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INVESTIGATION OF RAPIDLY DEPLOYABLE
PLASTIC FOAM SYSTEMS
VOLUME I: SYSTEM DEVELOPMENT

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Block 20 continued.

→ various times soon after generation were studied. Fabrication of fabric foam cylinders was also studied. Volume II documents a study of fabric-skinned, foam-filled cylindrical beams and an analytical/experimental study of their bending properties.

Results of the studies show that a low-density polyurethane foam system that will deploy within 5 seconds is practical to generate and to form into geometrically shaped lightweight fabric bags. The foam exhibits good impact absorption properties very quickly after formation; these properties can be used to attenuate rapidly applied loads of low to intermediate velocities. Finally, the fabric/foam composite beams possess interesting structural qualities commensurate with the fabric and foam used in making them. The analytical and experimental results compare very well. The analysis identified several factors of the mechanics involved that must be included in calculations to predict the loading response of such composites. ←

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FOREWORD

This research was conducted for the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Dayton, OH. Funds were provided by Military Interdepartmental Purchase Request (MIPR) No. FY1456-78-00006 and MIPR No. FY1456-79-00002. The Air Force Project Manager was Mr. S. R. Mehaffie, AFFDL/FER.

The work was performed by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (CERL), Champaign, IL. The analysis of the fabric/foam cylinders was performed by Assistant Professor S. S. Wang and A. Y. Kuo of the Department of Theoretical and Applied Mechanics, University of Illinois at Urbana-Champaign. Dr. G. R. Williamson is Chief of EM.

COL Louis J. Circeo is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director.

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INVESTIGATION OF RAPIDLY DEPLOYABLE PLASTIC FOAM SYSTEMS VOLUME I: SYSTEM DEVELOPMENT

1 INTRODUCTION

In 1979, the Air Force Flight Dynamics Laboratory published the results of an in-house study on a low-density polyurethane shock attenuation system designed for use with Remotely Powered Recoverable Vehicles (RPRVs).¹

The Air Force's system was composed of a commercially available foam system modified to RPRV use. This modified system could be activated on command (i. e., after chute deployment) and eject a foam mixture through a manifold device fitted with several small plastic helical mixers. The interval between foam mixture ejection and foam rise was approximately 60 seconds—a deployment interval considered adequate for most RPRV applications.

However, it was apparent that if a way could be devised to decrease the deployment interval to 5 seconds, the foam shock attenuation system could be applied to a wide range of other uses, particularly emergency systems such as aircraft ejection capsules. Therefore, the U.S. Army Construction Engineering Research Laboratory (CERL) was commissioned to investigate chemical formulations, to evaluate dispensing systems, to verify operating times, and to evaluate geometric foam container shapes with the goal of extending the applicability of the foam shock attenuation system.

Objectives

The overall objectives of this study were:

1. To reduce the operating time of a deployable plastic foam system to 5 seconds, to develop a mixing/dispensing system for the foam, to evaluate a range of geometric shapes obtainable with the foam, and to evaluate the stress/strain characteristics of the foam at various times during the foam curing process.

¹Stephen R. Mehaffie, *Investigation of a Deployable Polyurethane Foam Ground Impact Attenuation System for Aerospace Vehicles*, Volume I, AFFDL-TR-78-145 (Air Force Flight Dynamics Laboratory, January 1979).

2. To evaluate the performance of a high-strength fabric form filled with polyurethane foam to determine experimentally and analytically the roles of each component of the composite material as a potential structural material.

Volume I describes the first objective above and Volume II describes the second.

Approach

Three different formulas which produced a polyurethane foam with a 5-second deployment interval were evaluated. The most successful formula was used to test a modified foam mixing/dispensing system and to evaluate the deployment in fabric forms made in five different geometric shapes.

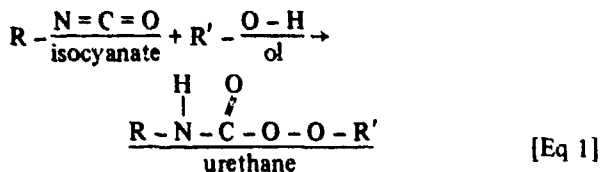
2 FOAM FORMULATION STUDIES

Polyurethanes

Polyurethanes are generally defined as the polymers obtained as the reaction products of isocyanates and alcohols. To assure development of macromolecules and molecule-to-molecule cross linking, it is necessary to use at least di-isocyanates and di-alcohols, so that chain extension can occur. In practice, multifunctional isocyanates and alcohols, known respectively as polyisocyanates and polyols, are used. Polyurethane foams are the expanded form of the polymer; i.e., they have a reasonably uniform dispersion of gas bubbles (cells) throughout the mass.

Reactions

The typical reaction leading to polyurethane polymer growth is shown in Eq 1—for simplicity, a single urethane linkage is shown, although most polymers involve a polyisocyanate and polyol reaction.



R and R' represent organic portions of molecules to which the isocyanate and hydroxyl group are attached. As Eq 1 shows, the reaction is an addition type and has no by-product. Polymer propagation occurs when both R and R' have additional reactive sites, i.e., polyisocyanates and polyols. Polymer growth ceases when either

of the constituents is depleted, when steric hindrance prevents necessary alignment and proximity of the isocyanate groups and the polyol group, or when some other condition prevails that is unfavorable for the reaction. If an excess amount of isocyanate groups is present, numerous other complex reactions may occur, causing crosslinking or branching. Since isocyanates will react with almost any hydrogen that is not covalently bonded to a carbon atom as in a hydrocarbon, the urethane group itself may be reacted with (note the N-H bond) to form linkages. Other similar reactions are possible, depending on the composition of the reactants. These secondary reactions lead to changes in stiffness of the polymer (or foam); the more crosslinks, the stiffer the foam. The urethane and *side* reactions are all heat releasing (exothermic).

Catalysts

Reactions between isocyanates and polyols occur fairly slowly at ordinary temperatures. Therefore, to increase both the rate of reaction and reaction completion (cure), catalysts must be used. Foaming of the polymer is based on a balance of the rates of polymerization and gas generation. The gas, trapped as cells, expands the polymer much like trapped carbon dioxide gas causes bread to rise. If the polymerization rate is too great, the viscosity of the liquid increases too rapidly and the foam does not fully expand; a rate that is too slow results in cell coalescence and collapse of the foam.

Catalysis is based on isocyanate activation, probably through chemical complex formation and disintegration stages. (The precise mechanisms are not important at this point and will not be discussed.) As shown in Eq 1, the urethane forming reaction, the double bond between the nitrogen atom and the oxygen-end carbon atom breaks, the hydrogen from the alcohol bonds to the nitrogen, and the alcohol oxygen attaches to the isocyanate oxygen-end carbon. This double bond rearrangement is strongly influenced by certain conditions, e.g., alkalinity.² Several organic substances are also catalytic to the reaction; as a class, simple amines are catalysts although tertiary amines are more active than secondary amines, which are more active than primary amines. Organometallic materials, especially those of divalent tin (Sn^{++}), are highly active catalysts, and certain combinations of amine and tin catalysts are synergistic, causing a combined rate greater than the sum of the individual rates.

²S. L. Reegen and K. C. Frisch, "Catalysis in Isocyanate Reactions," *Advances in Urethane Science and Technology*, 1 (1971), pp 7-11.

Surfactants

Surface tension regulation is often required to assure efficient foaming of the polymerizing liquid polyurethane mixture. Although several detergent-type or soap materials can be used, one of the most efficient controllers is a silicone fluid. Silicone surfactant technology is well developed and many different types of fluids are available, depending on the polyisocyanate and polyol characteristics. Silicone fluids appear to not only regulate viscosity/surface tension, but to provide gas bubble nucleation sites as well. These fluids are generally used at very low percentages, i.e., approximately 1 percent by weight of the polyol component.

Blowing Agents

A gas source is required to foam polyurethanes. The original polyurethane foams resulted from the release of carbon dioxide into the liquid mass. Isocyanates react with one of the hydrogens of the water molecule in much the same way as they do with those in polyols. Organometallic catalysts typically favor this reaction with water. The reaction, after proceeding through a series of intermediate steps, yields carbon dioxide and a substituted urea. The quantity of carbon dioxide produced depends on the amount of water present on a gram formula equivalent basis.

A favored method of generating gas is to boil an inert solvent such as a halocarbon refrigerant. Most ordinary rigid foam formulations use monofluorotrichloromethane or R11. However, in preblended systems, it has been found that R11 degrades to some degree after a period of storage. This leads to acidic conditions which cause a loss of catalyst activity. Therefore, stabilizers are added to the R11 to inhibit the conversion; the stabilized R11 is known as R11B. R11B boils at about 75°F (24°C) and the exotherm of the polymerization is sufficient to convert the liquid into a gas, thus foaming the polymer. One gram formula weight of R11B (approximately 137 grams) produces 22.4 liters of gas at standard temperature and pressure. Once the foaming action is complete, the R11B does not readily permeate the polymer; if the foam is closed celled (bubbles intact and not interconnected), the R11B will remain in the cells for as long as several years.

Closed cell, low-density foams often shrink as the foam mass dissipates exothermic heat and the temperature drops. This is because the cell walls and interstices are not strong enough to resist the pressure differential created by the contracting gas within the cells.

Stoichiometry

The amount of isocyanate and polyol used in making polyurethane should provide essentially equal numbers of reactive sites. Each -N=C=O group and each OH group counts as a reaction equivalent. The gram formula weight of the isocyanate divided by the number of isocyanate groups gives the equivalent weight of the compound. The same idea applies to the polyol. Equivalent weight or functionality quantities (the average number of reaction sites per molecule) allow direct calculation of the stoichiometric amounts of each of the constituents of the reaction system.

Isocyanates

For several years, toluene di-isocyanate (TDI) was the principal isocyanate used in making polyurethane foams. Because of its low molecular weight, TDI's vapor pressure is relatively high at ordinary temperatures. Like all isocyanates, TDI is toxic and exposure to its vapor can cause respiratory ailments. Today, TDI is used mostly in production plants; isocyanates with higher molecular weights have been developed to reduce vapor pressure and health hazards. These higher molecular weight materials are known empirically as polymeric isocyanates. Rigid polyurethane foams used for spray-on insulation and similar applications rely on polymethylene polyphenylisocyanate (PPI), which has a very low vapor pressure, a functionality of approximately 2.7, and an equivalent weight of 48.9.

Polyols

The type of polyols used with isocyanates will determine the properties of the final polymer, since the number and location of the OH groups in a molecule affect the reactivity of the polyol. Several other factors can affect polymer characteristics. For instance, polyols made with molecule OH groups which are built-up reaction products of organic acids and excess, multi-functional alcohols create polyester polyols. Polyols made by building up larger molecules by either ethoxylation or propoxylation give polyester polyols. Other atoms may be "built" into the polyol molecule for special purposes; for example, halogens may be included to provide flame-retardancy, or amine-containing polyols can be used to insure that a certain autocatalytic function is present.

Polyols have a wide range of molecular weights and functionalities. The equivalent weights of polyols are calculated in the same way as isocyanates; i.e., molecular weight divided by functionality. If the polyol's molecular weight is unknown, as is the case with many

manufactured polyols, the polyol hydroxyl number* may be converted to equivalency by dividing the OH number into 56,100. Formulation requirements are then determined based on the polyol equivalent weight.

Most polyols are of low toxicity and exposure is normally limited to skin contact. Reasonable care should be exercised when handling polyols, since repeated exposure to certain polyols can cause an allergic sensitivity to develop.

Exotherm

The reaction of the isocyanate and polyol to form the urethane linkage is always accompanied by a release of heat. The amount of heat generated is based on the number of urethane linkages formed. Slow reacting formulations generally can dissipate heat as it forms, resulting in low internal peak temperatures. However, highly reactive formulations generate heat much faster than it can be dissipated, resulting in very high peak temperatures. High peak temperatures make foam production particularly difficult, since polyurethane foams are usually excellent thermal insulators. For example, if a highly reactive formulation produces large masses of foam with thick cross sections, the exotherm thermal energy will be held within the mass. Unless this energy is controlled somehow, it can cause decomposition (charring or rapid oxidation) of the polymer.

Formulation

The isocyanate selected for use in the Rapidly Deployable Foam System (RDFS) was the PPI type.³ This isocyanate, which has an equivalent weight of 48.9, is characterized by high reactivity, low freezing temperature, and low vapor pressure.

The polyols selected for the RDFS were amine based⁴ and ranged in hydroxyl number from 220 to 530. The amine-based polyols were autocatalytic and required comparatively little additional catalyst. This characteristic tends to improve storage stability when the polyol is blended with other materials.

Catalysts considered for formulation were both amine and organometallic. Catalysts were selected for

*Some manufacturers use other methods of stating polyol reaction site number, but the hydroxyl number is the most common.

³Mondur MR®, a product of Baychem Corp., Pittsburgh, PA.

⁴Thanol® R350X and R650®, products of Jefferson Chemical Corp., Houston, TX.

long-term stability in preblends, as well as for catalytic activity. The amine catalyst giving the best overall performance was 1,4-Diazabicyclo (2,2,2)-Octane (or Triethylenediamine).⁵ The unique cage structure of this compound combines the tertiary amine with the highly exposed amine nitrogens. A 33 percent solution of the catalyst in dipropylene glycol was used; the solution is stable and is convenient to measure and to disperse in the polyol. The organometallic catalyst selected⁶ was an adduct that displayed both high initial reactivity and good reactivity retention in polyol preblends. (Generally, organometallic catalysts begin reactions at lower temperatures and the exotherm helps stimulate amine catalyst activity.)

The blowing agent selected was a type of monofluorotrichloromethane, R11B,⁷ designed for stability in preblends. R11B served as both a blowing agent and a viscosity reducer in the polyol preblend.

Both silicone and organic-based surfactants were evaluated, and two types of silicone oils were selected. One type promoted small, closed cell foam⁸ and the other caused a relatively open celled structure.⁹ (The appendix lists manufacturers of the various materials used in the study.)

Initial formulations were made and tested to balance the desired foaming rate, foam density, and cell structure. These formulations were evaluated by preparing two component preblends and charging to pressure tanks; tank regulated pressure was provided by dry nitrogen from a cylinder. The two components were mixed with a commercially available foam spray gun. This allowed small quantities of foam to be made quickly so that properties such as rise time, density, and exotherm could be easily evaluated.

The reaction (rise) time obtained in preliminary studies was approximately 8 seconds. The foam density was measured (uncorrected for air buoyancy) in cubes cut from the cured foam; it ranged from 1.0 to 1.15 lb/cu ft (16 to 18 kg/m³). Initial temperature peaks of up to approximately 335°F (168°C) were noted in

the small (less than 1 cu ft [.028 m³]) foam masses. Foam shrinkage after cool-down was noted in some formulations.

The formulation giving the best initial performance was Polyol Preblend B Component and Isocyanate Preblend A Component (Table 1). This formulation was based on a stoichiometry relationship in which

$$\left[\left(\frac{\text{Iso index}}{100} \right) (\text{Iso eq wt}) \right] \cdot \left(\frac{100}{\text{polyol eq wt}} \right) = \text{g of iso per 100 g of polyol}$$

[Eq 2]

The addition of other materials that react with the isocyanate, e.g., other polyols and water, can be accomplished by summing (within the third term) each of the parts used, and dividing by its respective equivalent weight.

Eq 2 illustrates how the amount of polyol and isocyanate can be directly determined. The other constituents are based on nonreaction criteria; i.e., the amount of surfactant is quite low, about 1 to 2 percent by weight of the polyol, and the catalyst amounts are adjusted by experimentation. The density of the resulting foam is approximated by estimating the R11B required to generate a given volume of gas. R11B gives about 0.8 cu ft (.02 m³) of gas per gram formula weight (i.e., 137 grams). From this relation, the foam density can be determined. For example, if 2 lb/cu ft (32 kg/m³) of foam is required, it is necessary to have approximately 1.25 gram formulas of R11B in the mix, i.e., (.8) × 1.25 = 1 cu ft (28 l). Actual density must be refined by density measurements; the R11B must be adjusted, as required, since some gas usually escapes and does not expand the foam. The foam can also "set" so rapidly that the gas cannot fully expand.

Table 1 lists the percentage of each formulation constituent required for each preblend. The formulation described in Table 1 was calculated in this way to facilitate subsequent equal volume (weight) mixing. For example, volume weight balance was achieved by placing part of the R11B into the polyol and part into the isocyanate. The R11B reduced the viscosity of the polyol from approximately 10,000 centipoises (cps) at room temperature to less than 200 cps. The isocyanate viscosity was reduced from approximately 300 cps to approximately 100 cps.

⁵ Dabco®, Air Products, Allentown, PA.

⁶ Fomrez® UL-22, Witco Chemical, Chicago, IL.

⁷ Freon® 11B, Dupont, Wilmington, DE.

⁸ L-5420®, Union Carbide Corporation, New York, NY.

⁹ Y6690®, Union Carbide Corporation, New York, NY.

Table 1
First Formulation

Polyol Preblend B Component

Constituents	% Required for Preblend
Polyol (amine based) OH No. 530	58.0
Silicone surfactant (nonhydrolyzable, reactive)	0.2
Amine catalyst (1, 4-Diazabicyclo [2, 2, 2]-Octane, 33% solution in dipropylene glycol)	2.0
Organometallic catalyst	0.4
Blowing agent, R11B	39.7

Isocyanate Preblend A Component

Constituents	% Required for Preblend
Polymeric isocyanate (formula weight 132, functionality 2.7)	81.0
Blowing agent, R11B	19.0

The rise time of the formulation was determined by dispensing material from pressure tanks through a foam spray gun at a rate of approximately 7.6 lb/min (.058 kg/s). Two-second-long mix/dispense periods yielded foam that had a rise time of approximately 8 seconds. The materials were then heated from 70 to 110°F (21 to 43°C), resulting in a decreased rise time, i.e., approximately 5 seconds. Density measurements of the foams showed a density of 1.1 cu ft (.03 m³) (uncorrected).

The polyols were evaluated with various isocyanate indices (from 0.8 to 1.2). OH numbers of the polyols ranged from 220 to 530. The lower OH numbers gave more resilient polymers, while the higher OH numbers gave more rigidity. Since the eventual purpose of the foam was to absorb shock load energy, the more rigid foams were selected for further study. (Theoretically, more rigid polymers will crush without rebounding excessively, therefore minimizing secondary impacts.)

Internal temperatures (exotherm effects) were measured and peak temperatures of 325°F (163°C) or less were observed. The heat distortion temperature of the foam was more than 350°F (180°C);* this temperature

*Data from Jefferson Chemical Co.

represents the point at which thermal decomposition generally begins. The internal temperature was controlled by the large amount of R11B volatilized during the foaming. Even in large cross section masses (more than 2 ft [0.6m]), the exotherm did not cause significant problems. However, the peak temperature generally occurred as much as 2 hours after foam generation, depending on the cross section of the foam mass and reaction rate.

The foam produced by the selected formulation was hand mixed in small batches with a tongue depressor. It was determined that mixing could cause a substantial variation in cell size. Poor or inadequate mixing resulted in foam with coarse, unevenly sized cells, while good mixing resulted in uniformly fine cells. The latter cell size is desirable since mechanical properties of the foam are related to cell size and homogeneity.

The rise time, density, and appearance of the foam made from the selected formulation appeared to be excellent and the study of other basic formulations was discontinued.

3 DISPENSING SYSTEM

System Description

The anticipated use of the foam as a deployable shock attenuation system required that the dispensing system be comprised of pressurized tanks, suitable valve controls, and have a mixing capability. The entire system would be carried aboard an aircraft and would be activated either by local or remote command. It was necessary, therefore, that an inexpensive, simple to operate, and reliable system be designed.

Pressure cylinders with a capacity of 424 cu in. (.007 m³) were selected since they were approximately the correct volume and rated the internal pressure necessary to discharge the foam ingredients. These cylinders were commercially available with a built-in relief valve to provide safety.¹⁰ The tanks were welded drawn steel halves rated at 270 psi (1.86 MN/m²) with a 315 psi (2.17 MN/m²) relief valve.

Each of the tanks could contain approximately 20 lb (9.1 kg) of the preblended formulation. However, it was not practical to completely fill the tanks, since

¹⁰Products of AMTROL Inc., West Warwick, R.I.

the pressurized gas required room to expand to expel the tank contents and to maintain adequate pressure and a good flow velocity.

It was determined that 30 cu ft (.85 m³) of foam had to be produced. The density need was estimated to be 1 lb/cu ft (16 kg/m³). Therefore, the tanks had to provide room for enough chemicals to produce 30 lb (13.6 kg) of mix; i.e., 15 lb (6.8 kg) of mix had to be produced by each tank. The chemicals would thus occupy about 75 percent of the volume of each tank or approximately 320 cu in. (.005 m³). The remaining volume, pressurized to 250 psi (1.7 MN/m²), would expand to 424 cu in. (.007 m³) by Boyle's law, providing a residual pressure of approximately 60 psi (0.41 MN/m²):

$$V_1 P_1 = V_2 P_2 \quad [\text{Eq 3}]$$

$$(100)(250) = (420)(60)$$

This pressure was determined to be adequate to assure the necessary flow of materials from the tank.

The required delivery time (i.e., time required for material to flow from the tank, through the mixer, and into the container and begin foaming) was less than 2.5 seconds. This meant that at least 6 lb/s (2.7 kg/s) must flow through the plumbing from each tank, through the valved lines, through the mixer, and out. This rate is an average for the dispensing time, and requires approximately 40 gpm from each tank. Calculation of the fluid flow (including friction factors) through a standard 3/4-in. (19-mm) pipe* under the maximum and minimum pressure conditions showed this pipe size to be adequate. Fluid velocity from each tank was calculated to range from a high of 28 ft/s (8.5 m/sec) to a low of 6 ft/s (1.9 m/s). This velocity range appeared adequate for mixing purposes.

The commercial cylinders were modified by drilling a 0.82-in. (20.8-mm)-diameter hole in the end of the tank opposite the relief valve. A 2-in. (51-mm)-long nipple of standard 3/4-in. (19-mm) schedule 40 steel pipe (threaded on one end) was welded to the tank around the drilled opening (Figure 1). Necessary elbows, couplings, and pipe were attached to this nipple and were closed by a valve (Figure 2). The outflow side of the valve to the mixer was plumbed with polyvinyl chloride (PVC) 3/4-in. (19-mm) schedule 40 plastic pipe (Figure 3).

*Area = .52 sq in. (3.4 mm²)

The valves were solenoid-operated, pilot-assisted, full-area opening types* (Figures 4 and 5). Seals and gaskets in the valves were refrigerant resistant so they would not deteriorate when in contact with the preblended components of the system. The valve pilot piston holes were modified to accommodate a fluid viscosity of 200 cps. This was considered the maximum viscosity, since it was at the room temperature condition; increasing the temperature of the system to 110°F (43°C) reduced the viscosity.

Mixer Design

The required flow rate of more than 700 lb/min (5.3 kg/s) required that a new type of foam chemical mixer be developed. Further, the mixer had to be statically operating and inexpensive enough to justify single use. Commercially available mixers capable of handling the required capacity were either too large or too expensive. For example, helical flow path mixers require a very large helix and housing for rates of 100 lb/min (.76 kg/s) and would be prohibitively expensive for single use applications. The other two kinds of mixers available were the types used in foam spray guns; one used a spinning, slotted mixing impeller disc driven by dual stream fluid flow and the other brought the two liquids into a cylindrical chamber such that they mixed as they flowed toward the outlet orifice. Both of these mixers are made of metal and have capacities of only up to approximately 50 lb/min (3.8 kg/s).

A new mixer was designed to handle the required capacity. The mixing principle was based on mutual, highly turbulent impingement of the two liquid components at a fairly high velocity. Mixing by this method would be fast, easy to regulate, and simple. Turbulent flow was easily introduced into a stream of material by putting partial obstructions in the flow path; i.e., perforated steel plates were placed in the outlet lines of each of the A and B tanks. As expected, the flow rate or output of each of the tanks was related to the amount of open area in the plate and to the pressure. Little difference was found between A and B, since they were of similar viscosity. Tests showed that the selected pipe size was adequate even when approximately 50 percent of its area was blocked by the perforated plate.

*Two valve designs were evaluated. One was Model #230RA12P6-M with Coil AMG from Sporlan Valve Co., St. Louis, MO. The other was Model Q4-3T from J. D. Gould Co., Indianapolis, IN.



a.



b.

Figure 1. Hole cut in end of cylinder (a); pipe welded to tank (b).



Figure 2. Plumbing.

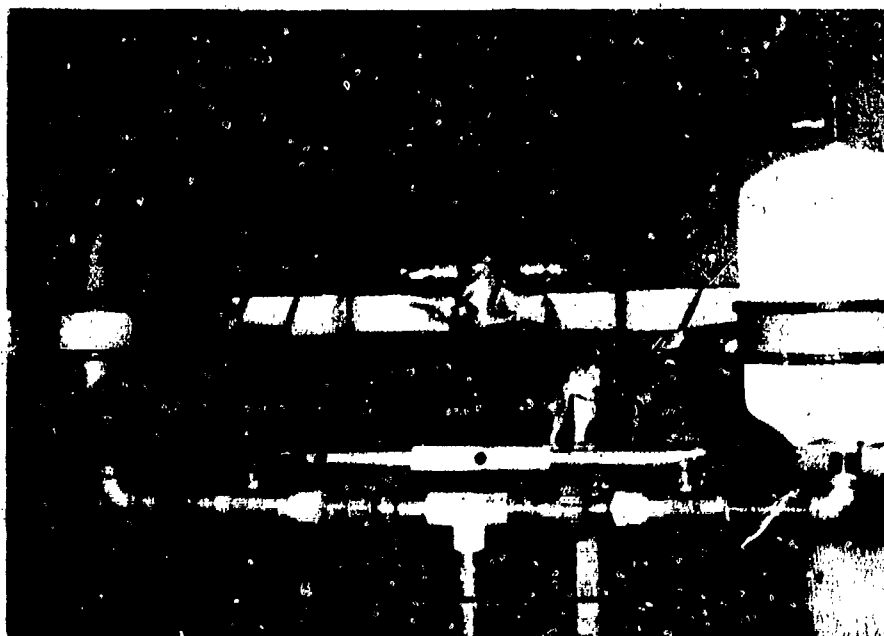


Figure 3. Plastic pipe.



Figure 4. Sporlan valve



Figure 5. Gould valve.

The perforated plate which gave the best flow and turbulence was 16 gauge steel with 0.1875-in. (4.76-mm) diameter holes on 0.25-in. (6.35-mm) center to center spacing. These plates allowed 6.75 lb/s (3.1 kg/s) flow at an initial internal tank pressure of 250 psig (1.72 MN/m²) and at a room temperature of 70°F (21°C). Flow at 110°C was expected to be more, but was not measured because of R11B boil off.

The new mixer design used one of the perforated plates in each of the two opposing sides of a ¾-in. (19-mm) schedule 40 PVC pipe tee. The plates fit within the tee against the pipe stop shoulder and were secured by plastic pipe sections which were solvent welded into the tee. A plastic pipe union half was affixed to the mixer inlet pipe. The other half of the union was integral to the plastic pipe on the outlet side of the valve of each tank. A 6-in. (152.4-mm) PVC pipe section was cemented into the other tee opening and served as an outlet pipe for the mixer. Figure 6 details the construction feature of the mixer.

Mixer Testing

The dispenser system described above was set up with the tanks, lines, valves, and mixer. The flow path distance from the tank to the center of the mixing chamber was 18 in. (45 cm). An additional 6 to 8 in.

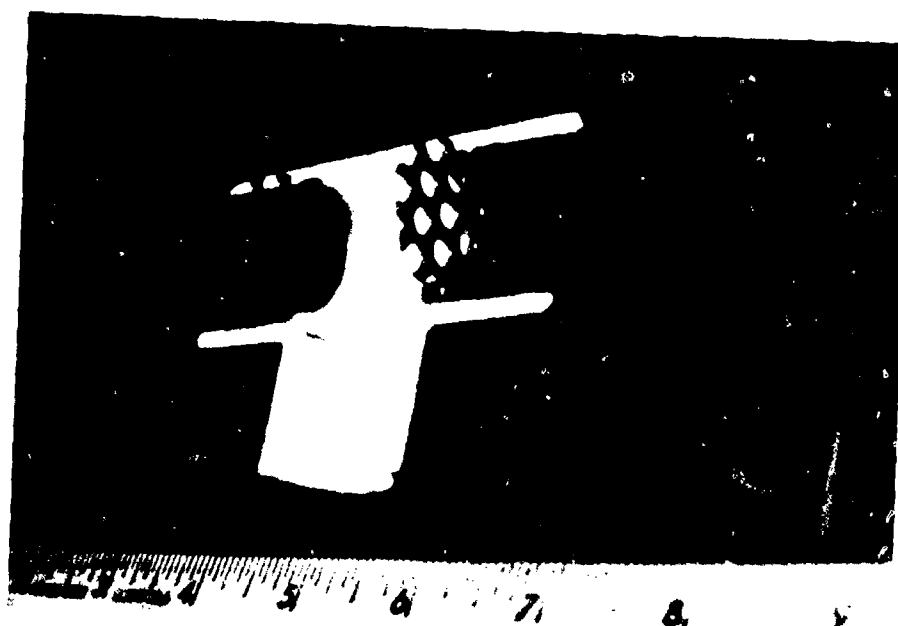
(152 to 203 mm) of water outlet pipe completed the system. Figure 7 shows the entire system on a support stand.

A and B preblends were introduced into their respective tanks through the ¾-in. (19-mm) pipe. Immediately after placing the material into the tank, the plumbing from the tank to the plastic pipe union (including the valve) was securely installed. Each tank was mounted on the support stand and the distance between tanks adjusted to fit the mixer unions into the tank plumbing. The tanks were pressurized with dry nitrogen to a regulated internal pressure of 250 psi (1.72 MN/m²). The nitrogen was injected via the tank relief valve. The relief valve was closed at equilibrium pressure.

The initial test setups included solenoid-operated valves that were fed electrical current by a single line switch. This assured that they would operate at essentially the same time. The solenoid valves performed well for the first few tests; however, as tests continued, the pilot piston area of the valve in the A (isocyanate) side began sticking, and prevented the valve from opening. This resulted in system malfunction. Full opening manual ball valves were used for subsequent tests with excellent results. An arm joining the two valve operating handles assured simultaneous opening (Figure 8).



a.



b.

Figure 6. Perforated steel disc (a) and cutaway view of mixer (b).



Figure 7. Component tanks on test stand.

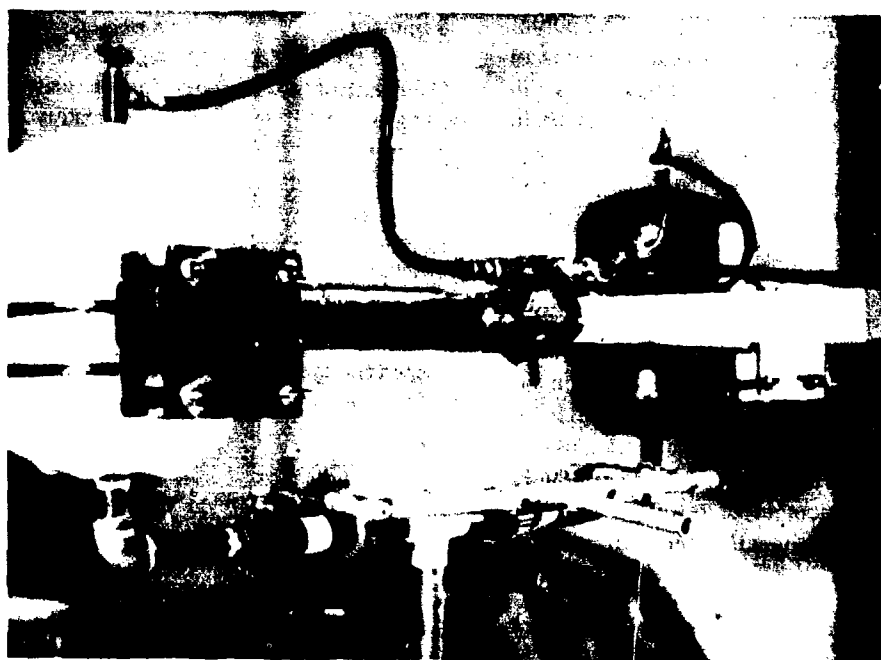


Figure 8. Operating arm for manual valves.

The foam produced by the mixer was excellent. Except for a minor amount of off-proportion material at the beginning and end of the dispensing period, the foam was uniformly fine celled and was a uniform color. (Foam was made by ejecting mixed material downward into a polyethylene film bag. Thus, it was possible to see the dispensed material from the time it exited the mixer assembly. Rise time could also be observed.)

The rise time of the foam when the materials were at room temperature was between 5 and 7 seconds. The addition of more catalyst did little to increase the rate, so the temperature of the material was increased as had been done in the earlier formulation work. The tanks were filled with material and the assembly completed as previously described, except the tanks were not pressurized. The entire assembly was placed in an air circulating oven set at 110°F (43°C) for a minimum of 2 hours to allow the foam materials to reach equilibrium temperature. The tanks were then pressurized and tests begun. The elevated temperature provided foam with a dispense time of approximately 2 seconds and a rise time of approximately 5 seconds. However, the precise duration of each event was very difficult to assess accurately, because of the rapidity of the ejection and foaming processes.

Several minor formulation variations were evaluated with the dispensing system. A formulation with a polyol having a hydroxyl number of 450 (the formulation in Table 1 had a hydroxyl number of 530) gave a semi-rigid foam (Table 2). This formulation was designed to produce a low-density, open-celled foam. It had an isocyanate index of 0.9. A and B preblends were mixed at a ratio of 1:1.

The composition described in Table 2 was loaded into the dispensing system, heated to the test temperature, pressurized to 250 psig (1.72 MN/m²), and mixed/discharged into a plastic bag. The resulting foam appeared acceptable, but approximately 2 hours after the foam was made, it started smoking and caught fire spontaneously; the addition of water to the formulation had increased the number of reactions and thus the exotherm and consequently the temperature.

Two more batches of foam were made and in each case the internal temperature exceeded 360°F (182°C) within 2 hours. It was concluded that large-section foam masses would not tolerate the heat.

Table 2
Second Formulation

Polyol Preblend B Component

Constituents	% Required for Preblend
Polyol (amine based) OH No. 450	71
Water	13
R11B	11
Surfactant (open cell promoting)	1
Amine catalyst	4
Organometallic catalyst	0.3

Isocyanate Preblend A Component

Constituents	% Required for Preblend
Polymeric isocyanate (formula weight 132, functionality 2.7)	97
R11B	3

A third type of polyol, one with a hydroxyl number of 220, was then evaluated. This polyol is normally used at an isocyanate index of about 0.8 with water in the B preblend and is often used for low-density packaging. However, four attempts to make a stable foam from the dispensing system were unsuccessful. Hand-mixed batches also failed to yield good foam.

Summary

A dispensing system capable of delivering 30 lb (13.6 kg) of mixed foam, low-viscosity chemicals was designed and fabricated from readily available components.

A new mixer capable of mixing in excess of 700 lb/min (5.3 kg/s) was devised. This mixer's size is adaptable to higher or lower quantities, if required.

Three foam formulations were evaluated with the dispensing system. Only one produced desirable foam; its formulation is given in Table 1.

4 VERIFICATION TESTING

Twelve tests were conducted to verify the foam operating time. Thirty-two pounds (14.5 kg) of material, half A and half B preblend, were charged to the cylinders. The A and B preblends were stored in their separate containers. The additional 2 lb (.9 kg) of material

was used since the preliminary tests had indicated that some material always remains on the container internal surfaces and is not discharged. The system was assembled and heated to a constant temperature of 110°F (43°C). Nitrogen gas was then added to each of the tanks to a pressure of 250 psig (1.72 MN/m²). The components were released from the cylinders by simultaneously opening the two line valves. During each test, mixed material was dispensed into a polyethylene film bag so that the discharge and rise time could be observed. The polyethylene film bags were 5-ft high X 6-ft long (1.5-m high X 1.8-m long) when laid flat. They were made of 6-mil (.15-mm) film.

The test results were all essentially the same—a dispensing mixing time of about 2 seconds and a rise time of about 5 seconds were observed in each test (as stated previously, it was extremely difficult to establish precisely the termination of each of these steps).

Two problems were identified. First, the plastic film bag had a tendency to rupture when material discharged into it with great force. This happened in two tests. Subsequently, all bags were checked carefully to make sure all seams were secure and that no fold line or crease would be struck directly by the material stream. The bags were also supported on a flat surface at the bottom, and the upper corners were vented to allow air in the bag to escape as it was displaced by expanding foam.

The second problem occurred only once. The perforated disc in the B side of the mixer turned within the mixer until it presented an edge to the incoming stream of material. The result was inadequate mixing which was immediately obvious by observing the appearance of the foam. When the mixer was examined after the test, it was found that the pipe stop shoulder in the tee had a very thin offset (approximately 1/64 in. [0.4 mm]). A modification was made to the mixer, and adequate support for the perforated disc was provided by placing a thin ring of plastic pipe, approximately 1/16 in. (1.6 mm) long, into the tee against the shoulder (Figure 9). This ring was cemented into place; when the disc and supply pipe were installed, the disc was held securely around its edge. No further problems were noted with the mixer.

The mixer appeared to produce the desired volume of foam. The bags were made oversize to essentially allow the foam to rise unrestricted. However, because the foam expanded rapidly, its shape was very irregular and only estimates of volume were made.

The foam was uniform in color and texture, indicating good mixing and mix proportions at various stages of the discharge. The valves were usually closed immediately after the liquid material was discharged. This reduced the effect of the pressurization gas blowing into the rising foam.

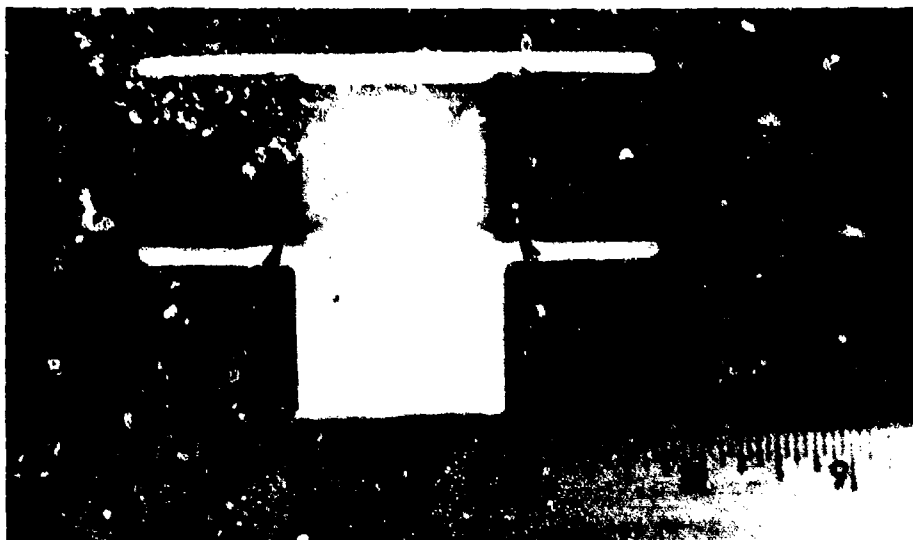


Figure 9. Mixer modification. (Arrows point to rings added to support the plates.)

The manual ball valves were cleaned after each test and reused. Cleanup consisted of rinsing the foam chemicals out of the valve with methylene chloride solvent. The solvent had no effect on the stainless steel ball or polytetrafluorethylene valve seat.

The mixer assembly was also reusable if it was cleaned with methylene chloride within a few minutes after mixing. The mixer was reused only to demonstrate that it could be salvaged, if desired.

Evaluation

A series of preliminary stress/strain tests were performed on the foam in conjunction with the verification tests. Cubes $6 \times 6 \times 6$ in. ($152 \times 152 \times 152$ mm) were cut from the interior of the foam almost as soon as foaming was complete. Tests were run as quickly as possible to determine the early-life strength properties of the foam. The earliest test time was about 2-½ minutes after initiation of the system. The longest test time was 15 minutes after initiation.

Loads were applied at a rate of 20 in./min (.08 m/s), which was the maximum stroke rate of the Tinius-Olsen test machine (Figure 10). The specimens were deformed to about 50 percent of the original height and the machine was reversed. The return stroke rate was also 20 in./min (.08 m/s). The response of the foam by maintaining a load against the load cell was noted by the "unloading" curve on the recording chart. Loading reversal was accompanied by a chart reversal so the unloading could be recorded. Figure 11 shows a typical loading/unloading curve and Figure 12 compares an early test time to a later one. The static loading rate was only about 1/300th of the anticipated dynamic loading rate of a foam impact attenuation system.

The loads were applied on some cubes perpendicular to the rise direction and on some in the parallel direction. Slight differences were noted in strength and stiffness in the two different foam directions. Normally, low-density polyurethane foam is quite anisotropic and typically shows this according to loading direction. The foam produced during the test described above was noticeably anisotropic; i.e., cell elongation was two to four times as long in the direction of rise as it was perpendicular to it. The "direction" of rise was somewhat questionable, however, since the mass formed so rapidly. The direction was both upward and outward, and cell distortion varied at different places within the foam.



Figure 10. Test cube in static test.

Results

The stress at 50 percent deformation was a minimum of 4.4 psi (30.3 N/m^2) at the earliest test time (2-½ minutes) and a maximum of 10 psi (68.9 N/m^2) at the longest (15 minutes) test time. Based on the results, the density and strength relationship of the foam appears to be near the desired levels. Dynamic testing ordinarily shows an increase in strength and modulus over static values.

Summary

The verification tests demonstrated that the dispensing, mixing, and formulation of the foam were operating within the observational error of the objectives of the study. A slight modification in the mixer design was required to increase the system's reliability. This modification was made without significantly adding to the cost of the mixer, complicating its construction, or altering its performance.

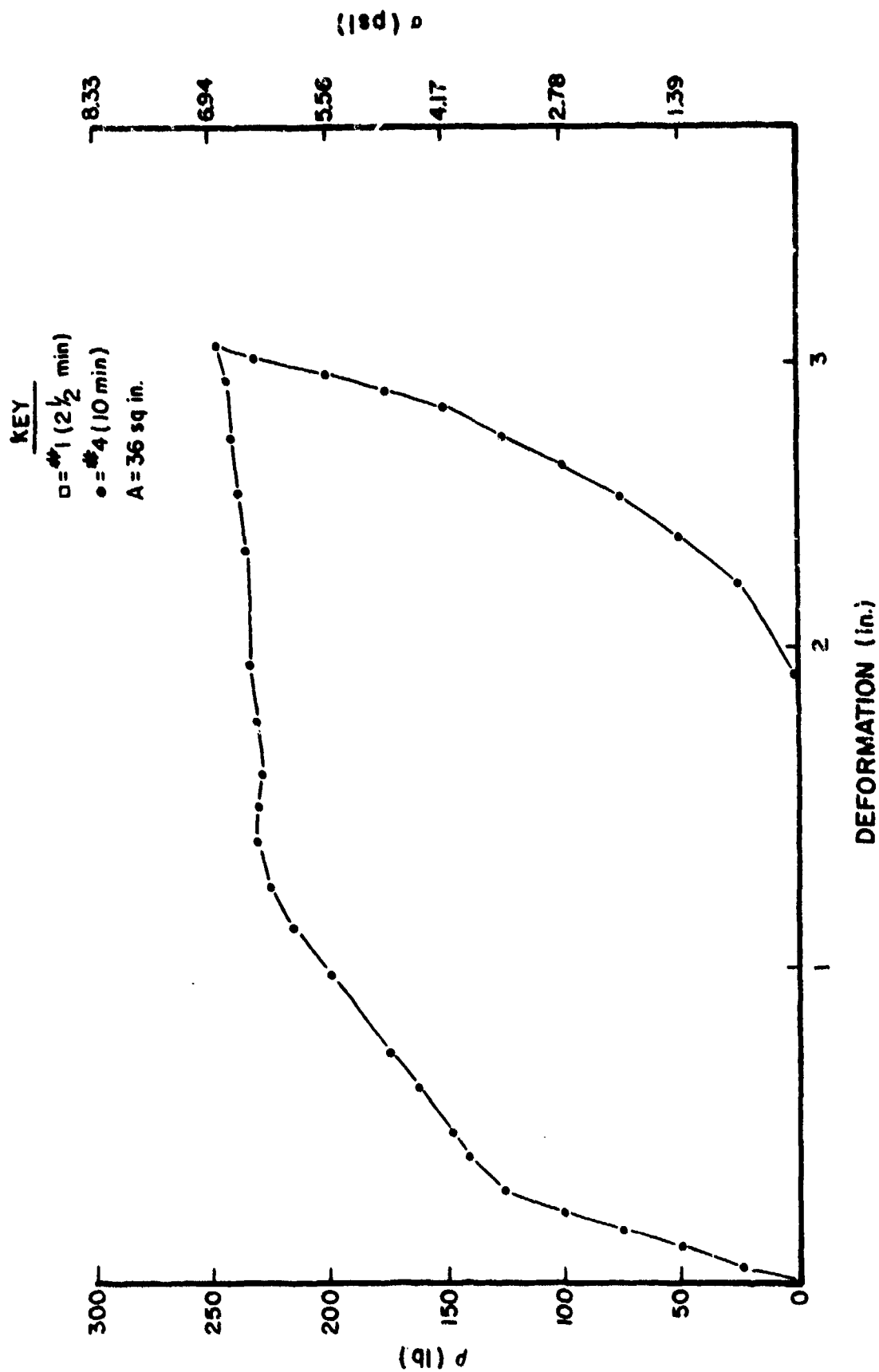


Figure 11. Deformation curve.

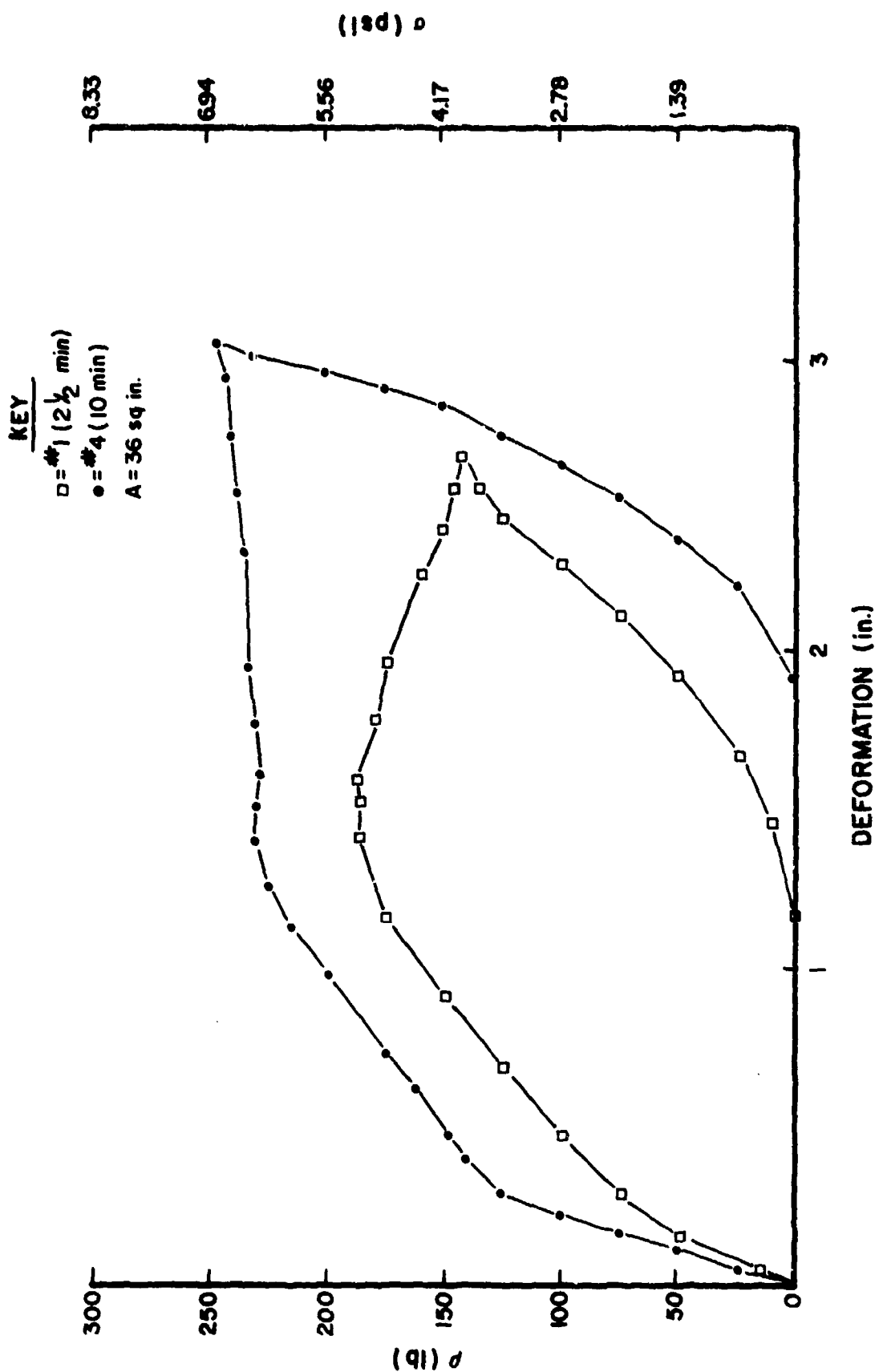


Figure 12. Comparison of deformation curves.

Tests conducted on foam specimens taken within minutes after system initiation showed the load-deformation characteristics of the foam under static loading conditions to be very near the values required under dynamic loading conditions.

5 FOAM DEPLOYABILITY

Shapes

To assess the deployability of the foam into various geometric shapes, five different shapes were selected for testing:

1. A sphere approximately 4 ft, 3 in. (1.3 m) in diameter.
2. A rectangle 1 × 6 × 5 ft (0.3 × 1.8 × 1.5 m).
3. A cylinder 3 ft (0.9 m) in diameter by 4 ft, 5 in. (1.36 m) long.
4. A cylinder 2 ft (0.61 m) in diameter by 9 ft, 6 in. (2.89 m) long.
5. A cylinder 1 ft (0.3 m) in diameter by 38 ft, 2 in. (11.6 m) long.

All shapes listed above had a volume of 30 cu ft (0.85 m³). The deployability study centered on determining the uniformity of fill, thermal gradients, and shape attainment of the selected shapes.

Fabric Forms

The fabric forms were made of a coated ripstop nylon, which weighed 2.2 oz/sq yd (60 g/m²) including a porosity-reducing polyurethane coating. A pattern was devised for the sphere gores; the other shapes did not require patterns. The sphere pattern was designed to give eight gores plus a seam allowance. The sewn forms were nonporous, and allowed the shape to be examined by inflating it with air from a shop vacuum cleaner outlet port. The fabric form shapes were very close to the specified dimensions.

Testing

Sphere

Sixteen pounds (7.3 kg) of each preblend was placed into its respective cylinder and the dispenser system as-

sembled. Each cylinder was heated to 110°F (43°C) and pressurized with nitrogen to 250 psig (1.72 MN/m²). The outlet pipe of the mixer was inserted through a slit in the fabric form, and the fabric was taped to the outlet pipe with 2-in. (51-mm) wide cloth duct tape. The mixing/dispensing process was initiated by opening both manual valves at the same time. Dispensing required approximately 2 seconds and foam rise was complete approximately 5 seconds after initiation. The fabric form was filled to only about 80 percent of its volume, and found to weigh 24.5 lb (11.1 kg). Thirty pounds (7.3 kg) of material was actually expelled from the system; thus, the weight of the foam was approximately 83 percent of the theoretical weight. This weight comparison agreed with the approximate volume of foam (at 1 lb/cu ft [16 kg/m³]) in the sphere. The expected vs actual amount of foam was considered to be caused by R11B loss (the blowing agent) resulting from the use of the open-celled, foam-promoting silicone surfactant.

The combined weight of the A and B preblend was increased to 38 lb (17.3 kg). While the cylinder capacity was adequate for this amount of material, the head space (volume) left for pressurization gas was reduced to the degree that pressurizing to the operating capability of the cylinder resulted in inadequate pressure as gas expansion discharged the contents. A ballast pressure tank was used to maintain the pressure at an acceptable level (Figure 13). This tank was another 424 cu in. (.007 m³) cylinder that had not been modified by welding on an outlet pipe. The tank was connected by pressure hoses and quick disconnects via a tee to the two material cylinders. Pressurization of the system was performed as before, except the ballast tank was pressurized and the relief valve closed. The hose was then disconnected from the nitrogen cylinder/regulator and connected to the tee connecting the lines to the material tanks. The valve on the ballast tank was then opened, followed by the small valves on the material cylinders.

This new arrangement was evaluated in another sphere form. This time, the form essentially filled completely. The shape was not quite a sphere, however. This was attributed to the effect of the weight of the foam and the fact that the equatorial portion of the form filled and expanded to greater than the nominal radius of the sphere. The result was an increase of approximately 4 in. (102 mm) in the radius; this caused the shape to become more ovate, with the short axis passing through the polar areas of the shape.



Figure 13. Ballast pressure tank.

A third sphere was made using the same material quantities and procedures as the second. The results were essentially identical.

It was noted that the operating time of the foam-generating system appeared to be unaltered by the modification and increased output volume capability. The approximately 25 percent increase in the amount of material dispensed was offset by the higher average pressure during delivery. The original system went from 250 psig (1.72 MN/m^2) to approximately 60 psig (0.41 MN/m^2) when discharging the materials. The modified system went from the same upper pressure to only approximately 85 psig (0.58 MN/m^2). Thus, the operating time of the system stayed about the same, i.e., 2 seconds dispensing/mixing and 5 seconds rise.

Rectangle

The modified dispensing system was used. The mixer outlet pipe was altered to laterally display the expelled material. This alteration consisted of attaching a splatter plate to the end of the pipe (Figure 14). The splatter plate was made of 20 gauge sheet metal cut into a disc 1 in. (25.4 mm) in diameter with three 1-in. (25.4-mm)-long by $\frac{1}{4}$ -in. (6-mm)-wide strips attached at 120° points around the circumference. A $\frac{1}{8}$ -in. (3-mm)-diameter hole was drilled near the distal end

of each of the three strips. The strips were then bent at the edge of the circle until their direction was perpendicular to the plane of the disc. The holes in the strip were used as pilot holes for drilling comparable holes in the outlet pipe. The disc was set out $\frac{1}{4}$ in. (6 mm) from the end of the outlet pipe, the holes were drilled in the outlet pipe, and assembly was completed by pop riveting. The gap between the end of the pipe and the plate was equal in area to the area of the pipe and did not cause a significant obstruction of material flow.

Two rectangular mattresses were made. Both essentially filled completely. The location of the strips holding the splatter plate could be recognized by shadows of slightly less foam in areas of the mattress masked by the strips.

The operating time for the rectangle was approximately 5 seconds.

Cylinder (3 ft [0.9 m] in diameter)

The modified dispensing system was used. The outlet tube was altered by installing a $\frac{1}{4}$ -in. (19-mm) PVC plastic tee on the end (Figure 15). This tee was directed toward the ends of the cylinder.



Figure 14. Mixer with splatter plate at outlet.

The first cylinder did not fill completely in the region about the outlet tube. This was because the material had all been directed to the ends of the cylinder.

The second cylinder was made by the same technique, except the outlet tube tee was vented by three 3/8-in. (9.5-mm)-diameter holes (Figure 16). One of these holes was directly across the tee from the outlet tube itself, and the other two were through the center of the tee, perpendicular to the arms of the tee. This venting resulted in a better distribution of the foam and complete filling of the form. The shape was very cylindrical with bulged ends. The operating time was about 5 seconds.

Cylinder (2 ft [0.61 m] in diameter)

The modified dispensing system was used. The outlet tube was altered by installing a vented tee at the end. The principal discharge holes in the tee were aligned

with the axis of the form. Secondary vent holes were the same as those described for the larger cylindrical form.

Two cylinders of this diameter were made. The outlet tube from the mixer was inserted into the form at midlength. The form was held up by duct tape around the outlet tube. Part of the form was supported by taping it to the plumbing from each of the material cylinders. The remainder was suspended from the dispensing system test support.

The filling of the cylinders was excellent. The shape was uniformly cylindrical and the ends were slightly bulged.

The operating time was about 5 seconds.

Cylinder (1 ft [0.3 m] in diameter)

The modified dispensing system was used. The outlet tube was altered by placing a plastic pipe tee on it. This tee was directed with the openings along the axis of the cylinder to be filled.

The first cylinder to be attempted was fabricated from polyethylene film so the foam could be observed dispensing and rising. The outlet tube was inserted midlength to the cylinder form and the form was rolled-up longitudinally to points near the outlet tube. The form was supported by taping it to the outlet tube and the material tank plumbing. Tables were set up to help support the cylinder as filling progressed. These tables were approximately 2 ft (0.61 m) below the end of the outlet tube.

The system was initiated and the cylinder was rapidly unrolled by discharging material. Foam material shot approximately 10 ft (3.0 m) toward each end. Foam expansion accounted for another 4 to 5 ft (1.2 to 1.5 m) of axial flow. The overall length of the cylinder filled with foam was 29 ft (8.8 m). The expansion of the foam developed shear flow resistance as it expanded diametrically against the form, preventing the cylinder from filling completely.

A lightweight nylon cylinder was also foamed. This cylinder was gathered back toward the center in accordion pleat fashion so the foam would strike the ends of the form to move it outward. The gathered form was held by a thin paper sleeve and was supported on each end by taping the sleeve and fabric to the plumbing under each material tank. When the test was initiated, each end of the form shot outward approximately 12 ft (3.7 m) and the foam expansion caused the

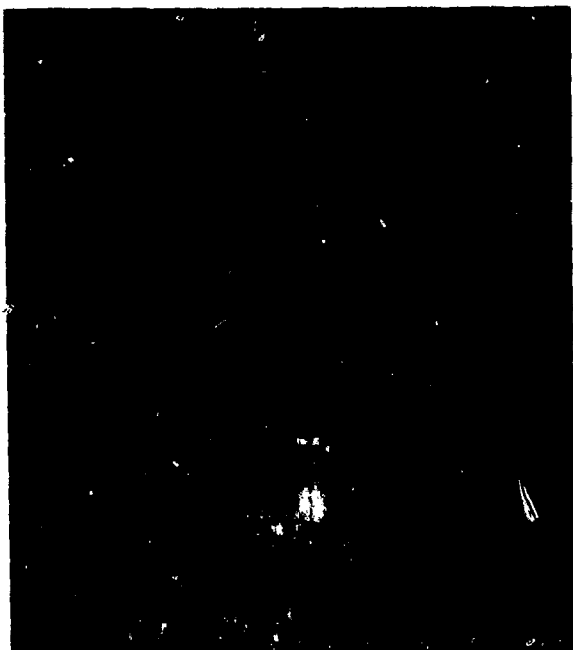


Figure 15. Outlet pipe with tee for directing output.



Figure 16. Outlet pipe for tee vents.

cylinder to "pretzel"; however, the cylinder quickly straightened out. This cylinder filled much better than the plastic film one had, but it still did not fill completely. About 34 ft (10.4 m) of good cylinder resulted.

The third cylinder was a fabric form and was filled in much the same manner as the second. This form was gathered about a sleeve that disengaged itself as the fabric played out. This arrangement worked reasonably well; however, the cylinder still did not fill completely. It was noted that a very even distribution of foam is required, an effect difficult to achieve with this system. The overall length of foam was about 35 ft (10.7m).

The operating time was about 5 seconds.

Results

Fabric forms representing three geometric shapes in five configurations were successfully filled with foam in 5 seconds by the modified foam dispensing system. The mixer outlet tube had to be altered to distribute the foam mixture to allow the forms to fill completely. An increase in the amount of foam mixture had to be made, since actual foam yield was approximately 80 to 85 percent of the theoretical. This deviation from the theoretical volume was caused by loss of the blowing agent (R11B).

Summary

Various simple geometric shapes can be filled by the rapidly deployable foam system within the designed operating time of 5 seconds. Directional distribution of the foam can be accomplished by modifying the outlet pipe. The principal problems associated with making the geometric shapes are foam distribution and foam rise time. It is extremely difficult to distribute the foam material evenly at the given discharge rate, particularly in long slender forms. More complete and uniform filling could be accomplished if it were possible to extend the setting time of the foam to allow better flow characteristics. This is not possible within the constraints of the desired operating time.

6 FOAM STRESS/STRAIN CHARACTERISTICS

Parameters

Based on probable stresses caused by impact loadings, areas impacted, and a nominal strain rate typical of parachute descent velocities, a compressive stress of not less than 5 psi (34.5 kN/m²) 5 seconds after system initiation and not more than 10 psi (79 kN/m²)

600 seconds after initiation were defined as the desired average stress limits at 50 percent deformation of a sample not less than 12 in. (0.3 m) thick at an initial impact velocity of not less than 100 in./s (2.54 m/s).

Experiment Design

The impact energy absorption characteristics of the foam were evaluated by submitting foam samples to a falling weight device at four different time intervals after foam generation. The drop height, velocity, penetration distance, and g force were measured for each test.

Test Fixture

An impact tester was designed and fabricated. The tester used a guided falling weight with a load surface arranged so that it could penetrate the foam mass without being influenced significantly by friction or interference by other surfaces (Figure 17).

The falling weight was 35.5 lb (16.1 kg). It was guided by two 1-in. (25.4-mm)-diameter hardened centerless ground round bars on which two linear "frictionless" bearings ran. The height of the weight was adjustable to allow the travel distance and therefore the velocity at the point of impact to be varied, as required. The falling weight was secured by a manually operated quick release device.

The loading area was 10 sq in. (6451.6 mm²). The edge of the load plate was tapered away from the load surface to reduce side friction. The load plate was attached to a support bar; the diameter of the support bar was smaller than that of the load plate but was long enough to allow full penetration into a foam mass without bringing the cross beam into contact with the foam.

The velocity of the falling weight was measured by interruption of two light beams. These beams used fiber optics that projected beams of light onto a target affixed to the weight. The first beam interrupted by the falling target started an electronic timer; when the target passed the second beam, the timer stopped. The two beams were placed exactly 2 in. (50.8 mm) apart near the point of impact (Figure 18). Several trial drops were made and the drop height was adjusted to compensate for frictional losses. The velocity was measured at 117 in./s (2.97 m/s). This rate met the requirements of the strain rate, i.e., in excess of 100 in./s (2.54 m/s).

An accelerometer was mounted on the falling weight cross beam such that it was axially centered over the

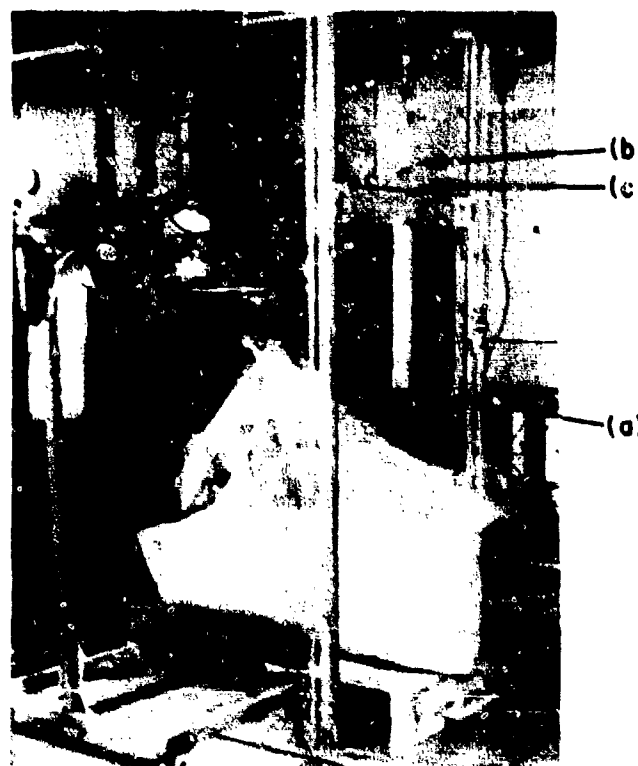


Figure 17. Impact tester; loading plate (a); manual release (b); accelerometer (c).

load center and responsive to vertical motion. This allowed measurement of the g forces resulting from the foam decelerating the falling mass. The accelerometer output signal was amplified and conditioned; the resulting signal was recorded on a storage oscilloscope. A photograph or graph of each drop test was recorded.

A circular potentiometer fitted with a follower arm was used to monitor the movement of the load. The output from the potentiometer was plotted by an X-Y recorder to provide measurements of foam penetration.

Foam Mass Generation

The test fixture operation was initially evaluated by deploying a 30 lb (13.6 kg) batch of foam from the dispenser system into a polyethylene film bag. The system was arranged so that one end of the bag was under the test fixture drop head. This test resulted in

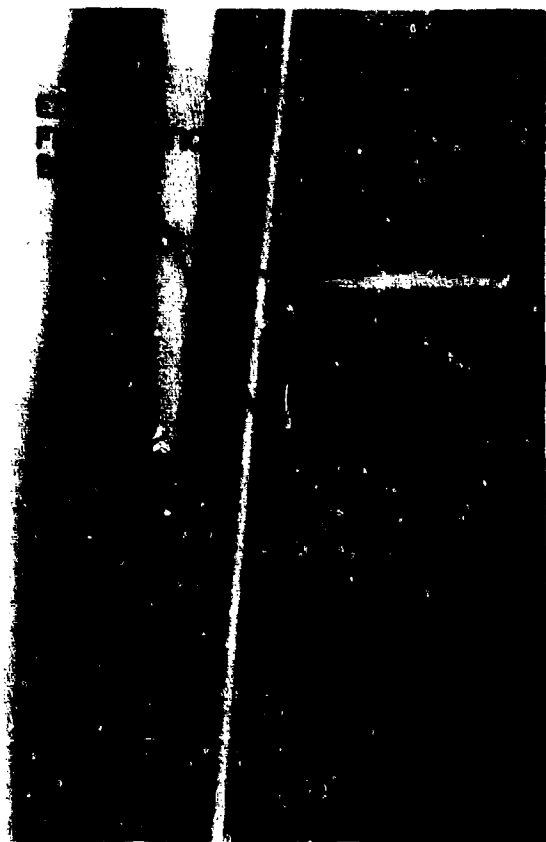


Figure 18. Fiber optic spacing.

a foam mass that was too large for the fixture, and a drop height too small to obtain proper impact velocity.

Subsequent tests used 15 lb (6.82 kg) (total weight) batches of material (50 percent A and 50 percent B); the resulting foam mass was of adequate size.

Arranging the bag (and foam mass) with one end already under the loading device allowed the initial testing to begin within a few seconds of foam initiation. The foam mass was shifted for each of the other tests in each series so that an undisturbed area away from the edge of the foam body could be impacted.

Testing

Tests were conducted at four intervals after foam generation:

1. As quickly as possible. A violent discharge of foam required that it be caught in a closed container (bag). This bag had to be opened and the film peeled back so the load head could impact directly on the foam. The first test took place 10 to 13 seconds after foam initiation.

2. One minute after foam initiation. The bag was moved to a new loading point and the impact test conducted.

3. Five minutes after foam initiation. The bag was turned around end for end and a new loading point used.

4. Ten minutes after foam initiation. The bag was shifted so an untested portion was under the loading head.

These different test intervals were used to try to establish a trend in strength/stiffness change intermediate to the extremes of the test intervals.

Eight test series were run. The eight test results were very similar for each corresponding time frame. The 10-second and 1-minute interval tests resulted in a large penetration distance to foam height ratio. The ratio became smaller for each succeeding test time.

The response of the material was also quite different for the different loading times. Tests conducted at 10-second and 1-minute intervals produced a cylindrical displacement of foam material under the loading head. Tests conducted at 5-minute intervals indicated a tendency for the load to distribute into a cone which projected out into the foam, away from the edge of the loading head. The 10-minute test interval produced a conical load spreading effect with a shear angle of approximately 45° from the edge of the loading plate outward into the foam. The increase in lateral transfer of the load into the foam appeared to contribute to the reduction in penetration distance at 5- and 10-minute test intervals.

Results*

The shear properties of the foam at the 10-second and 1-minute intervals are unknown and no suitable

*The data were not thoroughly analyzed in terms of stress/strain relationships; this section presents approximation methods.

means of determining them could be developed. Normally, the shear strength of low-density foams is found to be somewhere between the tensile and compressive strengths. For practical purposes, the tensile and shear values may be assumed to be nearly the same as the compressive strength. The circular loading platen was selected to minimize the edge (and thus the shear) effect of the load penetration. This approach was satisfactory for the 10-second and 1-minute test intervals, but was not adequate for the tests in which lateral load spreading was evident. Full area loading (to eliminate the effects of shear) could not be performed since the 10-second test interval precluded the preparation of uniform geometric shapes and closely controlled loading areas.

A second loading platen was fabricated and tests were conducted. This platen had an area of 30 sq in. (19 356mm²). The overall weight and velocity of the load at foam impact were maintained at the same values used with the smaller area platen. The penetration of the load into the foam was very similar but less extensive than in the previous tests. Cylindrical punching was prevalent at the 10-second and 1-minute test intervals and the conical spreading was obvious at the 5- and 10-minute test intervals. At each test interval, the degree of penetration was about one-third as great with the larger platen as it had been with the smaller one. The length of the shearing edge of the larger platen was 1.73 times the smaller one, even though its area was three times larger. The amount of shearing in the foam was therefore less per unit of loading area in the larger platen. However, the degree of penetration observed for the two cases seemed to be related only to the ratio of the bearing areas. This suggests that the shear factor may not have been particularly significant.

Comparison of Tables 3 and 4 shows the effect of area vs deformation. The loads and impact velocity were essentially constant in all tests. The variable was loading area and the only obvious resulting variation was in the amount of foam material deformation.

It is interesting to note that the negative acceleration (deceleration) of the load after impact with the foam was fairly consistent in all cases. Since the load weight and impact velocity (momentum) was a constant, a longer time for deceleration of the load to zero velocity would be expected for the greater penetration distance or deformation at the 10-second and 1-minute test intervals. Minor time differences were noted for

Table 3
Average Foam Displacement Relative to
Foam Age (Small Loading Area)

Time After Foam Initiation	Foam Displacement*
12 seconds	15.2 in. (386 mm)
60 seconds	12.1 in. (306 mm)
300 seconds	9.8 in. (250 mm)
600 seconds	6.8 in. (171 mm)

* Weight = 35.5 lb (16.1 kg);
velocity at impact = 117 in./s (2.97 m/s);
loading area = 10 sq in (6452 mm²).

Table 4
Foam Displacement Relative to Foam Age
(Large Loading Area)

Time After Foam Initiation	Foam Displacement*
12 seconds	6 in. (152 mm)
60 seconds	3.5 in. (89 mm)
300 seconds	2.5 in. (64 mm)
600 seconds	1.0 in. (25 mm)

* Weight = 35.5 lb (16.1 kg);
velocity at impact = 117 in./s (2.97 m/s);
loading area = 30 sq in (19 356 mm²).

the tests, but they were not of the magnitude anticipated. Similarly, the much-reduced material deformation by the larger loading area did not significantly reduce the deceleration time for the second test case (Table 5). Photographs of the oscilloscope traces of tests with the small load platen and with the large load platen illustrate the times of deceleration (Figures 19 and 20). There were relatively small differences in peak g values in each of the photographs. This is because the lesser deformation of material during the 5- and 10-minute test intervals did not cause greatly higher g load characteristics. The scale on the photographs is .01s/mm on the X-axis, and .02v/mm on the Y-axis* These results suggest that the energy absorbing capability of the foam did change substantially from the 10-second test interval to the 10-minute test interval in terms of unit volume efficiency; however, the change in total deformation accounted for the uniform amount of energy absorption.

*1v on the Y-axis = 30 g; grid spacing is 10 mm.

Table 5
Raw Displacement Data
(Tests 1 to 6, loading area = 10 sq in. [6452 mm²];
test 7, loading area = 30 sq in. [19 356 mm²])

	Test Number*						
Time After Foam Initiation	1	2	3	4	5	6	7
12 seconds	13.5 in. (343 mm)	17.3 in. (439 mm)	14.9 in. (378 mm)	14.7 in. (373 mm)	15.0 in. (381 mm)	15.7 in. (399 mm)	6 in. (152 mm)
60 seconds	10.6 in. (269 mm)	15.5 in. (394 mm)	12.1 in. (307 mm)	8.8 in. (224 mm)	10.2 in. (259 mm)	15.1 in. (384 mm)	3.5 in. (89 mm)
300 seconds	7.7 in. (196 mm)	12.7 in. (323 mm)	7.9 in. (201 mm)	7.2 in. (183 mm)	9.6 in. (244 mm)	14.0 in. (356 mm)	2.5 in. (64 mm)
600 seconds	5.6 in. (142 mm)	5.6 in. (142 mm)	8.2 in. (208 mm)	5.6 in. (142 mm)	6.4 in. (163 mm)	9.1 in. (231 mm)	1 in. (25.4 mm)

* Weight = 35.5 lb (16.1 kg); velocity at impact = 117 in./s (2.97 m/s).

There was more material restitution (rebound) at the 5- and 10-minute test intervals. The restitution caused the load to bounce more (Figures 19 and 20). Some bouncing did occur at the 10-second and 1-minute test intervals. This was caused principally by two factors. First, the foam material was compressed to a thin wafer (particularly by the smaller platen) of a much higher density material. Second, a reaction through this wafer from the load being passed to the base of the test fixture accounted for the small rebound.

The tests described above indicate that a rigorous solution to the stress/strain characteristics of the foam is not feasible, since the problem has too many undefinable parameters. Attempts at solution using conservation of energy, conservation of momentum, impulse and impact loading were unsuccessful. An approximation of the stress/strain characteristics was made, however, and it was considered sufficient for the purposes of this study.

Considering the material as a cushion and treating it in a very simplistic manner provided some basically logical stress/strain characteristics. A modelling study by Woolam¹¹ provided a method by which a rough approximation of the stress could be determined. This

method uses Newton's first law of motion to define an energy absorbing cushion for a mass M:

$$M\ddot{x} + \int_A \sigma dA = 0 \quad [\text{Eq 4}]$$

where σ is the stress exerted by the energy absorber. In this equation, the material strain is defined as the displacement of the material divided by the initial material thickness. Stress is considered uniform over the cushioned area (A) and the equation is reduced to

$$M\ddot{x} + \sigma A = 0 \quad [\text{Eq 5}]$$

The second derivative of x is acceleration. Solving for the maximum acceleration condition from Table 5 gives a solution for stress:

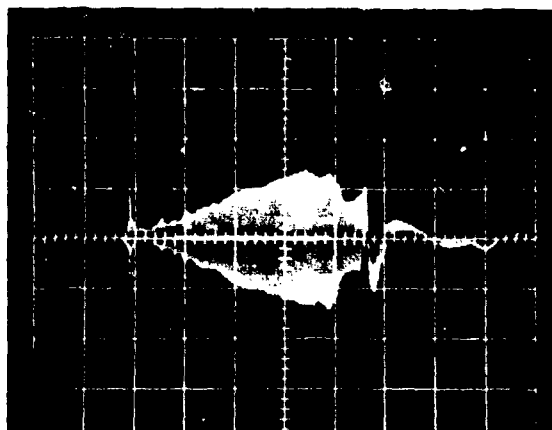
$$\frac{(35.5 \text{ lb})}{g}(7.8) + \sigma(10 \text{ sq in.}) = 0 \quad [\text{Eq 6}]$$

$$\sigma = 27.7 \text{ psi (191.0 kN/m}^2\text{)}$$

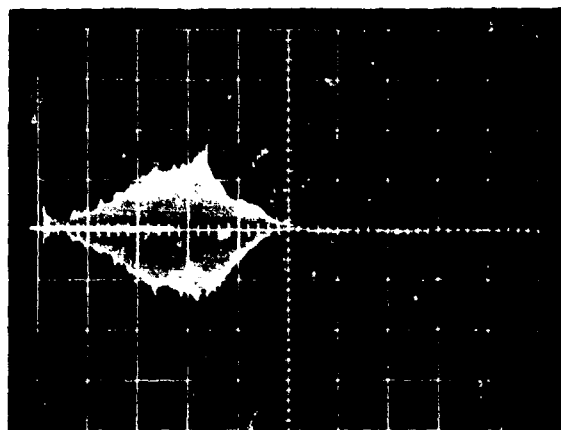
An evaluation of the average measured stress was made during the first 50 percent of strain measured on a sample not less than 12 in. (.3 m) thick at a strain rate of not less than 100 in./s (2.54 m/s). Solution of the same equation gave a stress of 6.9 psi (47.6 kN/m²) at the various test intervals for the 10 sq in. (6452 mm²) loading area and a stress of -10.6 psi (7.31 kN/m²) for the 30 sq in. (19 356 mm²) loading area.

The maximum material deformation occurred at the 10-second test interval. The 1-, 5-, and 10-minute test

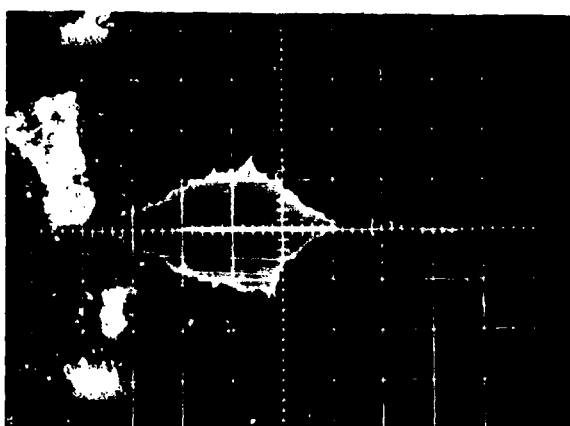
¹¹W. E. Woolam, "A Study of the Dynamics of Low Energy Cushioning Materials Using Scale Models," *Journal of Cellular Plastics*, 4, No. 2 (February 1968), pp 79-83.



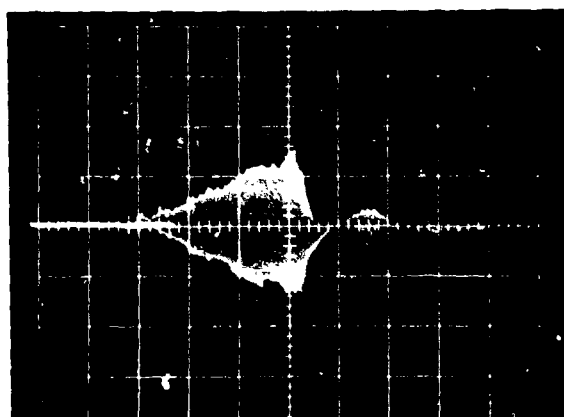
a.



b.



c.



d.

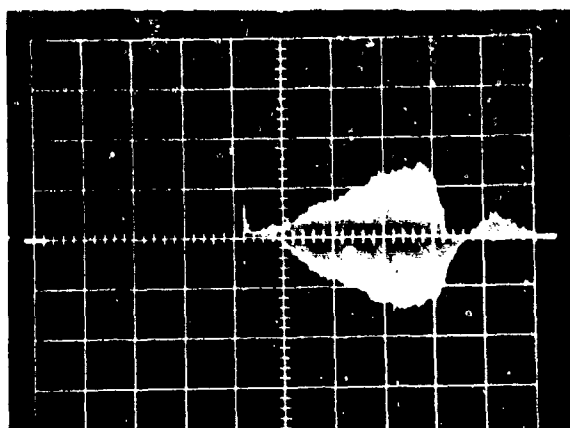
Figure 19. Oscilloscope traces of deceleration for 10 sq in. (6452 mm^2) of loading area 12 (a), 60 (b), 300 (c), and 600 (d) seconds after foam initiation.

intervals produced less displacement. The energy provided by the falling weight was constant at the initiation of material deformation (instant of impact) at all test times. It was therefore concluded that the energy absorbing or dissipation efficiency of the foam was changing significantly as cure progressed.

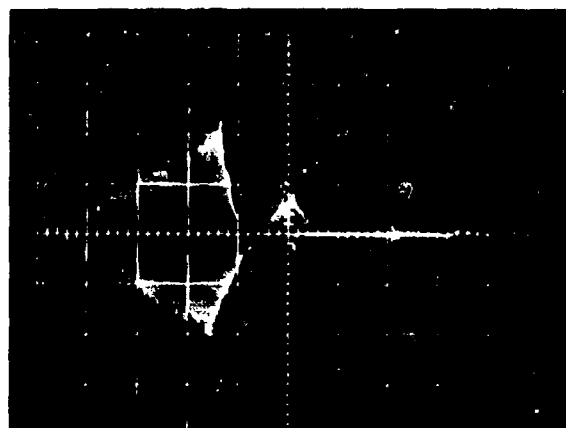
The range of values of stress from the lowest to the highest is considered to be consistent with the parameters required by the proposed RDFS system.

Kurauchi and co-workers¹² investigated the energy absorbing characteristics of rigid polyurethane foams by evaluating the energy absorption of their study materials and correlating it to the "plateau" stress in compression stress/strain curves at low strain rates.

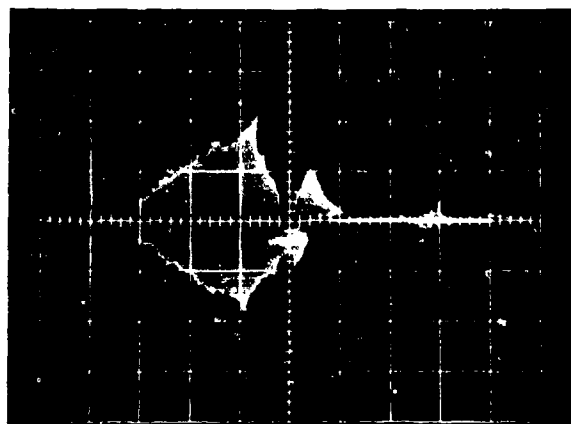
¹²T. Kurauchi, K. Negi, and N. Komatsu, "Energy Absorbing Characteristics of Rigid Urethane Foams," *The Fifteenth Japan Congress on Materials Research—Nonmetallic Materials* (September 1971).



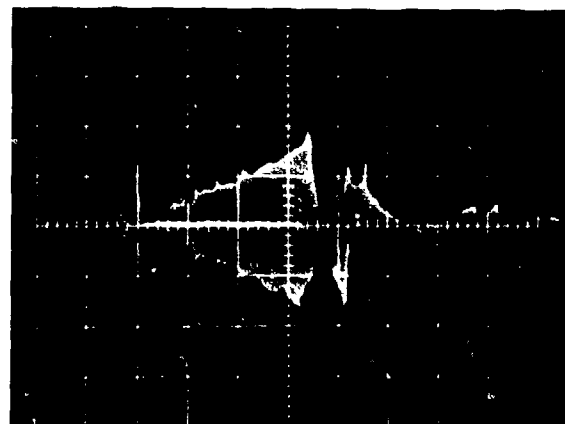
a.



b.



c.



d.

Figure 20. Oscilloscope traces of deceleration for 30 sq in. ($19\,356\text{ mm}^2$) of loading area 12 (a), 60 (b), 300 (c), and 600 (d) seconds after foam initiation.

They found that the plateau stress level was strongly dependent on foam density and increased with increasing density, while a critical strain (strain at the end of the stress plateau) decreased with increasing density. From these relationships, an energy absorbing efficiency was determined by analog computation. This technique revealed that the plateau region of rigid polyurethane foam in compression is close to that of an ideal energy-absorbing material (80 to 90 percent)

and is little affected by density. The critical strain was found to be nearly equal to the rise point of the stress/strain curve at the end of the plateau region.

A plateau energy absorbing rate (I_p) was defined as the energy absorption integrated to critical strain divided by the area under an ideal square wave ($E_{\sigma p}$). Kinetic energy absorption by crushing rigid polyurethane foam was calculated by the equation:

$$1/2 MV^2 = \sigma pSLI_p \quad [\text{Eq 7}]$$

where: M was the weight of the moving body
 V was the velocity at impact
 σp was the plateau stress of the foam
 S was the area of the foam
 L was the thickness of the foam
 I_p was the plateau energy absorbing rate.

The maximum acceleration (G) was assessed as:

$$GM = \sigma pS \quad [\text{Eq 8}]$$

Extension of the maximum energy absorption curve and the plateau energy absorbing rate curves so the density of the foam in the foam impact attenuation system would be included, and calculation of the plateau stress of the foam gave stress levels essentially the same as by the method described by Woolam, i.e., stresses ranging from about 5 to approximately 15 psi (104 to approximately 34.6 kN/m²) for the various cure stages of the foam at the time of the test.

However, these theoretically calculated g levels disagree with the g values recorded in the experiments. Calculated values were approximately 3 to 8 g. The deceleration g levels obtained in the experiments ranged from approximately 7 to less than 9 g.

The greater displacement of material at the 5- to 10-minute test intervals is attributed to the relative ease of displacement of the gas inside the foam cells. Pneumatic effects in the foam noted by Mehaffie¹³ were reduced. For this reason, the recommended foam formulation makes use of the open cell producing surfactant.

Summary

Impact loading tests of the foam at various intervals ranging from about 10 seconds to 10 minutes after foam system initiation provided some indication of the initial strength and strength development of the foam. A simple cushioning analysis provided the basis for a logical interpretation of the stress data. Material displacements varied with time after foam generation, but measured deceleration times and g values did not

vary widely. The energy absorbing or dissipating characteristics of the foam appeared to be satisfactory for use in a foam impact attenuation system.

7 SAFETY

Chemical Formulation Safety

The reactants used in the chemical formulation for RDFS were all commercially available polyurethane foam grade materials. All highly reactive chemical substances are potentially hazardous to living organisms and should be handled with due caution.

The polyisocyanate used in the formulation (PPI) has the toxic properties common to all isocyanates. However, because of the high molecular weight of the PPI, the vapor pressure of this substance is very low, i.e., approximately 0.00016 mm Hg at room temperature. Protective glasses, gloves, and clothing should be worn while working with PPI to avoid eye or skin contact.

The polyol used in the formulation was derived from an aromatic polyamine. Manufacturer's data indicated a slight potential for dermatitic reaction if repeated or long skin exposure is allowed. Therefore, protective clothing, gloves, and glasses should be worn when working with this material. The vapor pressure is sufficiently low that vapor toxicity is generally absent.

The catalysts (both amine and organometallic) must be handled with care. They are highly reactive and may be corrosive to tissue. Protective clothing and glasses must be worn when handling these materials.

The silicone surfactants represent little hazard but it is suggested that they be handled with caution as a matter of good safety practice.

Repeated exposure to the refrigerant blowing agent (R11B) can cause skin chapping. R11B also has a very high vapor pressure, and since its vapors are heavier than air, may cause oxygen deprivation if breathed. The material is a halogenated hydrocarbon and should be handled with caution.

Pressure System Safety

The dispensing system cylinders and valves are commercially obtainable and are rated at the working

¹³Stephen R. Mehaffie, *Investigation of a Deployable Polyurethane Foam Ground Impact Attenuation System for Aerospace Vehicles*, Volume I, AFFDL-TR-78-145 (Air Force Flight Dynamics Laboratory, January 1979).

pressure used in the study. They present no special hazard to operating personnel unless they are damaged, dropped, or abused.

Safety in Service

The dispensing system should be filled and pressurized only by trained and experienced personnel. Normal packaging and handling criteria for pressurized vessels will suffice for distribution and use. The vessels should be protected from impact (dropping or being struck) and the plumbing should be supported in a manner that will prevent damage.

8 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The conclusions reached in this study were:

1. A polyurethane foam formulation with a deployment interval of 5 seconds is practical, especially at slightly elevated temperatures.
2. A self-contained, prepressurized dispensing system is an adequate way of storing and making rapidly deployable polyurethane foam.

3. A new mixer design capable of delivering a mixing rate of greater than 700 lb/min (5 kg/s) is simple, reliable, and inexpensive. Simple sizing modifications can adapt the mixer concept to other flow rates.

4. Rapidly deployable polyurethane foam can be generated in a variety of geometric shapes by using forms made from lightweight fabric bags.

5. Rapidly deployable polyurethane foam attains impact energy absorbing properties immediately after formation and can be used for shock attenuation within a time interval of 5 to 600 seconds. The extent of foam deformation is related to time elapsed after deployment for a given load-velocity condition.

Additional Research Requirements

The rapidly deployable polyurethane foam system developed as a result of this study should be applied to a particular impact shock attenuation application and full-scale tests should be conducted to verify laboratory findings.

Recommendations

Based on the results of this study, it is recommended that rapidly deployable polyurethane foam be used in shock impact attenuation systems.

**APPENDIX:
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