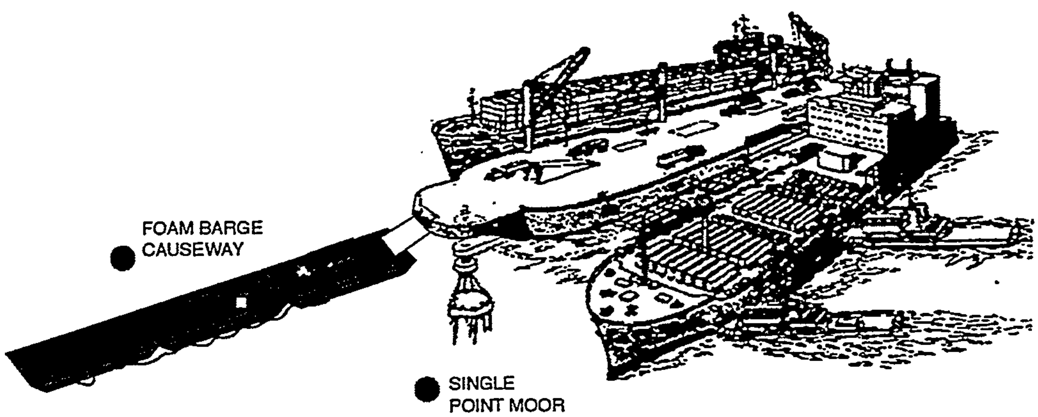


FIGURE 2A
Artist Concept of Barge

FIGURE 2B
Photo of RPF Filled Block

FIGURE 3
RPF FLOAT IN SCALED SURF POND

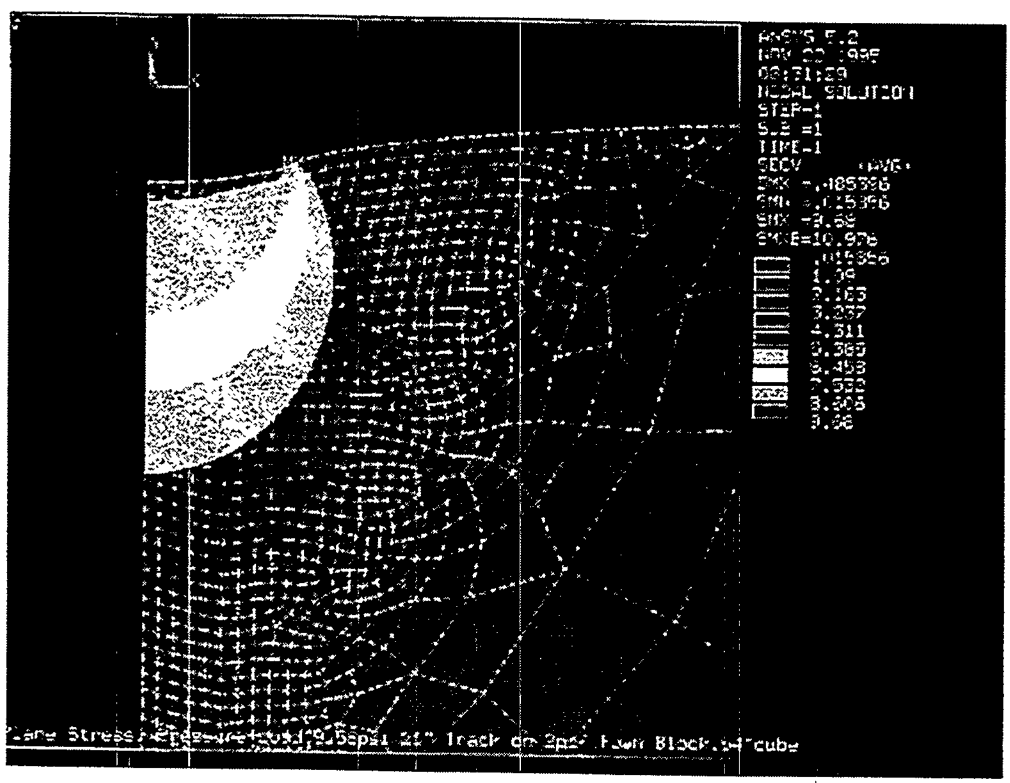


FIGURE 4
PLANE STRESS CONTOURS FROM ANALYSIS OF 54-INCH CUBE OF 4 LB/FT^3 RPF LOADED BY M60 TANK
(AXIS OF SYMMETRY IS ON LEFT EDGE: SIDEBAR NUMBERS ARE IN PSI.)

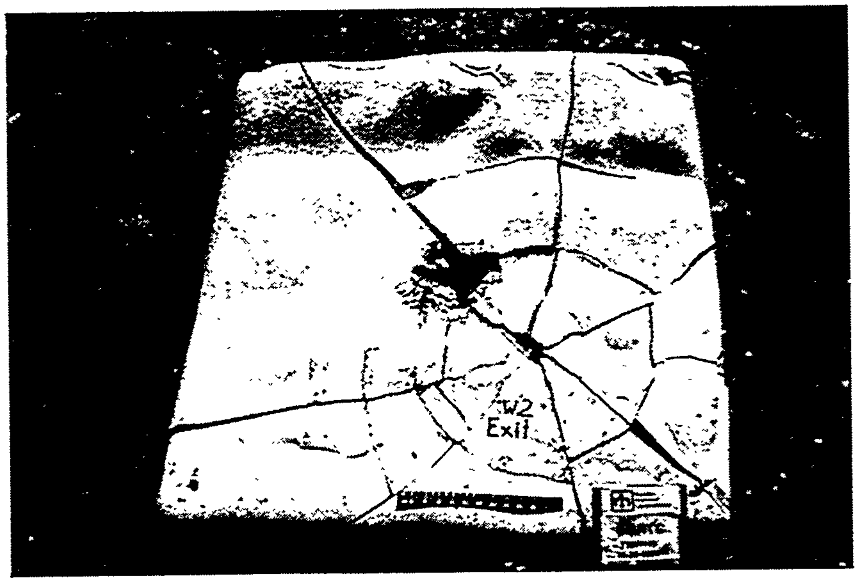


FIGURE 5
UPPER SIDE OF RPF BLOCK FRACTURED BY DETONATION OF 30 GRAMS OF PETN
POSITIONED 12 INCHES BELOW THE CENTER OF THE PATTERN.

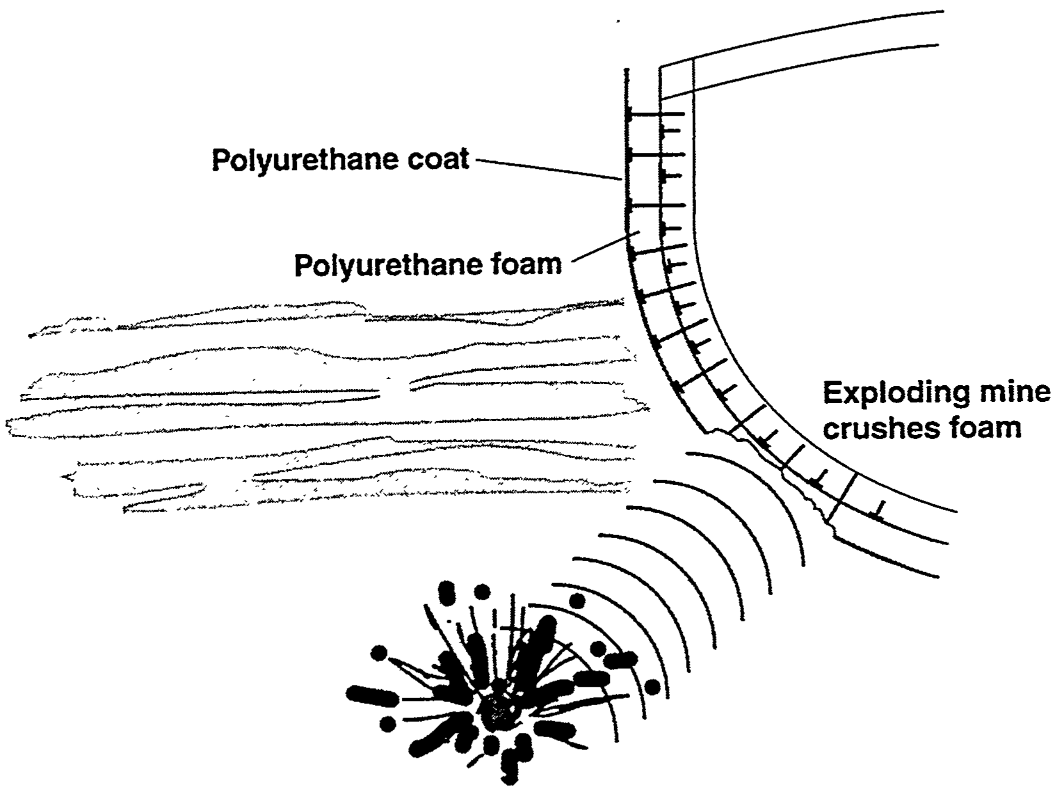


FIGURE 6
RPF IN SHIP STRUCTURE

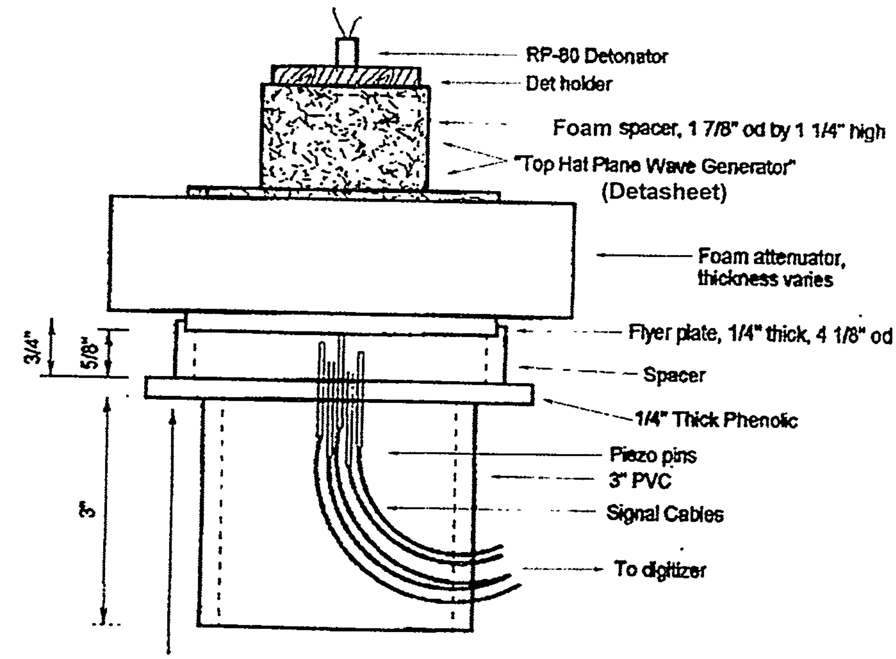
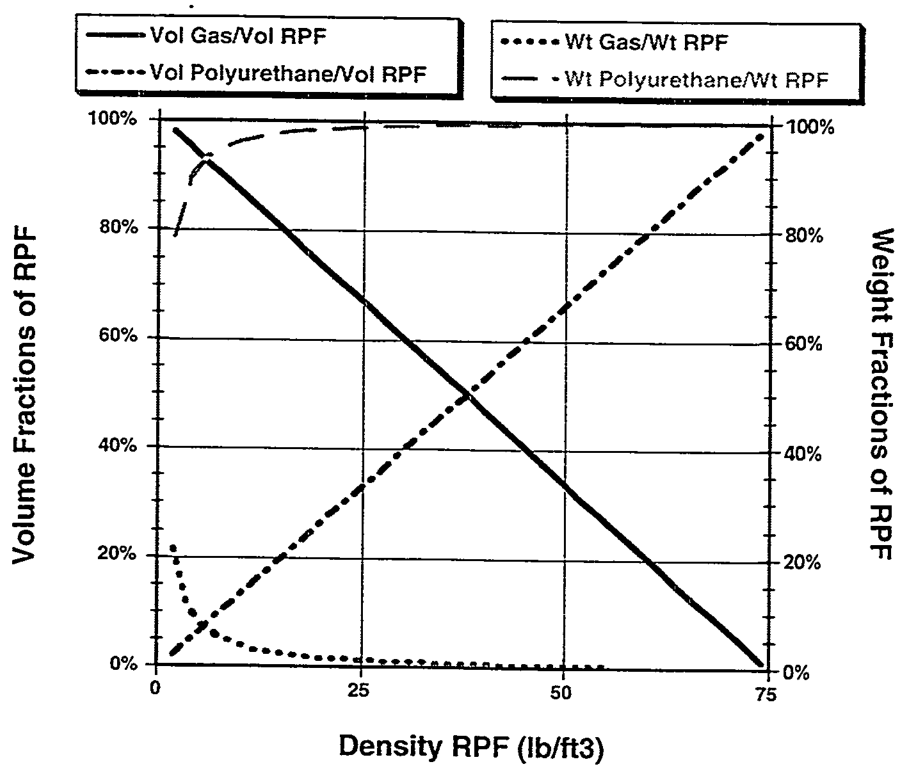
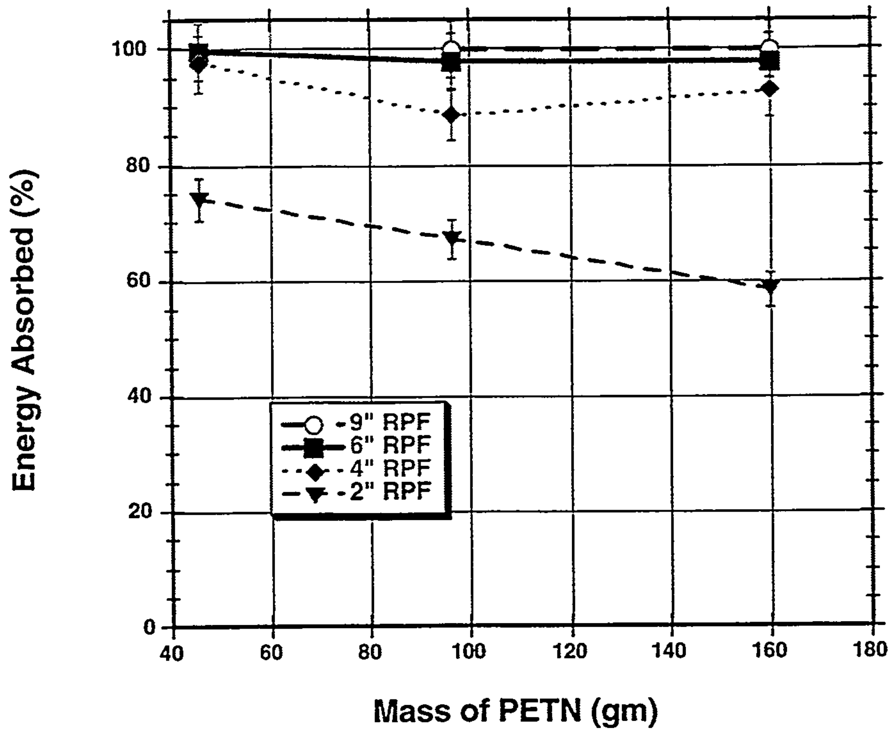


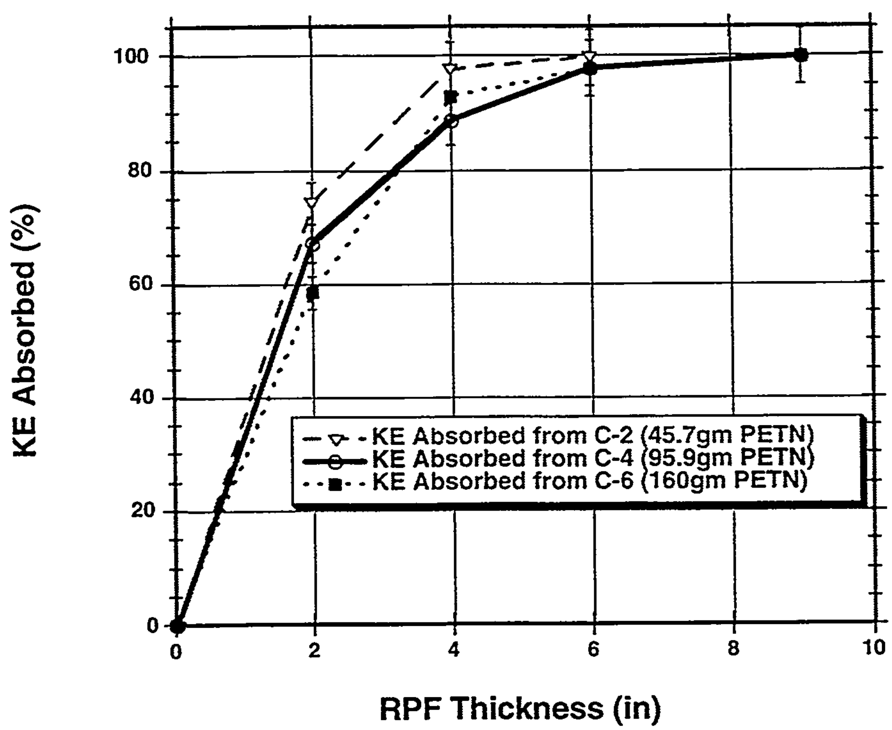
FIGURE 7
FLYER PLATE EXPERIMENT ASSEMBLY



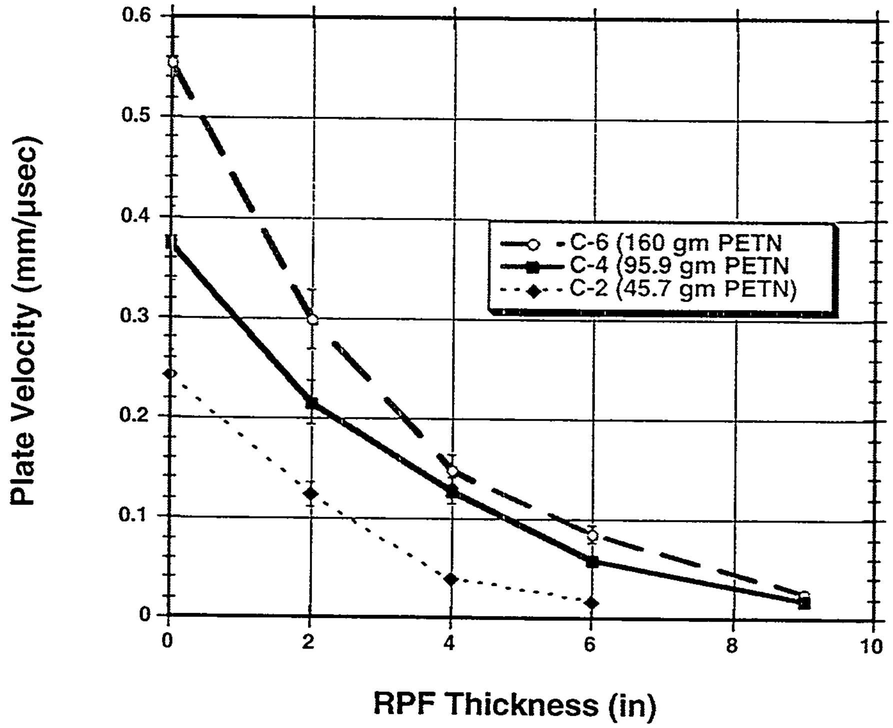
GRAPH 1
POLYURETHANE VS. RPF DENSITY



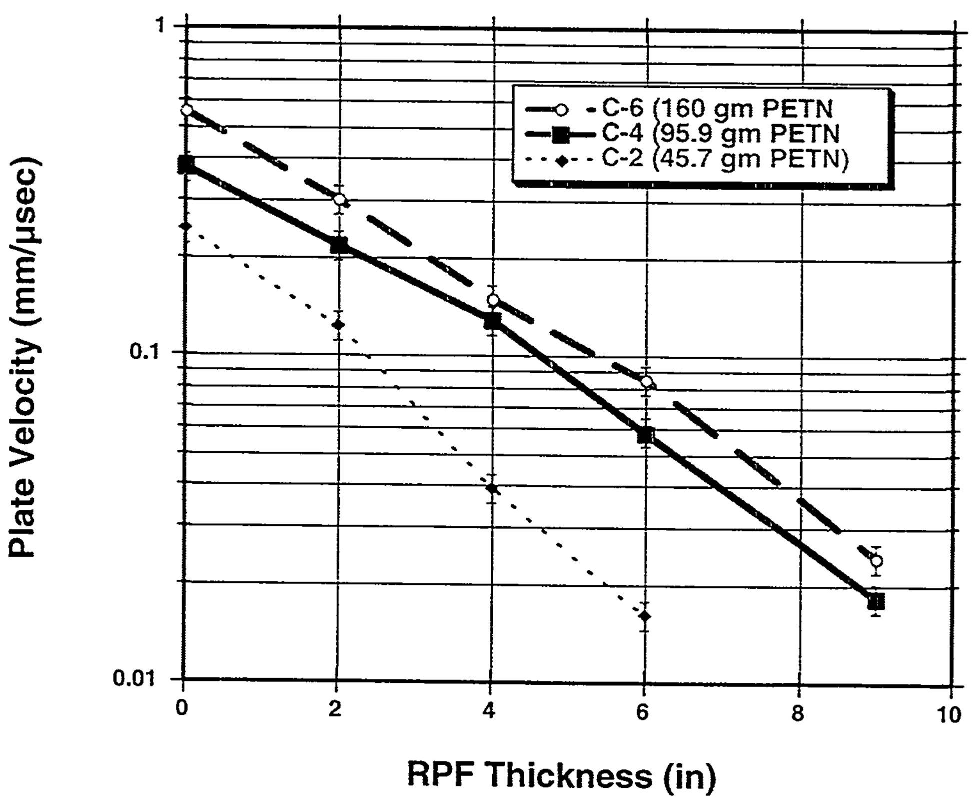
GRAPH 2
ENERGY ABSORBED BY 5.7 lb/ft³ RPF



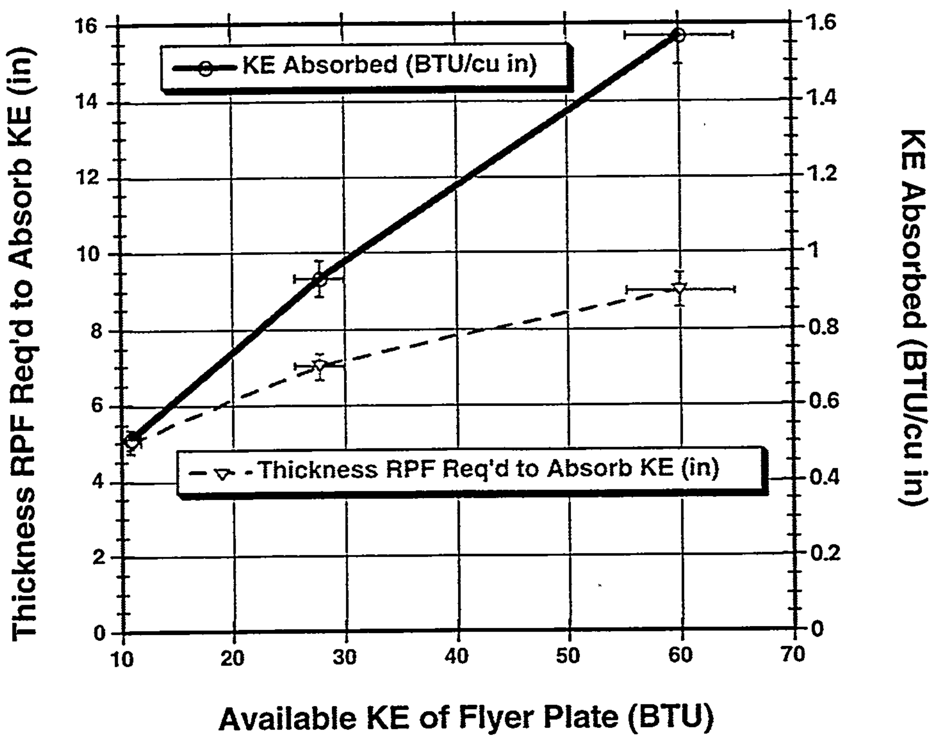
GRAPH 3
KINETIC ENERGY ABSORBED BY 5.7 lb/ft³ RPF



GRAPH 4
DATA AS RECORDED (LINEAR VIEW)



GRAPH 5
DATA AS RECORDED (LOG. VIEW)



GRAPH 6

ENERGY ABSORPTION OF 5.7 lb/ft³ RPF

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Appendix I

Report of Industry Demonstrations of RPF Materials; EMRTC, Socorro, NM

This appendix briefly describes the demonstrations done by industry for the military in June 1998.

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21 June 1998

MEMORANDUM FOR THE RECORD

C.O. Schmidt, LATA/621

Report of Industry Demonstrations of RPF Materials; EMRTC Socorro N.M. 15-16 June 1998

On 15 and 16 June 1998, Sandia National Laboratories sponsored demonstrations by interested industry representatives as a follow-up to discussions previously held in Albuquerque, NM. Personnel from Futura Coatings, Gusmer Corporation, IPI International, and UCSC, Ltd. represented the foam industry. The Naval Facilities Engineering Service Center, Port Hueneme, CA and CSS Enterprise Next Generation, Camp Lejune, NC represented the military. The Sandia team was directed by Dr. Ron Woodfin. See attached list of attendees for addresses. Monday morning and early afternoon were devoted to setup of the machinery and power sources on the EMRTC Main Pad area. All demonstrations were recorded on both video tape and still photos.

The first major demonstration was made with the IPI canister foam setup consisting of 500 lb containers of XP-EEJ-04-217 A&B foam. This setup required only the two canisters and two Nitrogen bottles (or compressed air) to produce a froth foam. This rig appears to have excellent potential for military use, being very compact and simple. It would probably require the least training time, for a military crew, of any equipment we have seen so far. The first pour of canister foam was done onto the water in the 16 X 100 ft experiment pond without the wave machine operating. The foam frothed well and stayed on the surface of the water without sinking like straight-poured foam. It did punch through the fresh foam if a second layer was applied too quickly, but this is primarily operator experience. The foam made a solid layer and, if left only a few minutes, was able to support a new layer on top. After three layers in about 15 minutes, the foam raft was approximately 10 X 16 ft by about 12 inches thick. The foam raft was easily capable of supporting several people and may have supported a small vehicle, but was not tested in that manner.

Once the foam raft had been evaluated, a section of it was removed to provide access to the surface of the water. Using the Gusmer H-3500 spray equipment, a layer of Futura Corporation's polyurea elastomeric coating was applied directly to the surface of the water. Although the high application pressure made it difficult to quickly build up a very thick layer of material (the water was being displaced at the point of application) a sheet of elastomere 18 X 18 X 1/8 inch thick was ultimately achieved. This sheet was capable of supporting about 100 lbs and would have supported more if the edges of the sheet had been more completely adhered to the surrounding foam of the previously made raft. This same material was sprayed over the surface of the foam raft in some spots and noticeably improved the puncture resistance of the surface of the raft.

The second IPI demo was the filling of two "craters" about 2.5 ft in diameter and 2 ft deep dug into the hard soil. The foam expanded and locked into the crater walls very nicely and was topped up to just below grade level in a second pour. After curing for only a few minutes, Futura Coatings supplied an instant set polymer based on a fast set structural urethane. The system is designed to provide a self leveling grade over the foam. After the two were partially cured, approximately 30 minutes total, a 23,000 lb rough terrain forklift was driven over the patched holes and then parked on them. There was minor distortion due to the low density of the foam (2.5 pcf) and minor cracking of the plastic covering, but this appears to be a simple and expedient method to patch roads and runways that have been cratered by use, weather, or combat action.

The third IPI demo constructed an expedient footbridge by pouring foam onto a sheet of garden weedblock, 3 X 25 ft long, to about a 4" finished thickness. The bridge was poured on one side only in a single pass in about 5 minutes and allowed to cure for a few minutes. It was then pushed across the experimental pond in about 3 ft of water where it floated with both ends up on the banks. The bridge proved capable of holding a single person walking over it and several different people made the crossing. The two outer ends fractured due to the lack of shear strength in the base material, but the bridge functioned perfectly even with no support from the banks.

The last IPI demo involved the pouring of a small scale (4X8 ft) tent platform with a wooden form lined with sheet polyethylene. The material was poured in two passes, beginning the second pass as soon as the first was complete, and filled the frame to over the wooden 2X4 stock. Finished size was approximately 4 X 8 ft X 7, ". The block came out of the form easily and was thrown into the pond about 15 minutes after beginning the pour. The block was quite capable of supporting a fairly large Marine.

A Futura Coatings polyurea elastomer was demonstrated over the ground, the foam, and over the water. It could be used as a liner for water, fuel or other liquid stores. A tough fast cure membrane was formed but it was determined that the polyurea elastomer would have more value in other military applications.

On 16 June, Gusmer and UCSC demonstrated their products in a number of experiments. UCSC demonstrated their "Romer " automated spraying machine laying a narrow roadway several inches thick. The machine was not set up to pour foam and ride up over it but could be rigged that way if desired. It did pour a fairly even pathway 4 or 5 inches thick and about 15 ft long (to the end of the hose) in a few minutes. The Romer is designed to place foam automatically in an even swath on large roofs, but appears to be the first step toward a large machine that could be capable of laying down a usable roadway for tracked or wheeled vehicles. Such a vehicle would be a real asset in making roads from the craft landing area to the hard ground above a landing beach. The Roamer vehicle completed two paths approximately 6 by 15 ft in an uphill direction with little or no trouble.

The Gusmer H 3500 fast froth foam machine was demonstrated in the experiment pond in a wind that averaged 15 to 20 knots with higher gusts. The initial pressure was a bit too high, but was adjusted downwards and with a few minutes operator experience a solid raft was formed in the pond. The foam used, USC's SPS III (2.5) with catalyst and blowing agent, had a very quick cream time but stayed liquid just long enough to fill in the low spots. The final pour of the third layer resulted in a very level raft on the water. The foam product used did not sink into the water at all and seemed to build up strength quicker than the poured foam used in previous experiments with the Sandia machinery.

A second hasty footbridge was constructed using the H 3500 and a material called Geotextile. This material is a synthetic that looks and feels like thin felt. It was spread on the ground in a sheet about 4 X 16 ft and foamed to a finished depth of about 1.5 inches. The sheet was then turned over and foamed again on the back side to a similar thickness. The whole sheet was then lifted up on edge and cut in two at about the midpoint. Four pieces of half-inch manila line were placed evenly across the gap and foamed in on the rope side with another 2 inches of finished foam. The whole operation took about 10 minutes from start to finish. The foam pieces bent at the rope hinge to 180 degrees folding the footbridge to half length. When thrown into the pond the foam was fully capable of supporting a walking person and Major Lawson jumped up and down without effect.

SUMMARY:

This demonstration of just some of the capabilities of Rigid Polyurethane Foams by the industrial representatives in attendance showed the military representatives and Sandia team a number of practical things that can be done with the material. In a number of the demos, the industry representatives were quick to point out that these results were only barely satisfactory and that the foam chemistry and machinery could be optimized to produce better results. All the machinery and all the foam mixtures did just what was requested and did it in very short order. The canister foam demonstrated by IPI International appears to be the closest to an off-the-shelf militarized system and deserves some further research. The Gusmer machine and Romer vehicle can obviously be simplified and made "sailor proof" if they were asked to do less varied work. This too deserves some thought and research.

Sandia National Laboratories is grateful to all the industry representatives who gave up their time and energy to conduct this demonstration. Our thanks to management who supported the concept and our particular appreciation to the field people who came out and sweated through this fast paced demonstration in the Great American Desert.

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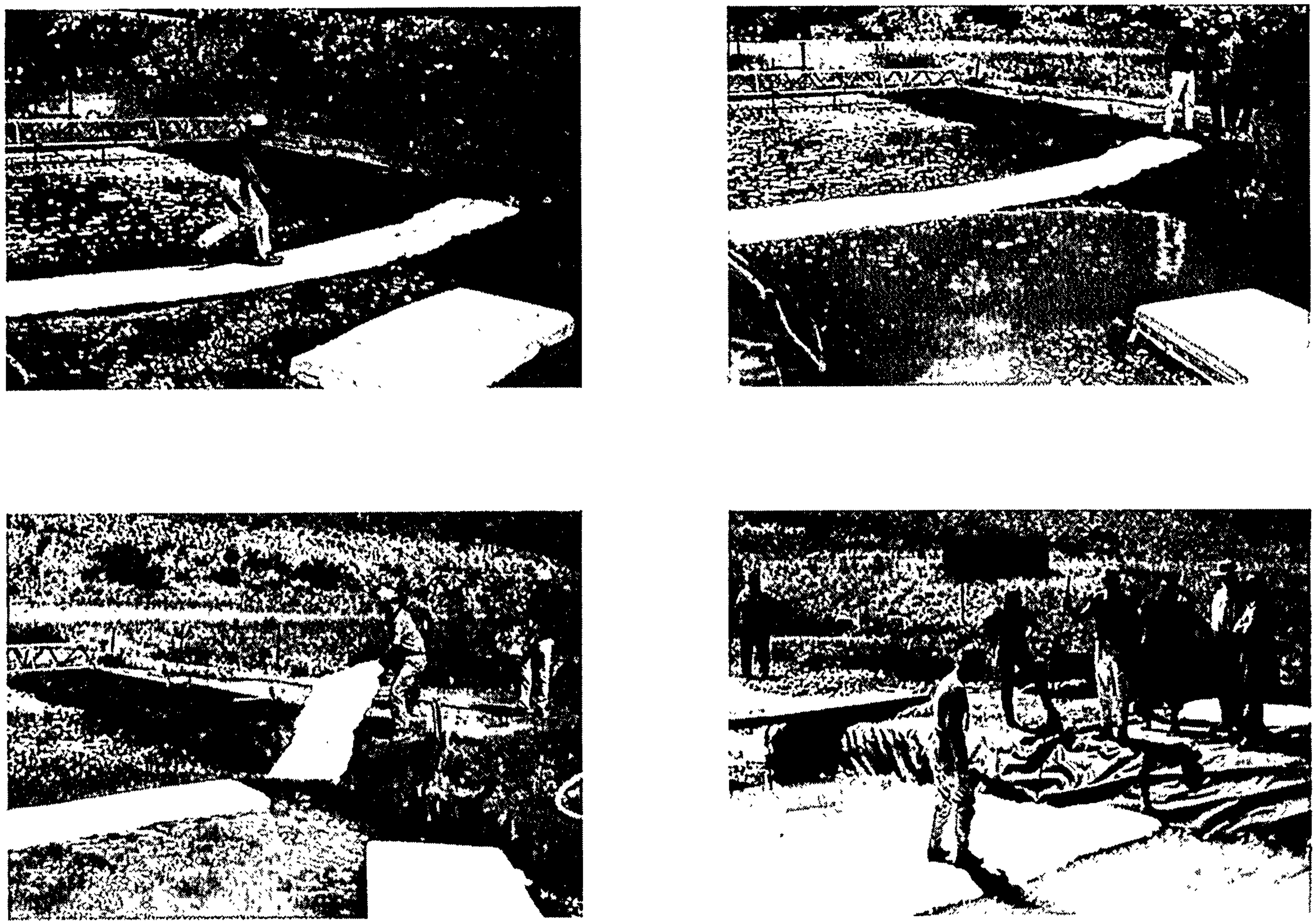
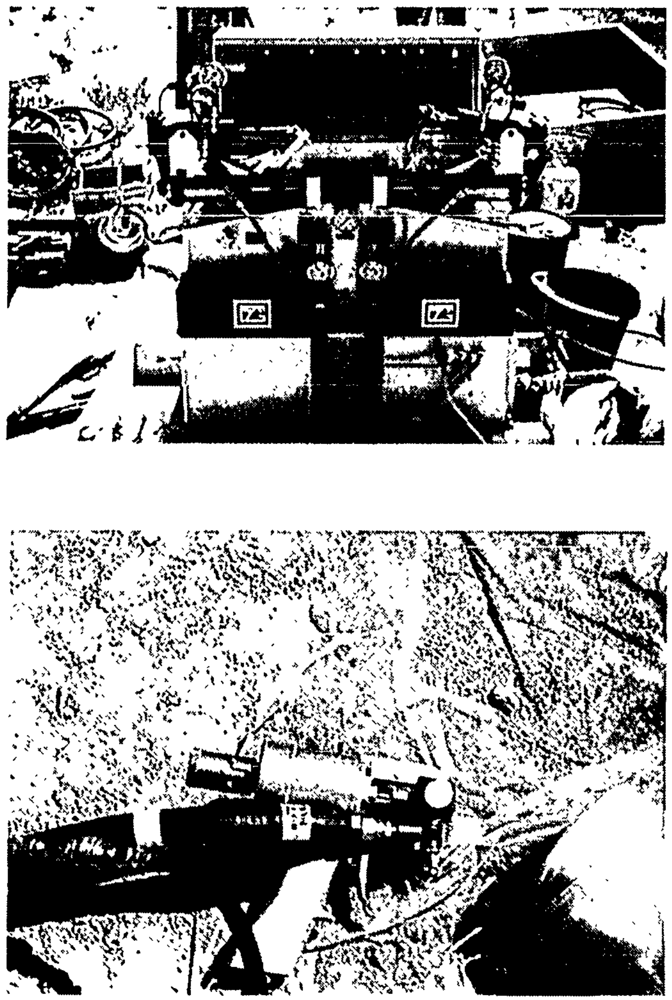
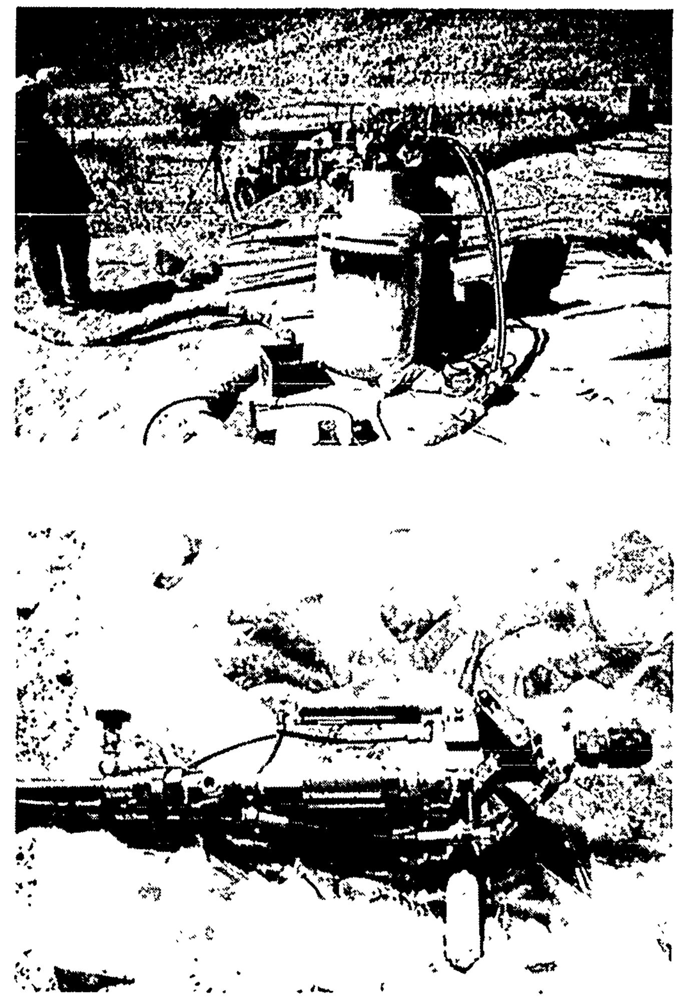
Charlie Schmidt	LATA 2400 Louisiana NE/400 Albuquerque, NM 87110	(505) 880-3466 Fax 880-3560



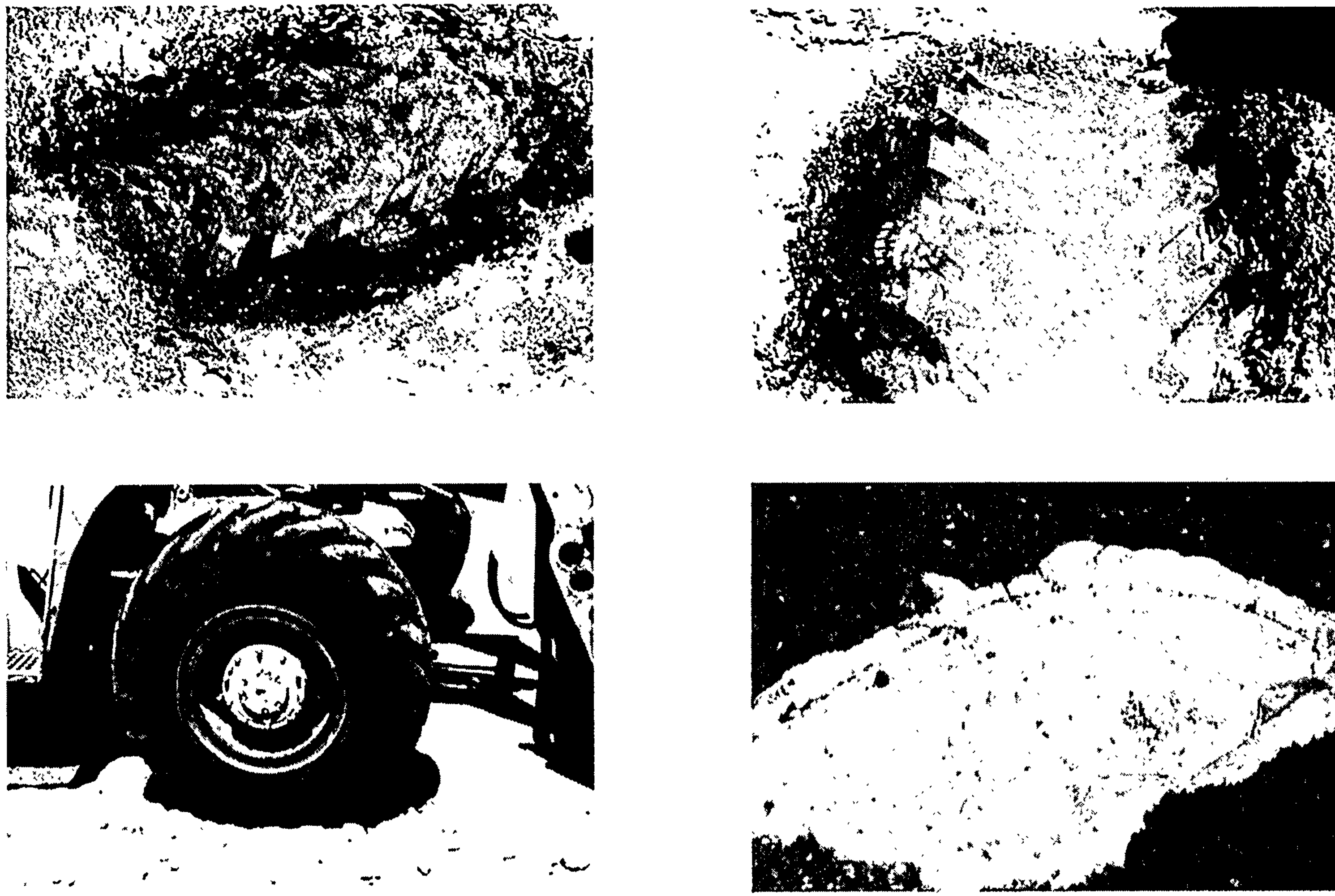
Testing the First Expedient Footbridge



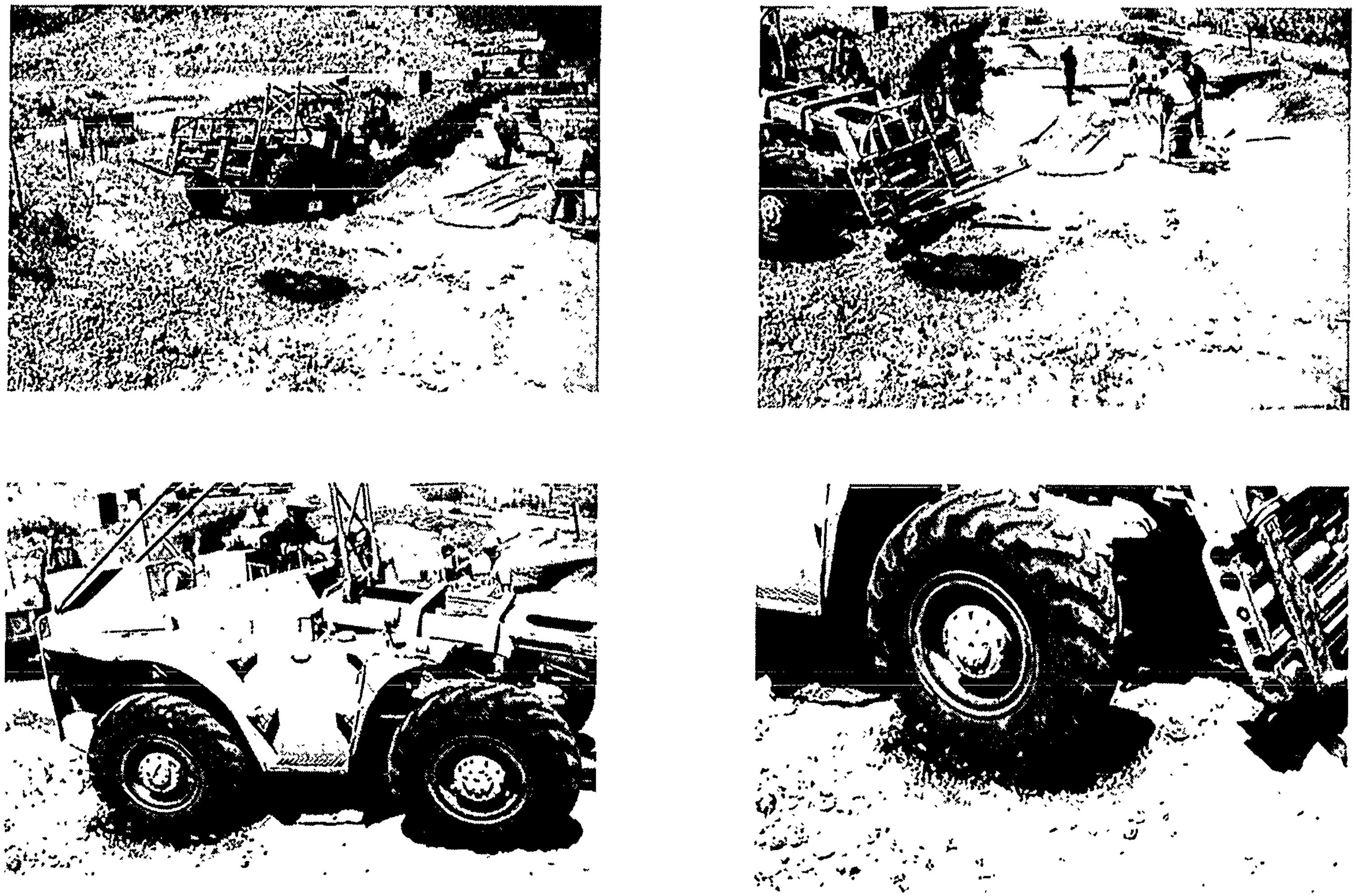
Gusmer H3500



IPI Canister System



Patched "Craters"



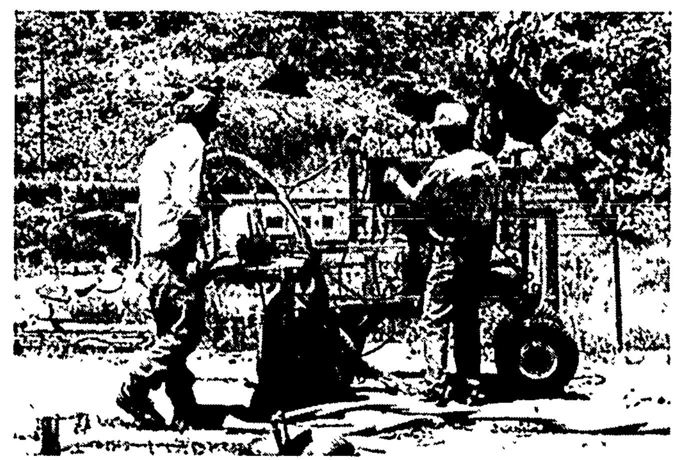
Load Testing Patched Craters

Application of Self-Leveling Polyurethane to Filled "Crater"

USMC Test of Foam Buoyancy

Gusmer H3500 Foam Machine Water Pour Demo

Checking Foam Strength



Romer Spray Machine

Appendix J

Report of Ship Hull Preservation Experiment at EMRTC; Socorro, NM

C. O. Schmidt, LATA/621

This appendix details the initial experiments with foam covered aluminum plates to determine if RPF could provide some protection from underwater explosions.

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22 June 1998

MEMORANDUM FOR THE RECORD

C. O. Schmidt / LATA 621

Report of Ship Hull Preservation Experiment at EMRTC, Socorro, NM, 18 – 19 June 1998

On 18 and 19 June 1998, Sandia National Laboratories conducted an experiment to make an initial determination as to whether RPF material can be used to mitigate ship hull damage from sea mines.

Sheets of aluminum 0.190 inches thick by 24" wide by 36" high were bolted into a 1½ inch angle iron frame on both sides to simulate the skin of a destroyer-size ship. Figure 1 shows one sheet with the stiffener frame in place.

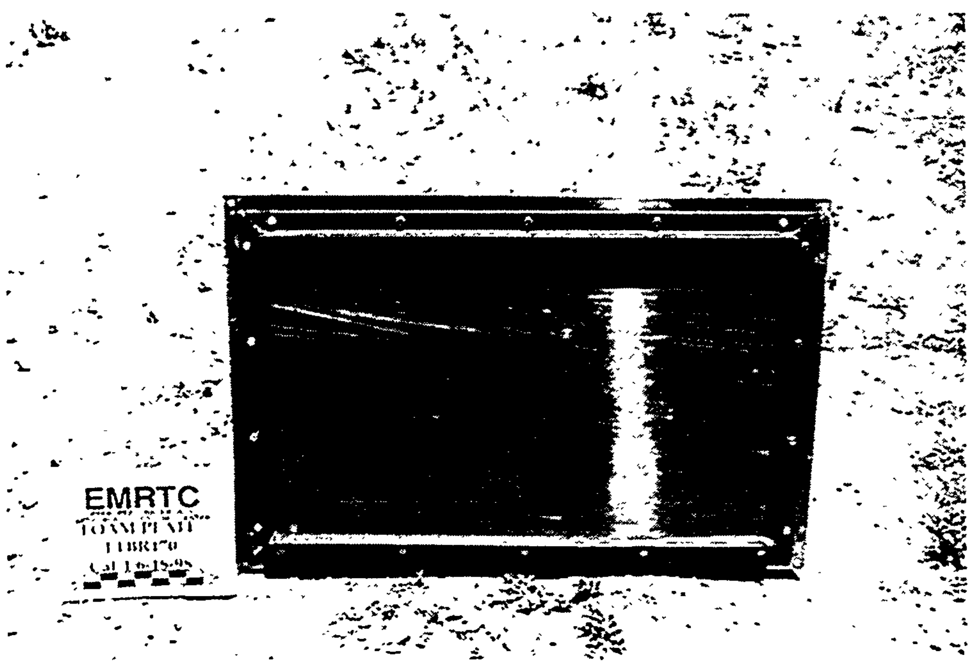


Figure 1. Aluminum plate with frame

The aluminum plate (0.190 thick, 6061 alloy, T-6 temper), readily available to Sandia, was much harder than required.

All the experimental shots were fired at EMRTC's Main Pad area in a 30' wide by 3' deep pond. The first two shots were fired on bare plates while the last three had different thicknesses of 8 pcf RPF foam between the plate and the charge. Charges were suspended 24 inches below the aluminum plates which were horizontal, at, or just above the water surface. Still photographs and video were taken of each setup and firing.

Five explosive experiments were completed. The first was an initial "locator" shot of 61.5 grams of PETN (Detasheet –6mm) to determine how the plate reacted. There was no distortion or damage to the plate. The next four experiments were conducted using 250g PETN charges to ensure that some visible damage was recorded. All shots were fired with the receptor (entrance) side of the plate in the water and the back (exit) site above the water. The first three plates were suspended from a light crane using ¼ inch steel aircraft cable. The last two foamed plates were floated in the experiment pond, foam side down, and tethered with steel aircraft cable for safety. Figure 2 shows a typical shot setup just prior to firing.

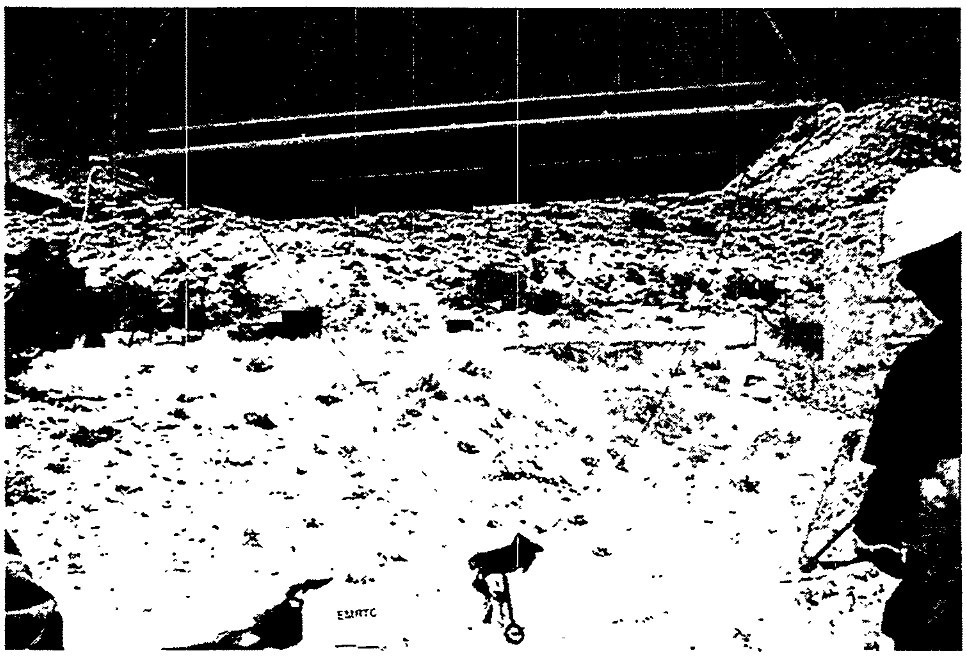


Figure 2. Shot #2; typical of the bare plate shots

Shot #2 was a 251g PETN charge fired at a 24-inch standoff below the plate. The same plate was used for shots 1 and 2 because no damage was apparent from the first 60g charge. When shot #2 was fired it produced a water column about 15 feet high and the plate remained attached to the crane. An oval-shaped hole was blown in the plate measuring about 10 x 5 ½ inches. The metal was petaled back approximately 3 inches toward the exit side and the edges of the aluminum appeared crystallized. It appeared that little or no metal was actually lost. Figure 3 shows the entrance and exit sides of the plate.

Shot #3 was accomplished with a 250g PETN charge at a 24-inch standoff on a plate with 9 inches of 8 pcf foam cut to size and glued in place. The shot was fired with the foamed plate floating on the water but still connected to the crane. On firing, the plate impacted the crane hook and traveled up the crane cable nearly to the top sheaves (about 16 - 18 feet). The plate finally came to rest on the lower (hook) sheave and had to be cut free with an acetylene torch. Shot #3 was declared a "no test" because there was no way to determine whether plate damage was caused by the charge or impact with the crane.

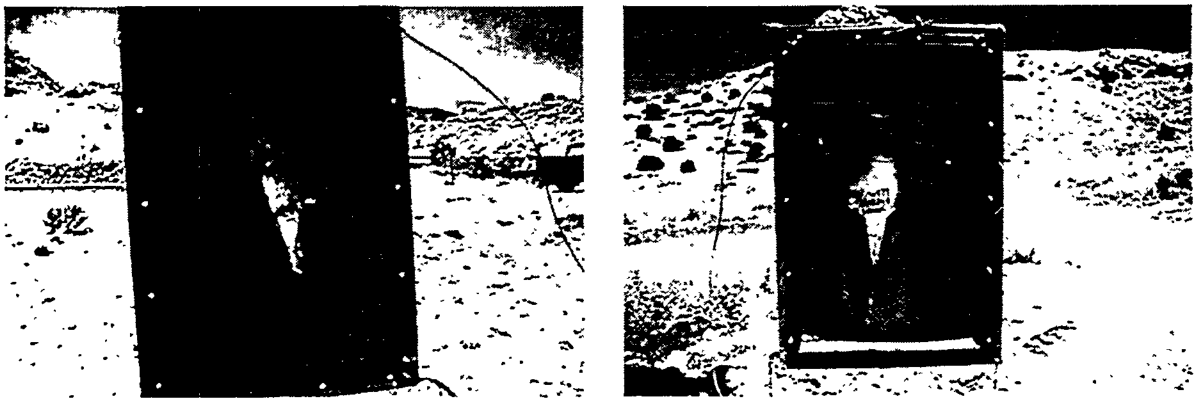


Figure 3. Shot #2 plate damage

Shot #4 was made up using a 250g PETN charge at a 24-inch standoff and a plate with 3 inches of 8 pcf foam glued in place. Scrap foam was used around the edges of the plate to add just enough buoyancy to make it float foam side down. This plate was secured to a large steel stake with aircraft cable to prevent it from flying free. Upon firing, the plate flew 8 – 10 feet into the air and east about 20 feet to the edge of the pond. On recovery the plate was seen to be only slightly bowed away from the foam side. The foam was detached from the plate in 4 or 5 pieces. When pieced back together, it had a ragged hole 3 x 4 inches blown out of the center. Figure 4 shows the plate after recovery and Figure 5 shows the foam from the shot side.

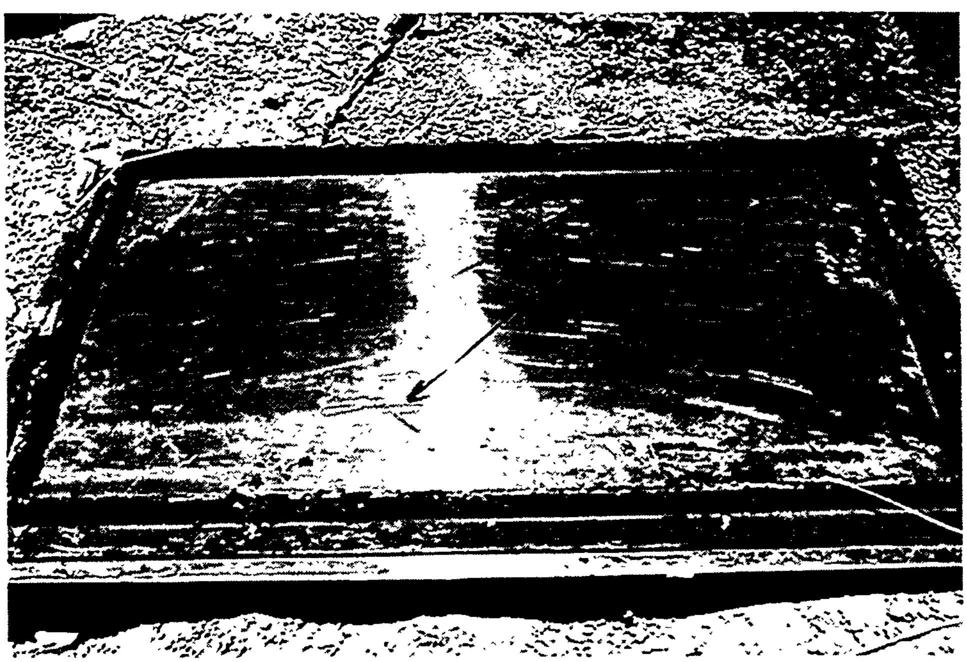


Figure 4. Shot #4 plate after experiment

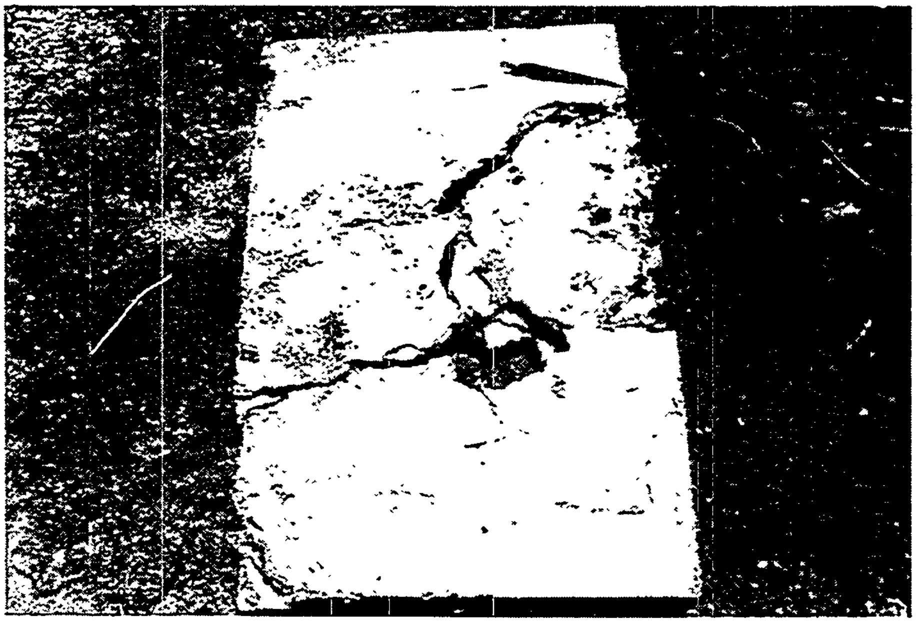


Figure 5. Shot #4 foam after recovery

Shot #5 was assembled using a 250g PETN charge at a 24-inch standoff and a plate with 1 ½ inches of 8 pcf foam epoxied in place. It was floated in the pond with extra foam around the edges for buoyancy and the foam side in the water. When this shot was fired, the plate flew 6 - 8 feet in the air and about 15 feet east toward the edge of the pond. On recovery, much of the foam was still glued in place but was crushed/washed out in a concave pattern extending to the edges of the test plate. The plate displayed minor bulging toward the bare side, slightly more obvious than the plate used in experiment #4. Figure 6 shows the foam side of plate #5.

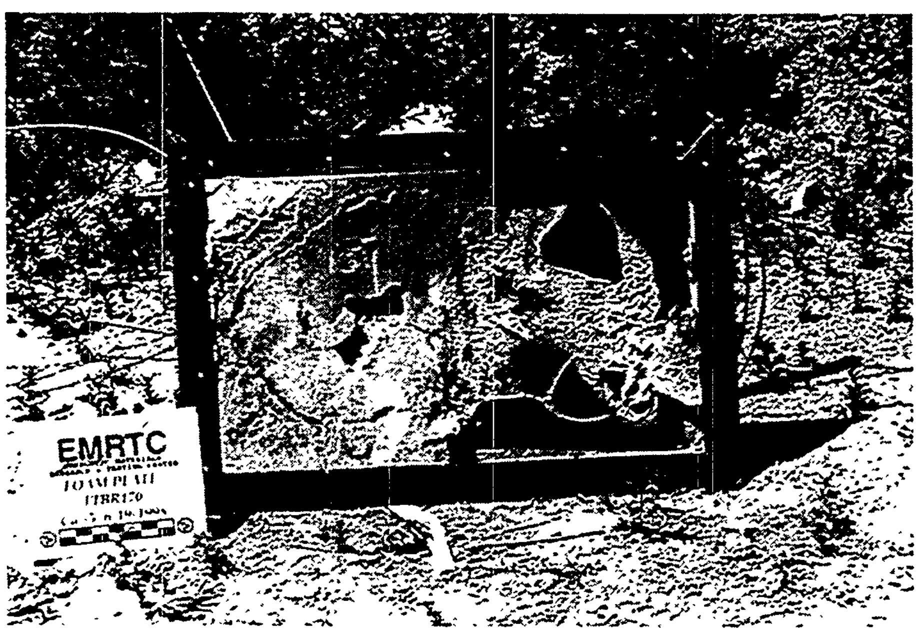


Figure 6. Plate 5 after recovery

Plates from shots 2, 4, and 5 were transported to SNL for detailed measurement of the distortions caused by the experiments.

Initial conclusions: It appears that 8 pcf foam does absorb a large amount of the blast produced by an underwater detonation. The obvious and dramatic difference in damage between plates 2 and 5 appears to result from the use of only 1 ½ inches of RPF material between the explosive charge and the aluminum plate.

Personal observation (COS): This experiment demonstrates sufficient blast mitigation that it could be useful in protecting countermine craft from mine effects. I would propose a series of vertical arena shots with increasing sized explosive charges to determine the shock absorbing limits at small scale. This should be followed by half scale experiments, on the order of a 500 lb explosive charge @ 25m, to determine a practical thickness of foam that can provide suitable protection. This process may be patentable.

Plate #3 (punctured): No Foam

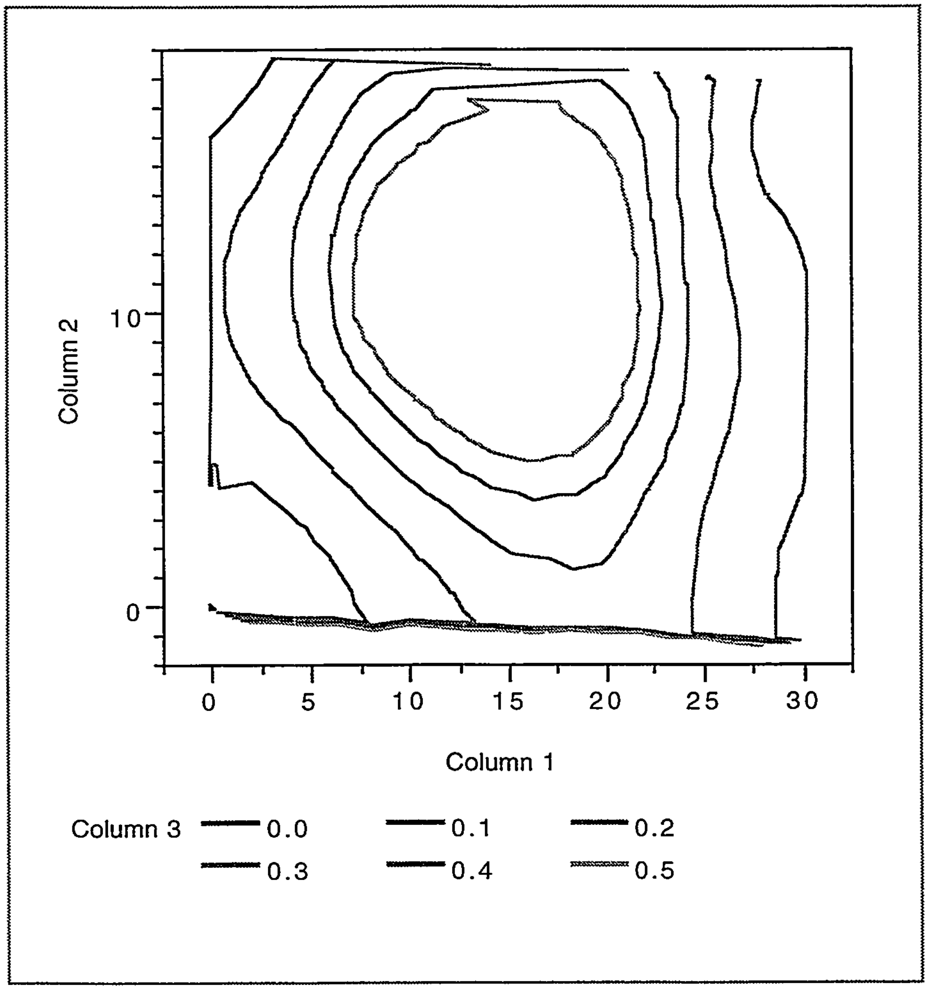
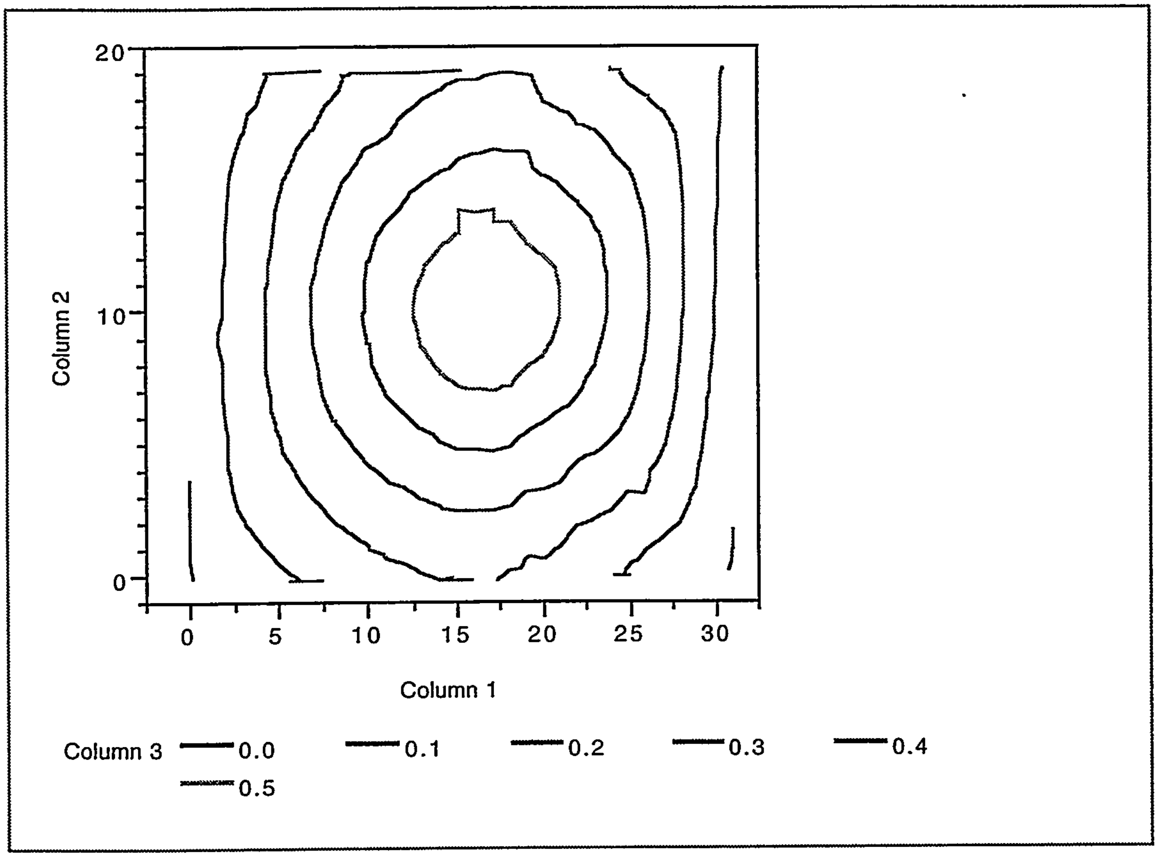


Plate #2: 1.5" of 8pcf Foam



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Appendix K

Bibliography of Literature Search

Amy Latham, Sandia
(N.M. Highlands University)

This bibliography lists the documents on previous RPF experiments uncovered in the course of the project.

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Bibliography of Literature Search Conducted by Amy Latham July 1998

Austin, S., McIntosh, R., *Contract Report CR-73-007:Development and Fabrication of Prototype Advanced Surfacing Systems for Military Use on Soils*, Boeing Company, Seattle Washington, 1972.

Charney, F.A., *Design Procedures for Rigid Polyurethane Foam Mine Enclosures*, Denver Research Center (and the US Bureau of Mines), Denver, CO, 1992.

Flynn, R.M., *Feasibility Study on the Use of Foam Plastics in Field Fortifications*, Army Research and Development Labs, Fort Belvoir, VA, 1963.

Giacofci, Thomas A., Costanzo, Andrea A., *An Investigation of Underwater Explosion Shock Mitigation Effectiveness of Rigid Syntactic Foam Materials*, Los Alamos Technical Associates, LATA Report: CT00106(01), Fairfax, VA, 1990.

> This investigation proposes the utilization of syntactic foam to absorb the shock wave energy of a submarine subjected to an underwater explosion.

Griffin, D.F., *Technical Note N-1346: Evaluation of a Synthetic Surfacing System for the Marine Corps*, Civil Engineering Laboratory, Port Hueneme, CA, 1974.

Hironaka, "Technical Memorandum TM 53-76-1: Fiberglass Reinforced Polyester Performance Under Dual Wheel Traffic Loadings", Port Hueneme, CA, 1976.

Hironaka, M.C., Brownie, R.B., and Truccillo, S., "Expedient Structural Sandwich Soil Surfacing...of Fiberglass Reinforced Polyester and Polyurethane Foam", *Rept. Ada 038417*, Springfield, VA, 1977.

> The development of an expedient surfacing system for the Marine Corps airfield, road, and logistic support area applications is investigated. Primarily, the execution of amphibious landing operations and the trafficable surfacings required for such aircraft and heavy equipment are targeted. (Explanatory diagrams and photographs are included.)

Lee, Thomas G.K., *Evaluation of the Fire Performance of a Dibromotetraflouroethane- Blown Rigid Polyurethane Foam: Final Report*, National Bureau of Standards, Naval Ship Research and Development Center, Carderock, MD, 1974.

> The evaluation of the fire performance of structural rigid polyurethane foam material is investigated as it may be exposed to potential shipboard fires.

Marsden, J., Chessin, N., *Quick-Setting Foam Research Support and Spray-Nozzle Sub-System*, US Army Mobility Equipment Research and Development Center, Fort Belvoir, VA, 1973.

> Dismounted troops may be able to safely cross tactical minefields on a series of foam pads.

Marshall, M.D., *Evaluating Rigid Foams for Construction and Repairing Mine Stoppings*, B of M-OFR-40-85, MSA Research Corporation, Evans City, PA, October 1984.

> Twenty-seven commercially available foam materials were tested to delineate those most suited for use as a sealant in underground mine stoppings

Military Application for Rigid Polyurethane Foam, Sandia National Laboratories- Video Report, Albuquerque, NM, 1997.

The video provides a brief introduction to the variety of military applications of RPF under investigation at SNL.

Smith, Alvin, *Concept Paper: The Use of Polyurethane Foam Plastics for Tactical Bridging and Rafting Operations*, Construction Engineering Research Laboratory, US Army Corps of Engineers, Springfield, VA, 1981.

A variety of tactical applications of RPF are investigated including: footbridges, rafts, vehicle flotation, foam-filled boats, railed bridges, and overhead cover for antitank weapons crews are investigated.

Smith, Alvin, *Investigation of Rapidly Deployable Plastic Foam Systems, Volume I: System Development*, CERL-TR-M-272, US Army Construction Engineering Research Laboratory, Champaign, IL, October 1979.

This report introduces rapidly deployable plastic foam systems, evaluates a number of geometrical shapes obtainable with RPF, and evaluates stress/strain characteristics at various times during the foaming process.

Smith, A., Wang, S.S., and Kuo, A.Y., *Investigation of Rapidly Deployable Plastic Foam Systems, Volume II: Nonlinear Deformation and Local Buckling of Kevlar*, CERL-TR-M-272, US Army Construction Engineering Research Laboratory, Champaign, IL, October 1979.

This report investigates the methods of pouring foam into cylindrical-shaped Kevlar bags without any external framework and the deformation and local failure of polyurethane foam-filled, thin Kevlar/urethane skin composite cylinders subjected to transverse loading.

United States National Highway Traffic Safety Administration, *A Study of Rigid Polyurethane Foam*, Dept. of Transportation, 1977.

This 300+ page report delves into a variety of foam properties and relationships from solvent tests to compressive strengths and thermal decomposition.

Weaver, S., Kraushar, K., *Chemicals and Structural Foams to Neutralize or Defeat Anti-Personnel Mines*, Belvoir Research, Development and Engineering Center, Countermine Directorate, Fort Belvoir, VA. 1990.

This report provides a market survey, study, and analysis of chemical and structural foam products to determine if current technology could be used to neutralize/defeat anti-personnel mines.

Wehr, Samuel E., Girton, Timothy .R.,*Field Test of Life Jacket Flotation Materials,* Coast Guard Washington DC Office of Merchant Marine Safety, Washington DC, 1982.

Tests are conducted on RPF to determine if losses of buoyancy occur among various flotation materials (primarily for lifejackets) when subjected to "field use" environments.

Woodfin, R.L., *Results of Experiments on Rigid Polyurethane Foam(RPF) for Protection from Mines*, Sandia National Laboratories, SAND98-0645C, 1998.

The report discusses the results of experimentation with RPF as a neutralization method for mines primarily in the surf zone area during an amphibious military landing.

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

The application of RPF in an amphibious military crossing is investigated. Data from a variety of experiments are presented including investigations of flammability, trafficablity, and strength.

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Appendix L

Coupling of Rigid Polyurethane Foam Barges

Amy E. Latham
Sandia National Laboratories
(N.M. Highlands University)

This paper outlines the barge configurations and finite element analysis used in selection of the bridge coupling scheme.

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Coupling of Rigid Polyurethane Foam Barges

Amy E. Latham, 2522

Electronic Fuzing Department

August 4, 1998

New Mexico Highlands University
Summer Internship Program 1998
Science and Technology Outreach

Latham, Amy
Electronic Fuzing Department

Coupling of Rigid Polyurethane Foam Barges

As part of a consortium between Sandia National Laboratories and New Mexico Highlands University, this project is scheduled for completion in May 1999. The project seeks to identify and evaluate several methods of coupling rigid polyurethane foam barges in a mined surf zone breaching. Military personnel may offload tanks, transport-vehicles, or equipment onto a temporary foam pier and safely move the materials onto the beach area, thereby effectively neutralizing the mined area. A thorough literature search of various foam applications yielded a number of related topics considered in the initial design evaluation. A list of design constraints resulted in an evaluation algorithm to rank the original design methods. Finite element analysis will aid in evaluating two or three designs and a scale-model of the favored design will be fabricated during the 1998-1999 academic year. The resulting analytical predictions will be compared to experimental results obtained from the model.

Introduction

Background

Sandia National Laboratories (SNL) is currently investigating the application of new and emerging technologies to develop countermeasures to sea mines and to enable the neutralization of barriers commonly used to defend beaches against amphibious assault[1]. A Memorandum of Understanding for Countermine Warfare between DOE and DOD funds this program through the fiscal year 1998. This portion of the program investigates the applications of rigid polyurethane foam (RPF) as a method of surf zone breaching during a military assault.

While sea mine neutralization possesses both humanitarian and military applications, this project targets the hazards of amphibious assault. At present, there is no acceptable method to neutralize mined surf areas during an amphibious landing that does not entail very high risk to personnel and to the success of the operation. It is currently necessary to send Special Forces swimmers into the surf zone before the assault to neutralize most of the mines. Unfortunately, most of the larger mines use anti-personnel devices to prevent such activity. Clearly, improved technology is needed to insure the success of surf zone military operations and the preservation of accompanying military personnel.

Sea Mine Classification

A minefield traditionally could only be laid in shallow water (100 fathoms or less), but rapid advances in mine technology have pushed the operating envelope into deeper and deeper waters. The United States' Navy classifies sea mines in three ways: 1) position in the water, 2) method of delivery, and 3) method of actuation. A mine's location in the water can be further classified as bottom, moored, or drifting. Bottom mines are those typically laid in shallow water. From a demining perspective this type of mine is the most prevalent. Moored mines are laid in deep waters and are most effective against submarines. Drifting mines float on or just below the surface of the water. Method of delivery is also divided into three categories: aircraft-laid, submarine-laid, and surface-laid. This classification tells little of the composition or design of the explosive material and is hence, of little importance in identifying the presence of a mine.

The final method of classification considers the firing mechanism. Contact mines contain the oldest type of firing mechanism. When the sensitive horn is broken, an ampule of sulfuric acid breaks. The acid supplies the electrolyte to the plates of a battery that generates sufficient current to fire the detonator. Defensive military applications often incorporate controlled firing mechanisms. The Viet Kong used this type of mine against U.S. Riverine craft during the Vietnam War. Lastly, the influence mine detonates when a specific signature is received from the detector. Older mines recognize one type of signature while newer mines may be programmed to identify multiple types[2]. Influence mines are the most common type found worldwide in demining endeavors. Figure 1 depicts the global threat of sea mines; this project focuses on the development of countermine technology that will effect mine neutralization in the surf and craft landing zones.

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[1] *Rigid Polyurethane Foam Technology for Countermine (Sea) Program*
[2] *Guide to Naval Mine Warfare*

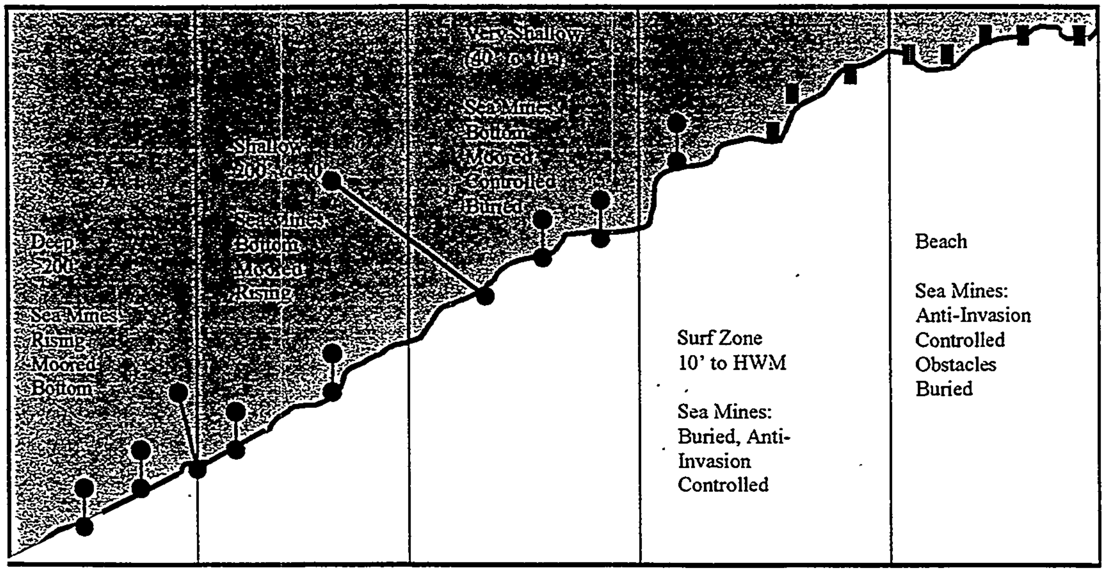

Figure 1: Post-Cold War Global Mine Threat
(Source: U.S. Navy Mine Warfare Plan)

RPF Technology

RPF products are formed from an isocyanate base (A) and a urethane resin (R) that react when mixed and agitated. Rigid foam results from the reaction of a toxic isocyante component with a polyol to form the final foam product. For this application, RPF is intended for an offensive beach assault where amphibious vehicles could be moved over a temporary bridge made of RPF deployed into a ramp-shaped canvas bag. North Carolina Foam Industry (NCFI) produces a foam, 811-91, that is mixed together as 1.06A: 1.00R to produce a foam 16 times its original volume. Lab tests indicate that NCFI 811-91 possesses characteristics, including trafficability, flammability, and strength, eminently suitable for an offensive beach assault[3].

Use of RPF as an expedient surfacing system drew avid interest in the late 1970s when several projects were funded by DOD agencies. In 1977 the Civil Engineering Laboratory at Port Hueneme, California investigated the use of a rapidly-deployable foam surfacing system as a temporary roadway or airfield. In this investigation, the researchers intended to find a rapidly deployable, readily trafficable, surfacing configuration. A sandwich surfacing composed of polyurethane structural foam between two outer layers of fiberglass-reinforced polyester resulted[4]. In 1981 the Construction Engineering Research Laboratory described several concepts for using polyurethane foam plastics for tactical flotation bridging and rafting operations. Their findings suggest that foamable bridging materials could be shipped in compact kits and converted to rafting devices while minimizing training and equipment requirements[5]. Complete bibliographical citations from the literature search appear in Appendix 1, as they will be published through SNL in October 1998. On the basis of these findings, SNL seeks to design a barge configuration made of foam-filled fabric bags that will insure successful military breaching of surf zone areas.

[3] *Rigid Polyurethane Foam Technology for Countermine (Sea) Program*
[4] *Expedient Structural Sandwich Soil Surfacing of Fiberglass Reinforced Polyester and Polyurethane Foam*
[5] *Concept Paper: The Use of Polyurethane Foam Plastics for Tactical Bridging and Rafting Operations*

Objectives

The preliminary 1:5 scale-model barge configuration is shown in Figure 2. Fabricated in rigid, pre-assembled molds, 1.33 cubic feet foam hexagons are fabricated to form the intermediary, hinge material between the barges. Each barge is 16' long X 8' wide X 1.25' thick and encompassed in a canvas material similar to that used in backpacks; the scale-model will be tested at Coastal Systems in Panama City, Florida with an approximate load of 1000 pounds in September 1998. A finite element analysis simulation of the barge under loading should provide a prediction of the experimental results. Secondly, a method of linking the hinge/barge configuration must be developed for the September testing. Finally, linking alternatives will be identified and evaluated using compression experimentation, finite element analysis simulation, and results from the testing in September. The linking alternatives will be evaluated for strength of attachments, ease of incorporating with the barge design, difficulty of adjustment (loosely or tightly strung), and to a lesser degree- appearance. Finite element analysis will be incorporated, where applicable, and an ultimate design will be chosen and modeled. Analytical modeling will consider full-scale barge models, and the consequent design will be tested, in some manner, during the spring of 1999.

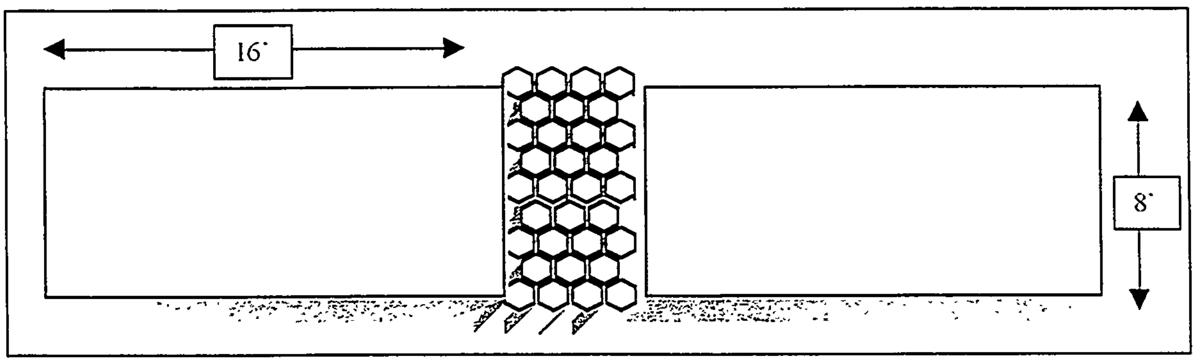

Figure 2: 1/5 Scale Barge Configuration

Materials and Methods

Coastal Systems Experimentation

Experimental testing scheduled for September 8-11 at Coastal Systems in Panama City, Florida will include the connective design as depicted in Figure 3. The design includes poly-vinyl-chloride (pvc) pipe across the three planes of the hexagon and a nylon loop through the vertical cross-section. The loop will provide the method of attaching the hexagons to the barges, and cables threaded through the pipe will cinch the hexagons to each other. In Figure 3, the barge edge is shown in purple with the corresponding attachments. Note that the loop extends through each block perpendicular to the top view shown and secures the hexagons to the barges; the cables thread through the loop on both the top and bottom. A small cart, 2.4' X 5.2', loaded with approximately 1000 pounds will pass over the dual-barge/hexagon configuration. The factor scale is approximately 20% of a full-scale representation using an M1A1 tank (126000 lbs.). Likewise, the barge is 1/5 scale of a 40' X 80' X 4' full-scale representation.

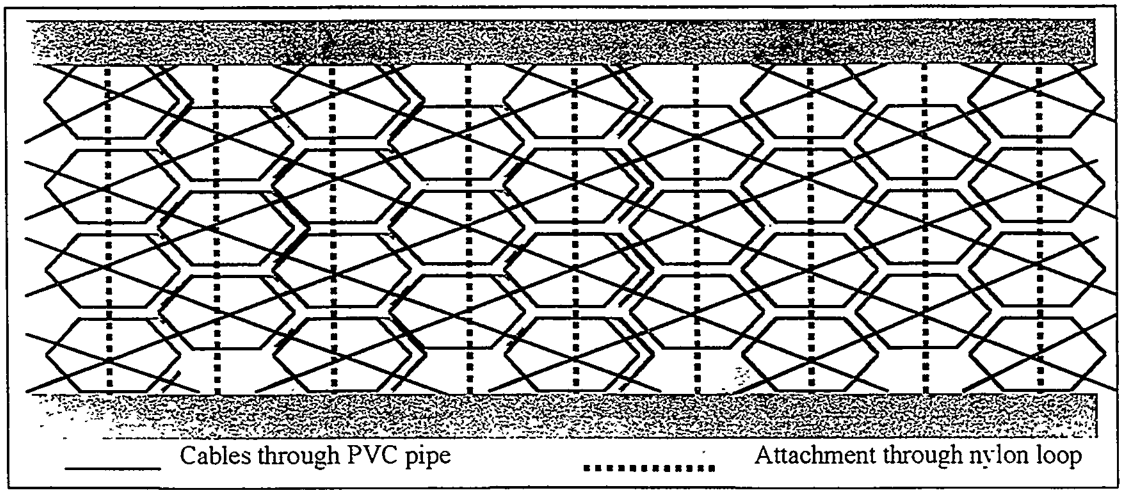

Figure 3: Coastal Systems Experimental Configuration

Alternative Barge Configurations

The initial analysis of the linking alternatives yielded a number of attachment concepts as discussed in Figure 4. In a) the barge attaches to the hexagon intermediary material by a number of small eyehooks mounted to a rigid length of lumber secured in the cross-section of the foam. The proximity of the length of lumber to the end of the foam compromises the strength of the barge, as external forces could tear the connection. To a lesser degree, the design depicted in d) also compromises the overall strength of the barge by requiring a number of cables be threaded through the length of the barge. The result is an area of higher localized stress along that plane. In b) the end proximity is addressed by placing the single mounting apparatus at the center cross-section. The central mounting serves as a guide for two steel cables that will attach to the intermediary material. The disadvantage of this design is the unrestrained motion allowed parallel to the water's surface. The design in e) addresses both former difficulties with the two cables through the longitudinal cross-section in conjunction with an external mesh. The difficulty in assembling the steel mesh should receive carefully consideration, however. Finally, the design depicted in c) requires either nylon or steel cabling be sewn into the fabric encasement prior to filling. This design ensures the integrity of the foam is not affected and assures an adequate connection between the barges and intermediary material but will require a more complex assembly.

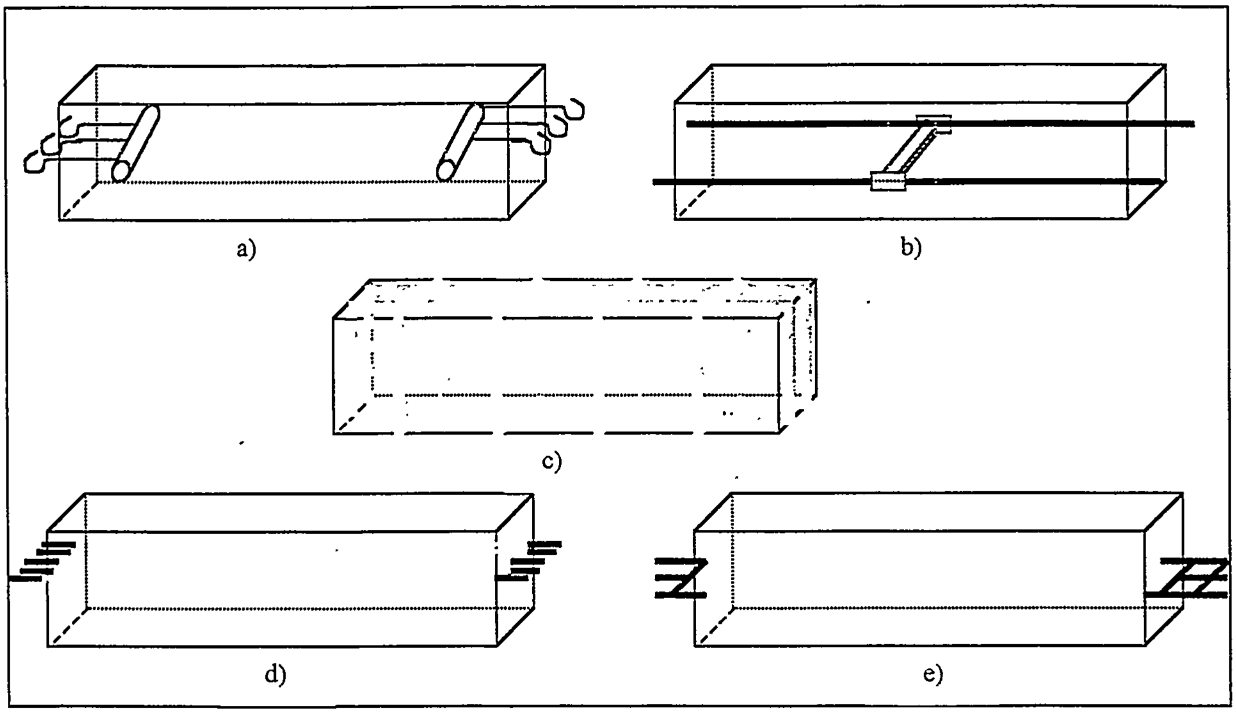

Figure 4: Sketches of Alternative Attachment Conceptions
a) rigid structure at ends of foam barge with eyehook type attachments b) steel cables with central mounting through longitudinal cross-section c) nylon or steel strapping stitched into fabric bag d) steel cables through longitudinal cross-section e) external steel mesh with longitudinal steel cabling through cross-section

Results

Evaluation Algorithm

The evaluation of each design requires several assumptions including a maximum two-month use, no detonation of charge, and a maximum sea-state of 3 (2-4 feet waves). While testing will not evaluate the effects of the elements present in a field setting (i.e. salt water, tides), a maximum two-month use establishes an appropriate expectation. The limitation of the charge detonation is necessary to allow accurate predictions of behavior using finite element analysis. At this time, research continues on foam behavior in the presence of PETN detonations at distances of two to ten feet. The maximum sea-state is derived from conditions routinely present in shoreline military operations. Extreme cases are not considered.

Criteria for evaluating the performance of a particular design include accuracy of analytical performance predictions, strength of attachments, and relative cost of fabrication. The accuracy of analytical performance predictions allows for evaluating the results of the finite element analysis. This result is crucial to prove the validity of the finite element algorithm. The strength of attachments refers to the ability of the design to withstand the forces applied by an M1-A1 tank (126000 lbs.) on a full-scale barge (40' X 80' X 4'). Table 1 depicts the weighting factors of the evaluation algorithm; this information will assist in consequent design iterations and evaluating the ultimate design conception.

Criteria	Weight
accuracy of analytical predictions	6
effects of connection material on strength of the barge	5
strength of attachments; evaluation of failure at connection points	5
relative cost of fabrication	5
ability to modify for loosely or tightly strung blocks	4
use of material readily available i.e. hexagon blocks	4
ease of incorporating with existing bag design	4
difficulty in attaching mechanical supports to foam	4
appearance	2

Table 1: Evaluation Algorithm

Finite Element Analysis

ALGOR finite element software was used to perform the initial analysis of the barge under a variety of loading situations. This approach will continue with the analysis of several connective configurations. ALGOR allows the user to readily alter design constraints and obtain affected results. The results will provide the analytical predictions to necessitate an adequate design result. Impending testing at Coastal Systems will provide a method of comparison between the single-barge analytical results of stress/strain relationships and the experimental results from the thousand pound loading experiment.

Figure 5 depicts the stress and strain results of the initial finite element analysis. The application of 1 psi over the range of the tire tracks of the scale-model resulted in the deformation shown in Figure 5. The simulation provides for a six-pound per cubic foot material with a Young's Modulus of 3910 and Poisson's ratio of 0.3. In addition, the side of the barge positioned against the water is pinned to simulate the effect of the water's surface. The stress relationships depicted in 5a) represent units of pounds per square inch. Likewise, the strain relationships in 5b) are dimensionless.

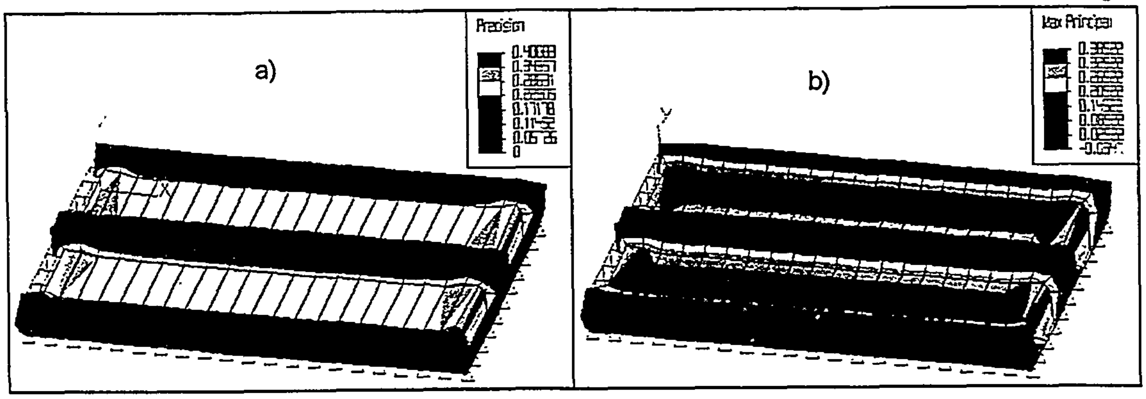

Figure 5: Results from Finite Element Analysis of Single-Barge Configuration
a) Stress Relationships and b) Strain Relationships

Conclusion

The fundamental results presented in this paper suggest the applicability of finite element analysis to accurately represent the behavior of rigid polyurethane foam in specific loading situations. Experimental results obtained at Coastal Systems will prove the validity of these results and test the suitability of the nylon mesh attachments. A final attachment configuration will be chosen and fabricated by May 1999 as part of my undergraduate degree requirements at New Mexico Highlands University. The literature search will be published in October 1998 through SNL's Electronic Fuzing Department.

Recommendations

Continued research in military mine detection technology will likely consider the benefits of chemical sensors in conjunction with neutralizing foam applications. Recently, a variety of political manifestations have directed global attention to mine detection capabilities. The need to produce effective, simple methods of mine neutralization necessitates an increased reliability from emerging technologies. In response to this demand, a new MOU between the DOE and DOD allocates additional monies to mine detection technologies.

References

Hironaka, M.C., *Expedient Structural Sandwich Soil Surfacing of Fiberglass Reinforced Polyester and Polyurethane Foam,* Civil Engineering Laboratory, 1997.

Morison, Samuel Loring, *Guide to Naval Mine Warfare*, Arlington: Pasha Pub, 1995.

Smith, Alvin, *Concept Paper:The Use of Polyurethane Foam Plastics for Tactical Bridging and Rafting Operations*, Construction Engineering Laboratory, 1981.

Woodfin, R.L., *Rigid Polyurethane Foam Technology for Countermine (Sea) Program*, Sandia National Laboratories, January 1997.

Appendix 1
Bibliographical Citations from Literature Search
Conducted by Amy Latham July 1998

Austin, S., McIntosh, R., ***Contract Report CR-73-007:****Development and Fabrication of Prototype Advanced Surfacing Systems for Military Use on Soils*, Boeing Company, Seattle Washington, 1972.

Charney, F.A., *Design Procedures for Rigid Polyurethane Foam Mine Enclosures*, Denver Research Center (and the US Bureau of Mines), Denver, CO, 1992.

Flynn, R.M., *Feasibility Study on the Use of Foam Plastics in Field Fortifications*, Army Research and Development Labs, Fort Belvoir, VA, 1963.

Griffin, D.F., *Technical Note N-1346: Evaluation of a Synthetic Surfacing System for the Marine Corps*, Civil Engineering Laboratory, Port Hueneme, CA, 1974.

Hironaka, "Technical Memorandum TM 53-76-1: Fiberglass Reinforced Polyester Performance Under Dual Wheel Traffic Loadings", Port Hueneme, CA, 1976.

Hironaka, M.C., Brownie, R.B., and Truccillo, S., "Expedient Structural Sandwich Soil Surfacing...of Fiberglass Reinforced Polyester and Polyurethane Foam", *Rept. Ada 038417*, Springfield, VA, 1977.

> The development of an expedient surfacing system for the Marine Corps airfield, road, and logistic support area applications is investigated. Primarily, the execution of amphibious landing operations and the trafficable surfacings required for such aircraft and heavy equipment are targeted. (Explanatory diagrams and photographs are included.)

Lee, Thomas G.K., *Evaluation of the Fire Performance of a Dibromotetraflouroethane- Blown Rigid Polyurethane Foam: Final Report*, National Bureau of Standards, Naval Ship Research and Development Center, Carderock, MD, 1974.

> The evaluation of the fire performance of structural rigid polyurethane foam material is investigated as it may be exposed to potential shipboard fires.

Marsden, J., Chessin, N., *Quick-Setting Foam Research Support and Spray-Nozzle Sub-System*, US Army Mobility Equipment Research and Development Center, Fort Belvoir, VA, 1973.

> Dismounted troops may be able to safely cross tactical minefields on foam pads.

Marshall, M.D., *Evaluating Rigid Foams for Construction and Repairing Mine Stoppings*, B of M-OFR-40-85, MSA Research Corporation, Evans City, PA, October 1984.

> Twenty-seven commercially available foam materials were tested to delineate those most suited for use as a sealant in underground mine stoppings. Perhaps, this application may provide useful background information for foam-filling shell holes.

Military Application for Rigid Polyurethane Foam, Sandia National Laboratories- Video Report, Albuquerque, NM, 1997.

> The video provides a brief introduction to the variety of military applications of RPF under investigation at SNL.

Smith, Alvin, *Concept Paper: The Use of Polyurethane Foam Plastics for Tactical Bridging and Rafting Operations*, Construction Engineering Research Laboratory, US Army Corps of Engineers, Springfield, VA, 1981.

A variety of tactical applications of RPF are investigated including: footbridges, rafts, vehicle flotation, foam-filled boats, railed bridges, and overhead cover for antitank weapons crews are investigated.

Smith, Alvin, *Investigation of Rapidly Deployable Plastic Foam Systems, Volume I: System Development*, CERL-TR-M-272, US Army Construction Engineering Research Laboratory, Champaign, IL, October 1979.

This report introduces rapidly deployable plastic foam systems, evaluates a number of geometrical shapes obtainable with RPF, and evaluates stress/strain characteristics at various times during the foaming process.

Smith, A., Wang, S.S., and Kuo, A.Y., *Investigation of Rapidly Deployable Plastic Foam Systems, Volume II: Nonlinear Deformation and Local Buckling of Kevlar*, CERL-TR-M-272, US Army Construction Engineering Research Laboratory, Champaign, IL, October 1979.

This report investigates the methods of pouring foam into cylindrical-shaped bags without any external framework and the deformation and local failure of polyurethane foam-filled, thin Kevlar/urethane skin composite cylinders subjected to transverse loading.

United States National Highway Traffic Safety Administration, *A Study of Rigid Polyurethane Foam*, Dept. of Transportation, 1977.

This 300+ page report delves into a variety of foam properties and relationships from solvent tests to compressive strengths and thermal decomposition.

Weaver, S., Kraushar, K., *Chemicals and Structural Foams to Neutralize or Defeat Anti-Personnel Mines*, Belvoir Research, Development and Engineering Center, Countermine Directorate, Fort Belvoir, VA. 1990.

This report provides a market survey, study, and analysis of chemical and structural foam products to determine if current technology could be used to neutralize/defeat anti-personnel mines.

Wehr, Samuel E., Girton, Timothy .R.,*Field Test of Life Jacket Flotation Materials,* Coast Guard Washington DC Office of Merchant Marine Safety, Washington DC, 1982.

Tests are conducted on RPF to determine if losses of buoyancy occur among various flotation materials (primarily for lifejackets) when subjected to "field use" environments.

Woodfin, R.L., *Results of Experiments on Rigid Polyurethane Foam(RPF) for Protection from Mines*, Sandia National Laboratories, SAND98-0645C, 1998.

The report discusses the results of experimentation with RPF as a neutralization method for mines primarily in the surf zone area during an amphibious military landing.

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

The application of RPF in an amphibious military crossing is investigated. Data from a variety of experiments are presented including investigations of flammability, trafficablity, and strength.

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Appendix M

Memorandum for the Record
Foam Bridge Feasibility Experiment and
TCG Demonstrations 14 – 18 September 1998

C. O. Schmidt, LATA/621

This memo report outlines the experiments at CSS Panama City, FL.

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MEMORANDUM for the RECORD

C. O. Schmidt/LATA 621
21 September 1998

Foam Bridge Feasibility Experiment and TCG Demonstration, Week of 14 September

The final experiment of the Rigid Polyurethane Foam (RPF) series took place at Coastal Systems Station, Panama City, FL. This was a feasibility experiment to determine if it was possible to construct a foam bridge that would provide an effective access for tracked and wheeled vehicles from seaward to a landing beach for follow-on clearance and resupply.

The bridging material consisted of two 8 x 16 x 1 ¼ ft pontoon sections joined by an 8 x 8 raft constructed of hexagonal foam cells 13 5/16 inches across the flats and 15 – 16 inches high. Both the hexagons and the pontoon fills were made of NCFI 3.3 pcf RPF. The hex blocks were lashed together with nylon line and strapped across, top and bottom, to attach to the two pontoons. The RPF pontoons were made up of 8 x 16 x 1 ¼ foot heavy nylon cloth envelopes with full length longitudinal straps top and bottom to spread the connecting loads. The weight of the pontoon fabric was not scaled. The same weight material was used for both the prototypes and these 1/5 scale pontoons. The envelopes were fabricated by CSS, shipped to Albuquerque, and filled by Sandia with NCFI 811-91-3.3 foam using the Decker dispenser at Socorro, NM.

The hexagonal blocks were cast by Sandia at EMRT in six molds fabricated by CSS and shipped to Sandia as well. Figures 2 and 3 show the assembled RPF bridge in the CSS demo pond. Figure 1 shows the overall setup.

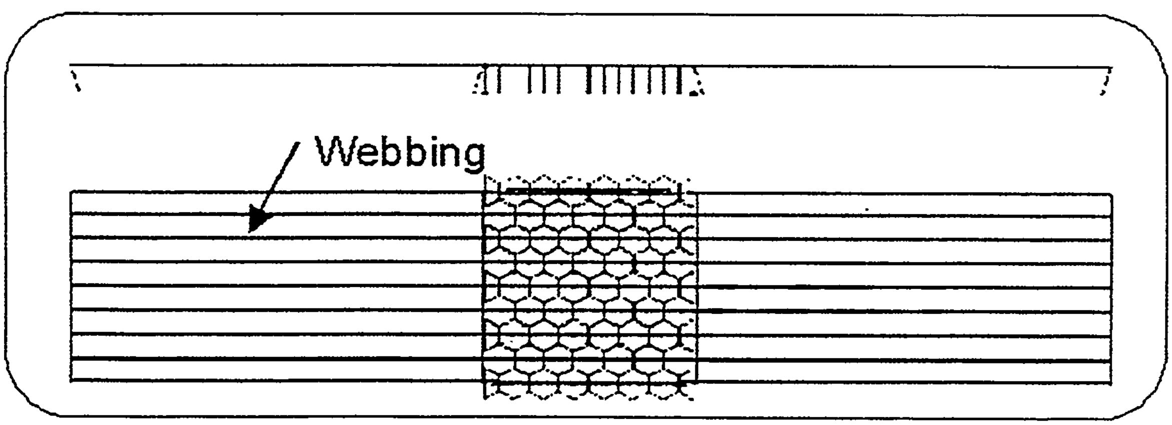

Figure 1. 1/5 Scale Prototype RPF Bridge

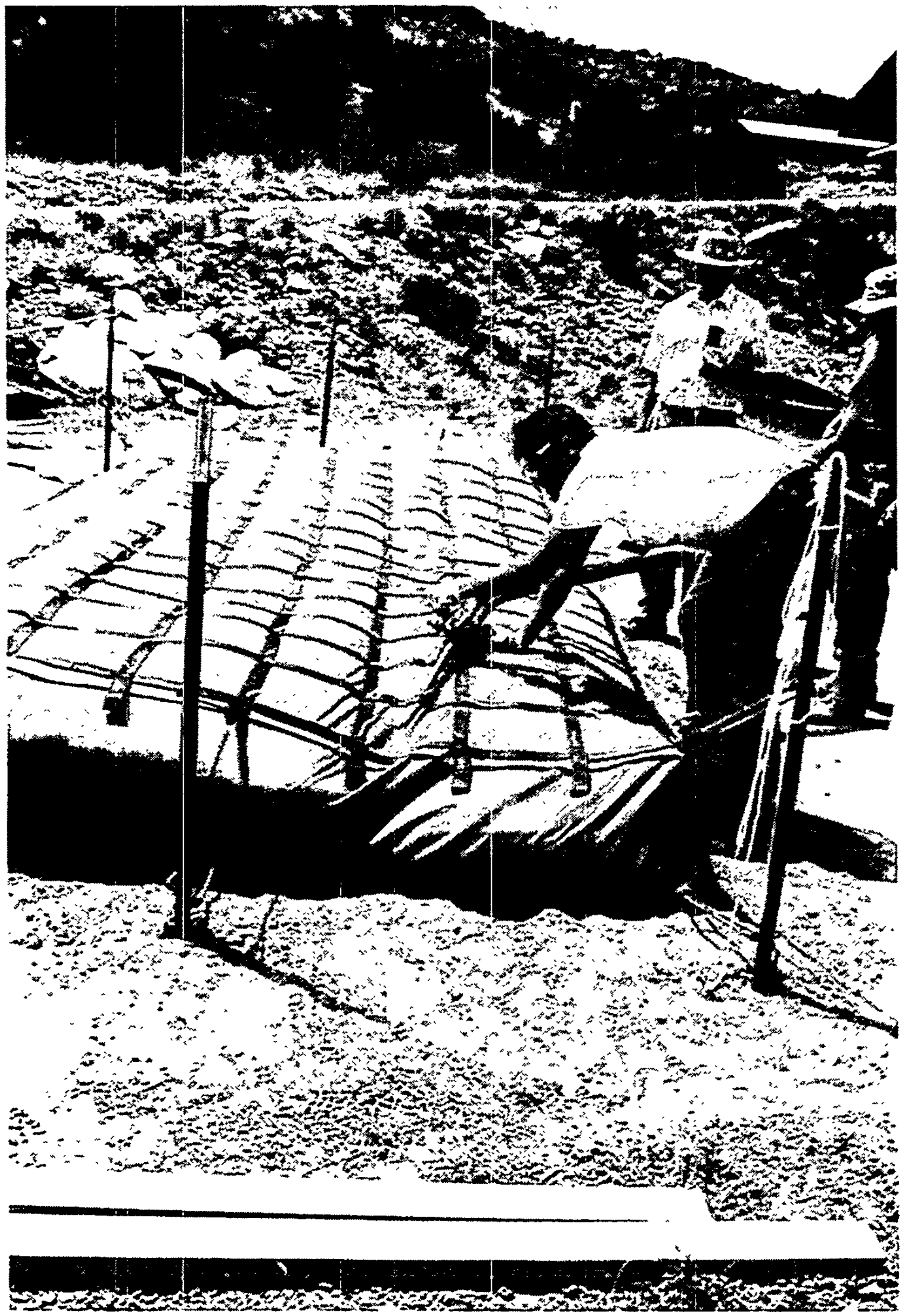

Figure 2. Filling RPF Pontoon Envelopes

Figure 3. Casting Hexagons

Scaling for the prototype was 1/5 of the expected full size requirement except for the thickness which was increased from 0.8 ft to 1.25 ft for ease of construction, transportation, and safety reasons. Figure 4 shows the scaled factors.

Scaled Pontoon Candidates
(Based on M1A1 on 40' x 80' x 4' prototype, 3 pf RPF)

Prototype		Factor
40' x 80' x 4', 126,000#		0.2
Width	40 ft.	8.00 ft.
Length	80 ft.	16.00 ft.
Thickness	4 ft.	0.80 ft.
Weight of Pontoon	47,500 lb.	760 lb.
Maximum Tilt (degrees)	42.35 deg.	37.8 deg
Vehicle	M1A1	Trailer
Width	12 ft.	2.4 ft.
Length	26 ft.	5.2 ft.
Weight of Load	126,000 lb.	~ 1,100 lb.

Figure 4. Prototype Scaling

The experiment was conducted as several separate events:

1. Deflection experiment: 5 lb C-4 charge 2 ft below surface at 10 ft standoff; hexes lashed tightly for the first shot and loosened for the second.

2. Deflection and tilt experiment: pull loaded cart the length of the bridge; multiple traverses on centerline, one traverse at edge of pontoons; no wave action.

3. Deflection experiment: pull loaded cart the length of the bridge; multiple traverses on centerline and edge, with wave action.

Experiment 1 was conducted on 16 September in the CSS magazine area demo pond. The pair of pontoons with hex section connection was loosely anchored at the shore end and tethered at the seaward end. The cart with 1,000 lb lead weight and marker float positioned at the inner end of the seaward pontoon. Two shots were detonated; both 5 lb C-4 spheres, located 2 feet below the surface and 10 ft out from the bridge opposite the cart. One trial was made with the hex blocks pulled tightly together and another with the blocks loosened up. Both shots fired as designed, throwing water and bottom mud 20 feet or more the air. Figures 5 and 6 show the two explosive experiments. No damage was sustained by either the pontoons or the hexagon raft.

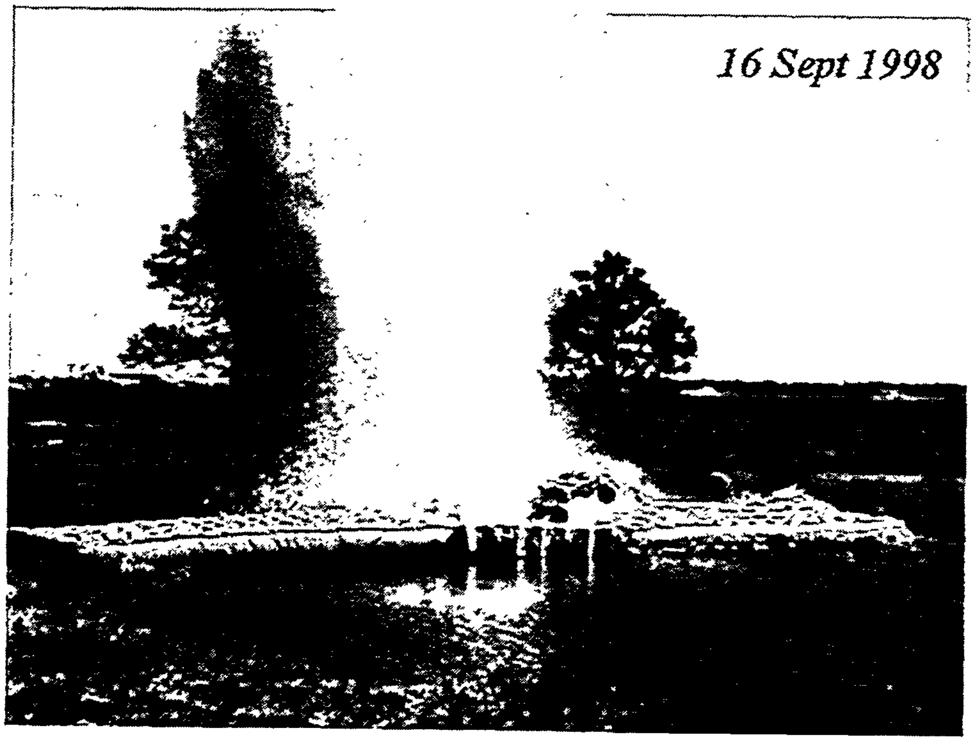

Figure 5. Explosive Experiment, Hexagons Pulled Tight

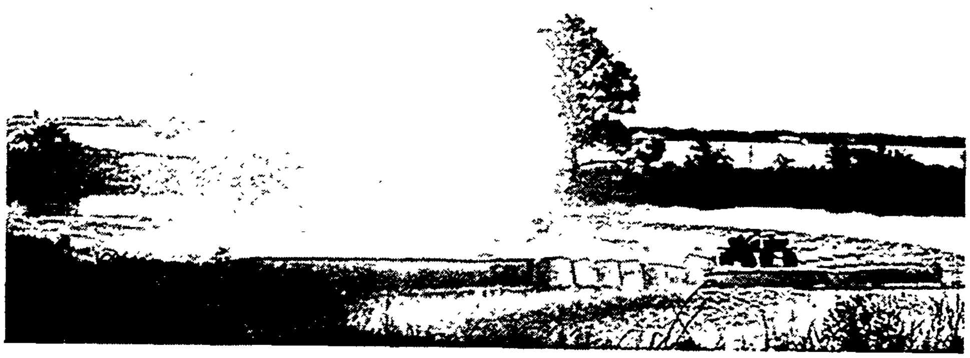

Figure 6 Explosive Experiment, Hexagons Loose

Lack of tension in the hex section allowed excellent three dimensional movement, preserving the pontoons but made traversing the hexagons somewhat more difficult with a wheeled vehicle.

Experiment 2 was conducted to verify the stability of the RPF bridge under load. The cart, with a 1,000 lb. lead block secured to it, was positioned at the seaward end of the bridge and pulled across the seaward pontoon, the hex section, and the landward pontoon. No wave action was created. The bridge was securely anchored at the shore end. The cart was towed several times the full length of the bridge by hand and by a half ton Ford pickup truck located at the edge of the demo pond.

The cart, weighted to 1,050 pounds, simulated at 1/5 scale the footprint of an M1A1 Main Battle Tank. An extra set of wheels was added for strength after one axle bent in the explosive experiment. It was towed the length of the foam bridge on the bridge centerline with no damage to the pontoons or hex section. The cart was then lifted, by crane, back to the seaward end of the bridge and towed the full length of the RPF bridge; again, tracking down the extreme edge of the pontoons and hex section. The bridge could be seen to tilt slightly in the water at less than a 10° angle. Figure 7 shows the traverse down the edge of the bridge.

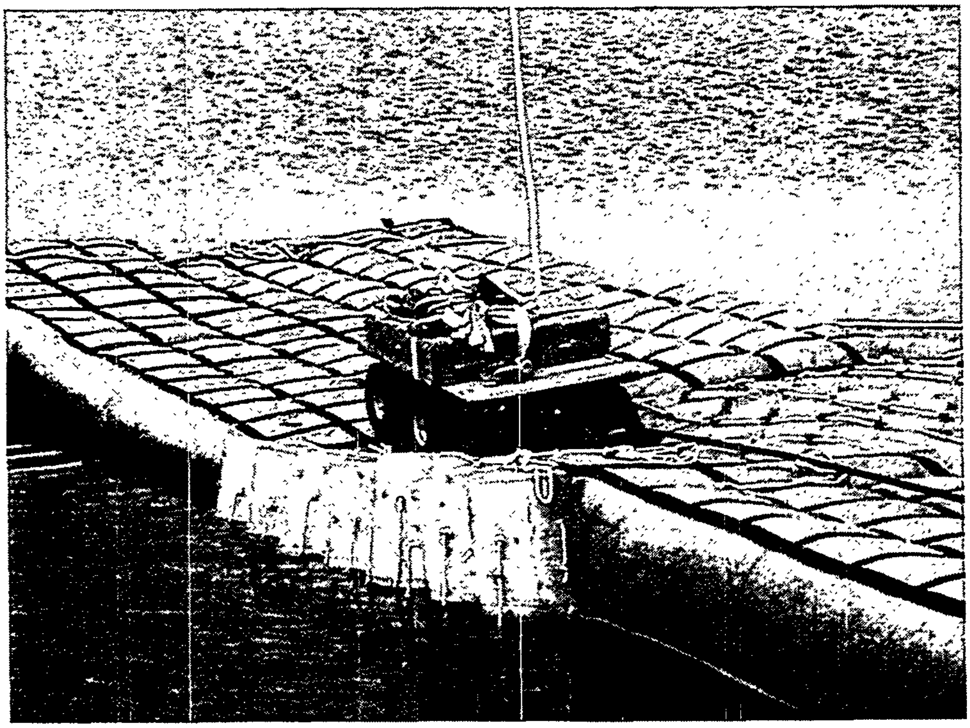

Figure 7. Cart Traversing the Edge of the Bridge

During this portion of the experiment there was no damage to the foam bridge and the cart traversed the hex section without problems and only moderate towing loads.

Experiment 3 was a repeat of part of experiment 2 with wave action in the demo pad. A Navy Special Forces Zodiac boat with a large outboard motor was run in circles around the pond to create waves about 12 to 15 inches high. The waves generally impacted in a quartering direction along the length of the RPF bridge and created a considerable amount of flex in all three dimensions. The loaded cart was towed down both the centerline and the edge of the bridge; again, with no problems. Figure 8 shows the cart and boat in motion during experiment 3.

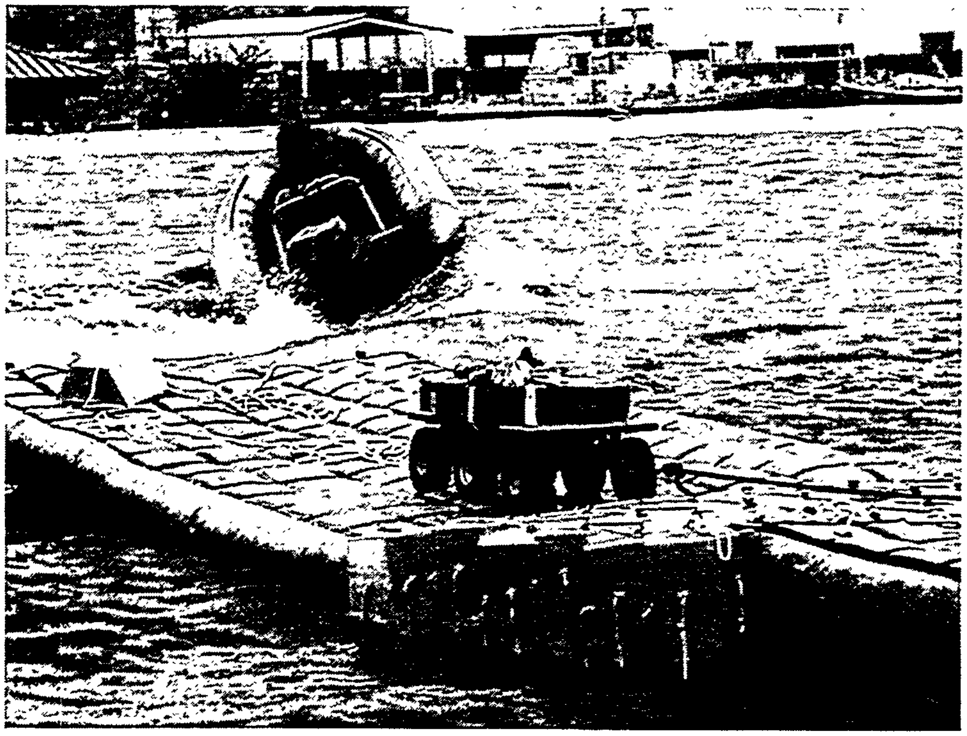

Figure 8. Experiment 3

Conclusions

It is certainly possible to create an RPF bridge or pier with pontoons joined by hexagonal sections that will expedite landing tracked and wheeled vehicles. Assuming the scaling holds, these pontoons represent a full scale roadway about 40 feet wide x 200 feet long x 6 feet thick operating in a 6 foot surf. There were no problems encountered in moving the wheeled cart over the pontoons or the hex raft and it is expected that a tracked vehicle would do at least as well. These experiments at 1/5 scale demonstrate that the concept is feasible and could be used to create an expedient causeway from an anchorage over an undeveloped beach with a reasonable amount of surf running.

The CSS memo report is attached as appendix N to provide detail.

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Appendix N

Foam Bridging for Surf Zone Breaching Operations

Randy Ledman, CSS
John Webster, CSS
Ron Woodfin, Sandia

This memorandum report details the foam bridge experiments at CSS, 14 – 18 September 1998 from the CSS perspective.

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Foam Bridging for Surf Zone Breaching Operations

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LONG-TERM GOALS

The goal of this project is to demonstrate the potential of rigid polyurethane foam (RPF) as a building material to allow building of bridges for transport of heavy material and troops over an obstacle and mine field. In the future such a bridge could be constructed in transit or near the anticipated landing site with very large savings in lift required over traditional bridging techniques.

OBJECTIVES

The objective of this project is to demonstrate an alternative non-explosive approach to breaching the surf-zone in an amphibious assault or rapid follow-on phase. Specifically this effort was to show the feasibility of this concept, identify any major technical hurdles with the proposed concept, and provide an initial model for analysis of the full-scale system.

APPROACH

This project built on the effort of Dr. Ron Woodfin and his team at Sandia National Laboratories who over the last several years have been developing and testing a foam technology for this application. Their efforts identified the most promising foam for this application and performed operational type testing including explosive testing, roadway survivability, and setup in water.

In order to demonstrate the potential for a foam bridge as an alternative to explosive clearance the approach was to develop a simple model of the floating bridge to estimate forces on the flexible sections. Next, we built a scale model of the foam bridge based on the model, and simulated on the model the motion of a large load in a wave environment.

As part of the concept assessment process the results of this feasibility development will be examined next year from an operational perspective and assessed against other concepts.

WORK COMPLETED

Coastal Systems Station and Sandia National Laboratories combined efforts to produce a 1/5-scale foam bridge model to demonstrate its feasibility for rapid follow-on clearance. The demonstration took place at CSS on 16-18 September. The bridge consisted of three sections; a hexagonal float section, and two barge sections. The individual hexagon shaped floats, which made up the float section, and the two barges, were made of Rigid Polyurethane Foam (RPF). The overall assembly is illustrated in figure 1.

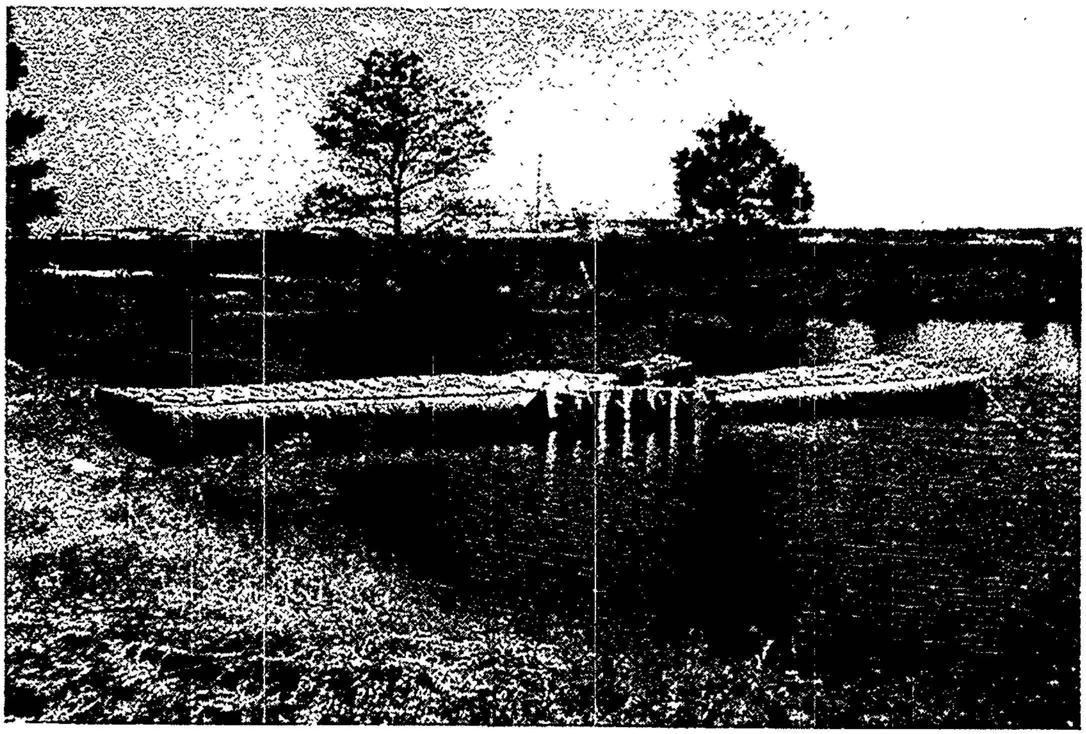

Figure 1. Assembled Foam Bridge at CSS Test Pond

CSS engineers developed a dynamic computer model of the entire bridge assembly. This model helped predict how the bridge would react under both loaded and wavy conditions. CSS engineers also designed and built the molds used for the fabrication of the hexagon shaped floats. This design also included the internal PVC conduit used as rope channels for the float assembly. In addition, CSS shops manufactured the two cloth-laminated vinyl envelope bags, which made up the shell of the barges. Finally, CSS manufactured the ½" thick plywood spacers, which acted as washers between all the adjacent faces of the float assembly. Sandia manufactured the individual hexagon shaped floats, and also filled the vinyl envelope bags with foam upon receipt from CSS. After completion, all components were shipped to CSS for assembly.

CSS assembled the hex section, which consisted of 58 whole hexagon floats and 10 half floats. The final assembly was tied together using 3/8", 3-strand nylon rope. The hex float assembly, which had a plan dimension of approximately 8'x 8', was tied between the two barges, which were each approximately 16' long by 8' wide. The purpose of the hex float section is to act as a flexible joint for the bridge, thus preventing buckling of the bridge when it is subjected to wave action and vehicle load. The flexibility of this joint was controlled by the tightness of the 3/8" rope, which was threaded through each float, via the PVC conduit, in three axes. The optimum flexibility was accomplished by several iterations under the direction of Dr. Ron Woodfin of Sandia.

Once the Foam Bridge was assembled, it was trucked to the CSS demo pond in preparation of the first phase of the demonstration, which took place on September 16. The assembly was then placed in the pond with one end tied next to the shore and the other end anchored out in the pond, perpendicular to the shore. Video coverage of the test event area was provided.

To simulate the effects of an M1A1 tank (1/5 scale) on the bridge, Sandia purchased a properly scaled cart. This cart had four wheels, but was eventually modified with an extra set of wheels (6 total) to better simulate the loading distribution of a tank track. A lead clump weighing 1080 Lbs. was strapped to the top of the cart, for a total weight of approximately 1160 Lbs. The weighted- cart was then placed at the center of the outboard barge, and was not secured in any way.

EOD personnel placed a five-pound explosive charge at a depth of approximately three feet and a distance of ten feet to the side of the center of the hex section. The weighted-cart was then placed over the seam between the outboard barge and the hex float section. With both the video and still cameras rolling, EOD personnel detonated the five-pound charge. The weighted-cart was then moved to the center of the outboard barge. A second five-pound charge was then placed in the general vicinity of the first charge and detonated. The bridge was inspected for damage; none was found.

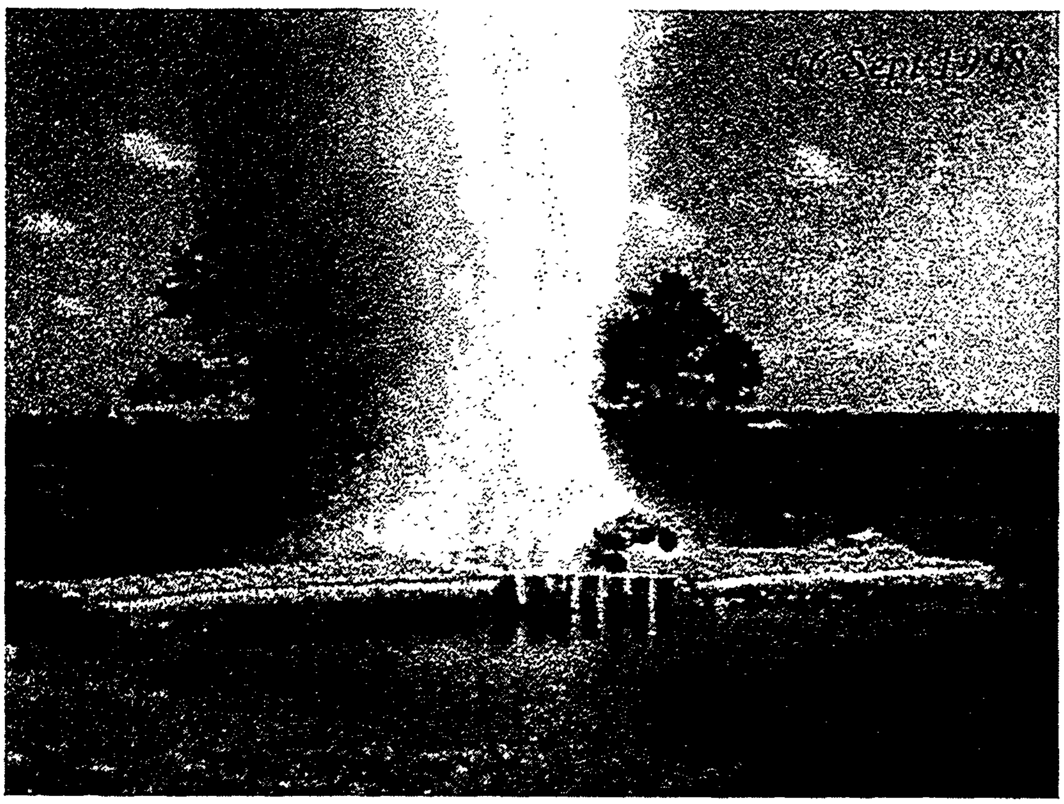

Figure 2. Assembled Foam Bridge Subjected to Nearby Explosion

After the completion of the explosive phase of the demonstration, the entire bridge assembly was moved to the nonmagnetic test pond. The second phase of the demonstration took place on September 17-18. The purpose of the second phase of the demonstration was to determine how the bridge would react when subjected to a moving load (M1A1 scaled cart) under both calm and wavy conditions. In addition, the ability of the bridge assembly to be towed was demonstrated. One video camera and two still cameras were used to collect the data. A total of 12 triangular, incremented, optical targets were attached to one side and the outboard end of the bridge assembly. They were evenly spaced and positioned to enable the 3" mark to be level with the waterline. Their purpose was to enable the testing team to determine the displacement of the bridge assembly at various locations as the weighted-cart passed over the bridge. The bridge assembly was placed in the pond perpendicular to the side and secured by ropes tied to existing cleats located on the side of the pond.

A crane was used to place the weighted-cart at the center of the outboard barge. A rope was then tied between the cart handle and the hitch of a truck. The truck then pulled the cart slowly over the entire length of the bridge assembly. This procedure was performed numerous times with the cart rolling down the center of the bridge. The centerline of the cart was then moved to a location approximately 2.5 feet from the side of the bridge and the procedure was repeated. A small RHIB boat was then placed in the pond to produce waves. The boat operator was instructed to run in circles near the bridge assembly until a consistent wave pattern persisted. At that point, the weighted-cart was pulled down the length of the bridge numerous times, both at the center and side location. The video and still cameras collected all the data.

The weighted-cart was then removed from the barge assembly, and the barge assembly was untied from the cleats. The RHIB boat then connected a towline to the bridge assembly and towed it around the test pond for a few laps. Once again, both photographs and video were taken for future reference.

Finally, the barge assembly was taken out of the water and disassembled. One barge section was placed back in the test pond by itself to perform an incline test. The weighted-cart was then placed at various locations on the barge and the angle of incline was determined by the use of an inclinometer. The hex float section was then placed in the pond and the same procedure was repeated.

RESULTS

The September demonstration/test of the Foam Bridge project provided some significant results and lessons learned. The 1/5 scale foam bridge proved to be easy to assemble and transport. However, the assembly was performed on land in a controlled environment. A full-scale model may prove to be difficult to assemble on a ship at sea. This can likely be improved by redesigning the hex matrix section as an integral unit and designing a better system for connection to the barges. The foam bridge assembly was easily towed by a small boat and appeared to be very stable. The hex float section proved to be a very efficient flexible joint between the barge sections. It provided stress relief for the bridge assembly when the bridge was subjected to waves, rolling and stationary load and shock produced by the detonation of a five-pound explosive charge. Without the flexible hex float joint, the bridge assembly would most likely buckle when subjected to these conditions. The hex section also provided a better than expected platform for the cart to roll over. The hex floats displaced in a group instead of individually when subjected to point loading by the cart's wheels. This made for a much smoother slope and thus, a smoother surface for the cart to ride on. However, it is imperative that the hex floats are tied together at the proper tightness. If the section is too loose, it is difficult to roll anything over it without a wheel getting stuck. If the section is too tight, the advantages of the flexible joint are eliminated.

The barge sections of the bridge assembly had remarkable buoyancy, and were not significantly affected by the addition of the weighted-cart. The 1/5 scale Foam Bridge was hardly affected by the rolling load except at the hex foam section.

Finally, the data collected from the test, especially the incline and displacement tests performed on the individual sections, will enable the CSS hydrodynamics group to accurately computer model the entire bridge assembly. This will provide a better understanding of the capabilities of the bridge assembly and aid in a future full-scale design, if warranted.

IMPACT/APPLICATIONS

The foam bridging technology demonstrated under this effort and the related Sandia effort illustrates the potential military use of expanding foam. Further development of this technology and development of larger pumping systems could lead to a system capable of quickly deploying a bridge in a moving surf environment to carry heavy equipment. Many other uses have been envisioned including large fabric filled pontoons, roadways over swampy ground, ship protection from underwater explosions, and many auxiliary military uses.

TRANSITIONS

This effort completed with a demonstration described in this report. Further development of large pumping systems for this foam is feasible, but will require an industry partner.

RELATED PROJECTS

This effort was part of the Concept Assessment task for FY98. The effort builds on the earlier work done by Sandia National Laboratories under a joint Department of Energy / Department of Defense Memorandum of Understanding for Countermine Warfare.

REFERENCES

Woodfin, R. L., D.L. Faucett, et al, "Rigid Polyurethane Foam (RPF) Technology for Countermines (Sea) Program - Phase II", SAND 98-2278, September 1998.

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