No. NA-69-43
DS-69-7

FINAL REPORT

Contract No. FA-67 NF-245

Project No. 510-001-04X

AN ENGINEERING INVESTIGATION AND ANALYSIS OF CRASH-FIRE RESISTANT FUEL TANKS

JULY 1970

Prepared for

FEDERAL AVIATION ADMINISTRATION
Aircraft Development Service

by

FIRESTONE COATED FABRICS COMPANY

Akron, Ohio 44317

FINAL REPORT

Contract No. FA-67 NF-245
Project No. 510-001-04X
Report No. NA-69-43
(DS-69-7)

AN ENGINEERING INVESTIGATION AND ANALYSIS OF CRASH-FIRE RESISTANT FUEL TANKS

Prepared by:

Merritt M. Yancey
and
Richard T. Headrick

FIRESTONE COATED FABRICS COMPANY
Akron, Ohio 44317

F O R E W O R D

This report was prepared by the Firestone Coated Fabrics Company for the Federal Aviation Administration. The work effort was part of a program of the Engineering and Safety Division, Aircraft Development Service, Washington, D. C.

Engineering liaison and technical review for this project were furnished by the Structures Section, Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

ABSTRACT

Subject: Use of available rubber, plastic and other materials to reduce probability of fire in fuel tanks during and after survivable crashes.

Techniques investigated apply to integral tanks and bladder cells as well. General contributions include prevention of original penetration, containment of penetration, maintenance of fuel integrity even with failure of above two systems; change in characteristics of fuel expulsion from major wound to non-vapor, low flow liquid leak; flame and explosion suppression and surge attenuation. Proper selection of "building blocks" to optimize desired performance characteristics indicates a major contribution is available with slight, almost unmeasurable displacement of usable fuel and addition of weight. Structures so protected may be inspected.

TABLE OF CONTENTS

LIST OF TABLES & ILLUSTRATIONS

INTRODUCTION

PURPOSE

By the use of available rubber, plastic and other materials, the contractor's purpose is to significantly reduce post-crash fire hazards in survivable airplane crashes by eliminating or reducing fuel spill from ruptured fuel tanks.

BACKGROUND

In even minor crashes where airplane structures and occupants are subjected to forces that are not seriously destructive, volatile fuels are spilled and result in post-crash fire that can cause catastrophic destruction.

Where fuel spill cannot be prevented by the concepts developed by the contractor, the rate of flow can be significantly reduced, thus extending the time before any potential ignition and combustion occur in an otherwise survivable crash. With this gain in time, safe passenger evacuation of the airplane becomes highly probable rather than highly improbable.

DISCUSSION

EVOLUTION OF THEORY

The aircraft fuel tank will always be subjected to the internal load imposed by the contained fuel and decelerative forces during a crash and may also experience an impact load from an external source. The loads these tanks may experience during a survivable crash are difficult to define since the portion of the airframe containing the tanks may experience loading much different from that experienced by the passenger compartment. The ability of the integral and bladder tanks to withstand the purely decelerative load is dependent on the basic design and fabrication of the tanks. Testing done in other programs has shown that these tanks can retain their liquid integrity when crash decelerative forces are survivable and when the tank structure is not subjected to impact loading. This is because impact loading may create an open wound in the tank or cause an object to penetrate into the tank.

Film or fabric solution. - Flow through a wound in a tank (from deceleration of impact) can be prevented by an inner-liner of film or fabric. This film or fabric would be capable of elongation and bridge the wound as it is created. Hydraulic forces will then tend to force this material through the wound. The shape of the film or fabric as it is draped through the wound can be considered to be a part of a thin wall sphere or cylinder. The tension in the fabric is then $T = PR/2$ in case of a sphere or $T=PR$ in case of a cylinder. It is obvious that R is a function of the wound size and the amount of drape through the wound. Drape is a function of the amount of elongation, which in turn depends on the pressure against the fabric. Therefore, as the pressure is greater, the fabric will elongate further through the wound reducing R, increasing the tension, but as a function of P and R, which are changing at different rates and in opposite sense. The mechanism is also used in the partially supported bladder cell to react loads encountered from support to support. The shear loads developed in the film or fabric in contact with the ragged edge of a wound may damage the film or fabric reducing the amount of tension that can be carried as elongation occurs. Likewise, firm bonding of the film or fabric to the tank wall, limits the amount or area of the material that is available for elongation into the wound. Thus, "frangible bonding" was developed. Film or fabric might also be carried into the tank by an object penetrating the wall. The inner-liner would then be carried into the tank by the object at initially high velocity and should encompass the object preventing fluid loss. Shear loads developed upon contact of this object could damage the inner-liner. Also, a firm bond would prevent the needed elongation of the liner.

Frangible bond. - The use of a frangible bond between the inner-liner and the tank wall assures a bond strong enough to support the inner-liner during normal operations but allowing it to pull away from a wound and move with a penetrating object. Test program has shown a second function, provided this bond is made of foam and has thickness. The foam rolls around the sharp edge of a wound and "chunks" out ahead of a penetrating object, greatly reducing the shear in the inner-liner by preventing a direct contact with the wound edge or penetrating object. This allows a reduction in the thickness of the inner-liner. The foam layer may be submerged in fuel since the extendible film inner-liner may not be continuous. Thus, no great penalty in fuel displacement is incurred.

Tank capacity reduction through distortion. - The drape of film or fabric through wounds in a tank may provide the necessary increase in volume required to contain the fuel where the original tank volume has been reduced through distortion to the extent that it cannot contain all the fuel.

External protection. - Vulnerable surfaces of bladder cells and of integral tanks can be protected from impact by placing cushioning materials outside the tank on selected areas. These materials protect by either absorbing energy before it reaches the tank or by increasing the area of contact on the tank wall, reducing the wall loading below the ultimate for the wall material.

The effect of foam on fuel expulsion. - The reticulated foam which has been effective as an infinite baffle and flame suppressor inside a fuel tank under combat conditions appears to be capable of effectively reducing flow through open wounds during deceleration due to two related phenomena. An increase in flow rate through the foam structure due to the hydraulic head present will increase the resistance generated by the foam causing an increasing pressure drop across the foam. This may in turn cause local collapse of the "legs" in the foam structure causing still further flow resistance and a partial blocking or closing of the wound when carried or pushed into the wound. The use of a foam with smaller pores but the same density, such as 40 pores per inch (ppi), is more effective in this regard than the 10 ppi foam presently in general use, since it would have a greater resistance to flow and lower strength in the "legs," thus resulting in a quicker collapse response and more effective plugging of the wound.

DESIGN AND APPLICATION CONSIDERATIONS

The effect of protective systems on pay-load and range. - The addition of materials to implement any of these protective concepts will increase to varying degrees the weight of the aircraft, reducing its pay-load and cruising range. Those materials which are put inside a fuel tank will displace fuel and reduce its capacity with the same result. Further, these materials must maintain their physical characteristics while immersed in fuel.

Installation consideration. - The materials are intended for installation when the airframe is fabricated, but still should be capable of removal and reinstallation to allow inspection of all parts of the structure in accordance with standard and conventional maintenance procedures.

Protection options. - The ultimate selection of combinations of materials for tank crash-fire resistant protection must be related to weight, volume, fuel displacement and compatibility and must attempt to accomplish optimum performance for the type of protection intended, since these materials may be used in different amounts. For example, the military requirements for flame propagation suppression and fuel slosh dampening during aircraft maneuvers make it desirable to fill the tank or tanks completely with thermally reticulated polyurethane foam.

Commercial aircraft do not have this baffle requirement and the possibility of flame propagation in a tank during flight is remote. Thus, justification for the use of foam to fill the tanks of commercial aircraft is debatable. The protection provided by the attenuation of fuel flow through a wound in a tank at crash may demand the use of foam in certain thickness on the interior surfaces of these tanks.

EVOLUTION OF MATERIALS

Single and multiple-ply rubber and plastic-coated fabrics suitable for bladder cell, airborne and ground storage flexible tanks. - The use of flexible tanks goes back in antiquity, the use of goat skin bags being recorded in many historical documents. Leather has been one of the materials used in modern aircraft fuel cells. The mass production of military aircraft during World War II and the expanding commercial market put great emphasis on the development of flexible tank materials. The materials may be required to retain their strength and flexibility through a temperature range from -65° to 160°F., resist deterioration from and not contaminate the material they contain (which may range from potable water to corrosive chemicals) and be compatible with their environment. The tank may be used in an application where it will be subjected to internal pressures intermittently or continuously. Vehicular use subjects the tank to inertial loads which must be reacted by the wall and transferred to the vehicle. The use of nylon fabric in various weights and weaves has become an industry standard due to its ability to meet these requirements at a relatively low cost. Dacron, fibreglas and similar materials have been used in some special applications. The material may be used in multiple plies to obtain greater tensile strength in some applications. The nylon is coated with the selected Nitrile, Buna, Hypalon, Neoprene and/or other compounds to obtain the needed interior and exterior characteristics and to allow the lamination of multiple plies where necessary. Strong, lightweight, fittings have been developed in several sizes and shapes for access to the interior of the tank. Hangers and strap attachments have also been designed to mount and distribute loads bearing on the tank. R and D continues in this field, with a great deal of interest in unwoven fabrics and plastic films. These materials demonstrate excellent chemical characteristics and increased mechanical properties.

Use of flexible fabric tanks for aerial bulk fuel delivery and ferry range extension. - Development of a patented surge attenuating system manufactured by Firestone, permitted the use of large capacity flexible fabric tanks (1,000, 2,000 and 3,000 gallons) in cargo or passenger aircraft. Fleets of these aircraft are now operating in Vietnam delivering fuel. One or two 1,000 gallon tanks are used inside the Douglas DC-9 commercial passenger aircraft on special knockdown pallets in place of passenger seats to provide extended range for over-ocean delivery. A similar system is used in large military jet transports. Tie-down harness for these systems had to accommodate 8G forward crash loading, 4G's in all other quadrants. This retention system was tested at the Navy Deceleration Facility at Lakehurst, New Jersey, on the steam catapult and passed successfully.

Technical problems associated with integral tanks. - The airframes industry has long recognized that the use of the properly sealed wing structure itself as a tank would provide maximum fuel capacity without a weight increase or volume loss for tank materials. However, metal-to-metal fabrication techniques do not provide a fuel tight seal between structural components, making it necessary to introduce a sealant system. Techniques used to establish this sealant system have varied from filling and draining the cavity to form a film on the interior of the cavity to the use of films and beads placed between structural parts as they are assembled. The system now employed most frequently includes the use of beads between parts during assembly and caulking at structural joints. Unavoidably, long leakage paths within the assembled structure make it practically impossible to obtain or maintain a complete seal. Relative motion and wracking between structural members may create additional leakage paths.

Backing board materials to support fuel cells structurally and to provide sealant compound formation support. - During ballistic testing of bladder and self-sealing fuel cells, it was determined that the wound created by the entry of the projectile was small and conformed to the frontal dimensions of the projectile upon contact with the tank wall. However, the back pressure created by passage of the projectile could open this wound and tear the tank wall further, leaving a much larger wound which was either more difficult to or could not be sealed. The action of the pressure caused the fabric wall to drape outward, creating tension in the fabric which, in turn, tore when the tear strength of the fabric was exceeded. This reaction was reduced or eliminated by mounting a high tension carrying, low elongation fabric made from impregnated fibreglas fabric next to the cell wall. The pressure forced the cell against this backing board, relieving the tension in the cell fabric and thus preventing further tearing. This back board also helps to realign the lips of the wound in the tank wall. Experience gained in backing board development has been useful in protection systems external to integral tanks or to cavities containing fuel cells. This investigation has been broadened away from exclusively military applications and now falls under the general classification of Energy Dissipating Materials.

Energy Dissipating Materials. - The integral and bladder fuel tank are both vulnerable when impact occurs with an external object. This vulnerability increases as the impact energy increases and the contact area decreases. Localized loads become very high and shear failure occurs, often long before the surrounding wall is loaded appreciably in tension. The use of energy dissipating or load distributing materials on the exterior of the tank working in much the same manner as a bullet-proof vest can dramatically reduce this vulnerability and allow the increased use of tank wall area to carry the load imposed. There are many materials such as unwoven nylon felts and high tensile fabrics which may be used to deform and distribute these loads over a greater area of the tank wall. These may be employed in combinations or "sandwiches" with backing board materials to obtain predictable levels of protection over large surfaces or small highly vulnerable areas.

Highly extendible film for penetration containment and frangible bond. - The concept of extendible film has been well proven in many tests at the Firestone, Los Angeles facility. Its theory was outlined above under "Evolution of Theory." Chisels weighing 20 pounds have been dropped as much as 18-1/2 feet penetrating tank structures and plunging into the tank interior approximately 12" before coming to rest. The extendible film material would detach itself from the frangible bond (foam layer) between the film and the tank structure and would form tight around the penetrant following it into the tank. This occurred consistently even though the tank was pressurized at 20 psi simulating the sustained decelerating conditions in a crash. Extendible film subjected to extended soaking in JP-4 fuel appears to approximate the performance of unsoaked samples. Some normal swelling is noted during soak which appears to present no known adverse effect in this application.

Attachment devices. - Several attachment devices may be used to install "curtain" assemblies inside an integral tank structure. These may operate somewhat similarly to Velcro which is a nylon hook and eye type of material with considerable shear strength and relatively low peel strength, or by continuous mechanical clamps at the edge of the material.

Combination of materials to provide variable option results. - Within the scope of the Firestone development ranging from external protection through tank wall construction, internal protection and infinite baffling lie many valuable tools which may be optionally combined to provide the specific performance and protection desired. It may not be practical to incorporate all of these in one aircraft due to weight, fuel displacement and various other considerations. However, Firestone Coated Fabrics Company is at least now capable of interpreting a protective performance specification in terms of available materials, assemblies and installation techniques so that hyper-protection with its attendant penalties is avoided but adequate protection is provided.

EVOLUTION OF TEST TECHNIQUES

Upgraded testing. - The original materials review undertaken in the contract program utilized data derived from standard tests for tension, permeability, tear and puncture. Available data were augmented by testing where necessary to obtain these data. However, the need for data obtained under crash conditions was recognized.

Air gun testing. - The air gun used in military qualification which drapes a relatively large panel of fabric and rapidly elongates it until it fails in tension was modified by the addition of a chisel, thus simulating impact and penetration. (See figures 2 and 6, pages 11 and 18.)

Impact testing. - An impact test used in work done for USAAVLAB was adopted for the program. The USAAVLAB test is an impact test performed by dropping a known weight from a given height on a rigidly mounted specimen which has a small active test area. Initial contact of the falling weight on the specimen simulates a small, sharp penetrating object. See figure 1, page 10. This device was used with a great deal of success early in the program to evaluate and compare materials. However, as the program progressed, questions were raised that could not be answered with the data obtained from the device. Limitations on drop height in the Firestone installation made it necessary to use different weights for the drop. The anvil which mounted the test specimen did not allow detailed observation and photography. Mounting the specimen on the anvil was time consuming. The test did not allow the simulation of an internal hydraulic head which would be present during crash. The small active test area was possibly limiting or changing the action of the test specimen at impact.

Description, new impact test device. - A new impact test device was designed and built. A 5, 10 and 20 pound dart was provided and additional weight can be easily added. The release and guide mechanism for the falling dart was completely changed and isolated from the specimen and its mounting. The method of clamping the specimen in place now provides for rapid mounting of the specimen. A maximum of 40 psi static pressure can be used when simulated hydraulic heads are included in the test plan. A cylindrical cavity, one foot in diameter and one foot high made from a heavy walled plastic tube may be pressurized to 90 psi (static and shock pressures) and provides for the observation and photographing of the specimen before, during and after the test run. The wall and ends of the cavity are instrumented, providing the pressure history during tests. These multiple readings may be used to evaluate baffling and shock wave phenomenon. The active specimen area can be varied from a 4-inch diameter to a 10.5 inch diameter. The cavity can be pressurized pneumatically or hydraulically. An external standpipe, which is connected to the bottom of the cavity through a 'U' tube, contains a plenum chamber where pneumatic pressure is introduced during hydraulic testing. The same space provides for the displacement of fluid when the dart penetrates the test cavity.

<u>Other uses of device beyond impact testing</u>. - The test device may also be used to evaluate materials in drape by introducing simulated structures with closely controlled wound sizes. Materials such as thermally reticulated polyurethane foam placed in the cavity can be evaluated for their shock mitigation, fluid flow and energy absorbtion characteristics. (See figures 3 and 4, pages 12 and 13.) The expulsion of fluid from the test cavity through a given orifice mounted in the specimen position, provides an excellent means of evaluating fluid flow through a body of foam simulating flow of fluid through a wound in a tank containing foam. (See figure 5, page 14.)

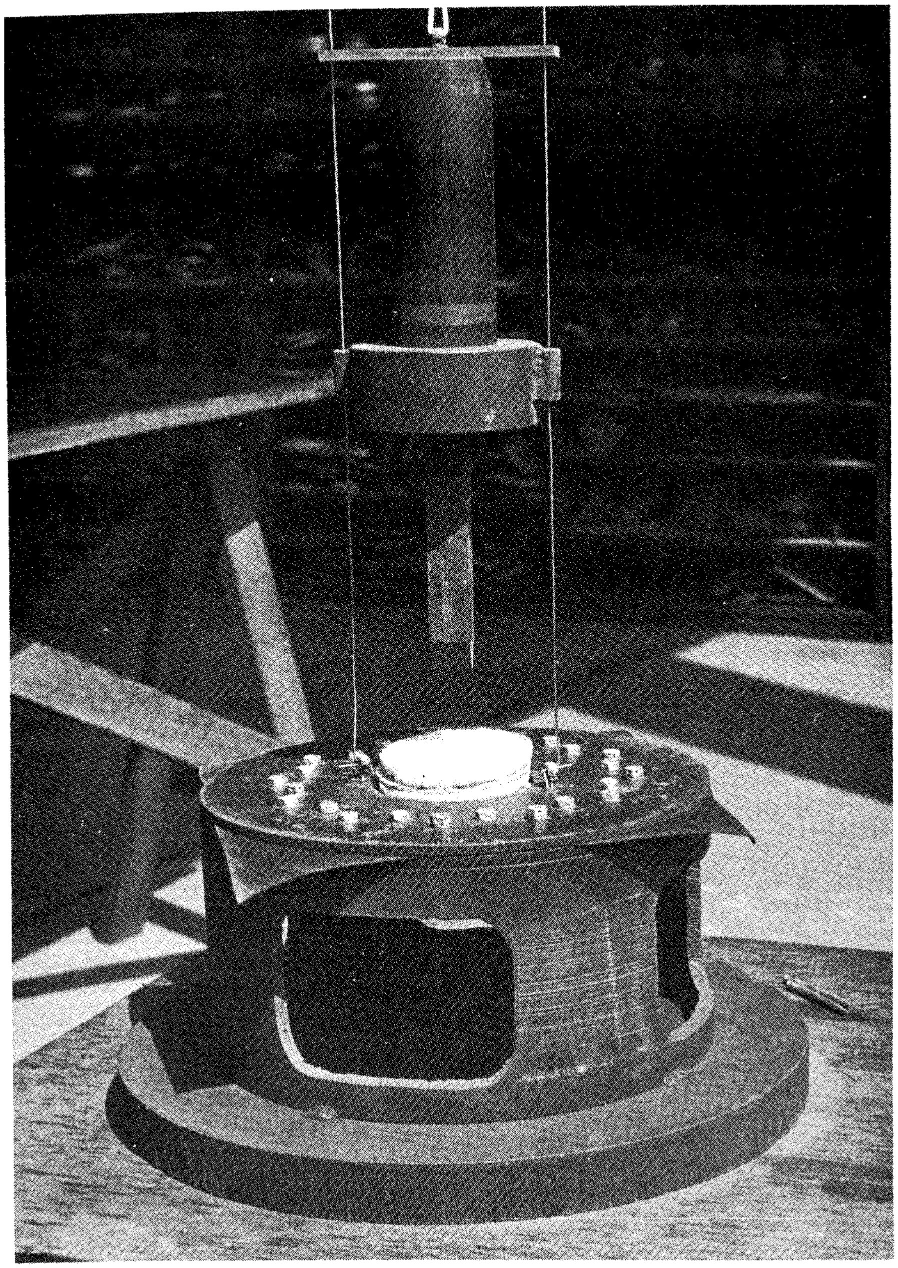


FIGURE 1 - ORIGINAL IMPACT TEST FIXTURE

The original impact test fixture with twenty-pound falling dart. The chisel shank is one inch square, reducing to an edge one inch wide with a 1/32 inch radius at the point of specimen contact.

A fabric specimen with nylon felt and backing board impact protection is mounted for test.

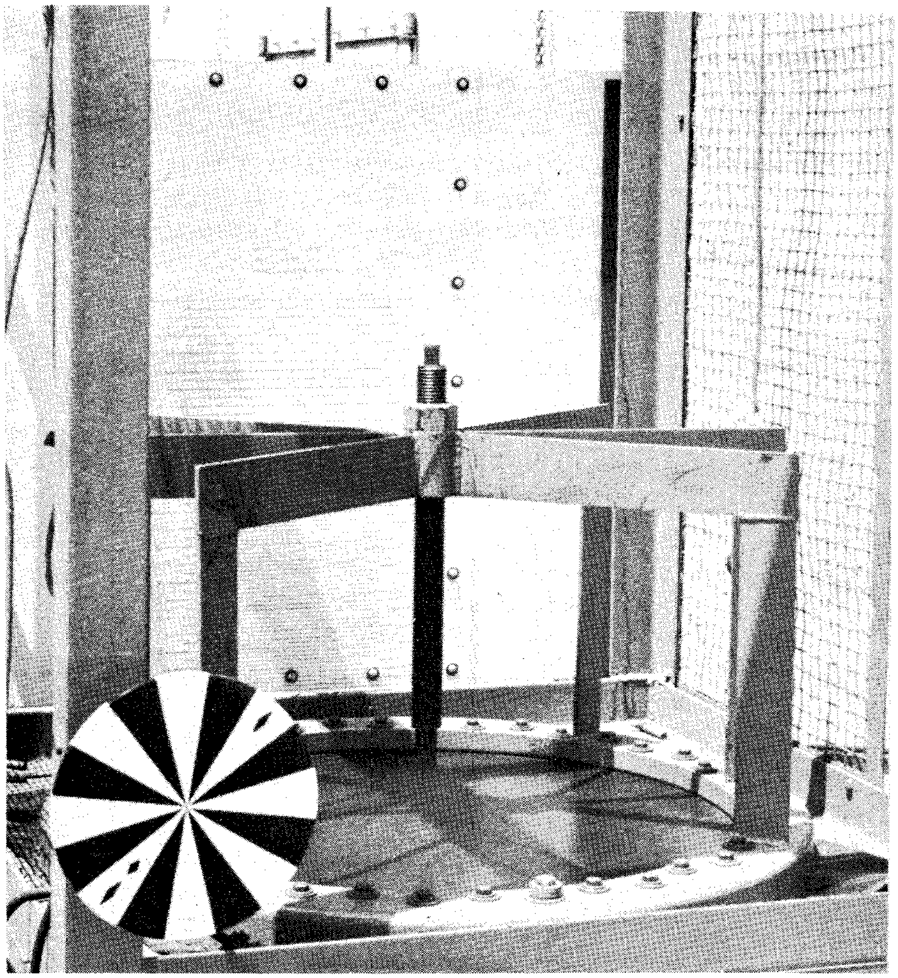


FIGURE 2 - THE MODIFIED AIR GUN

The mounting of the chisel as shown provides a means of evaluating the impact of penetrating object on fuel cell materials which are under typical tension loads which may be encountered during deceleration due to crash load.

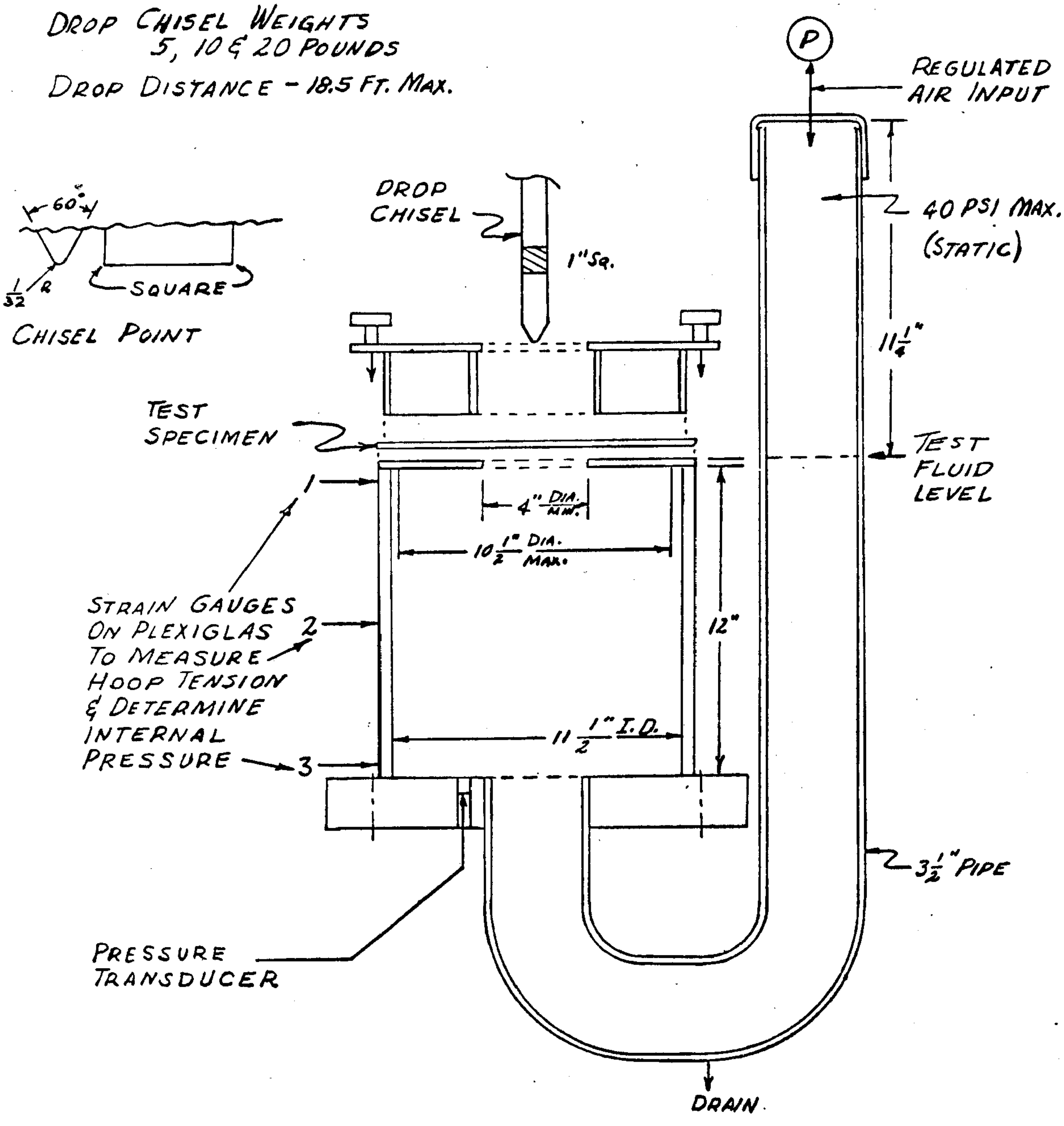


FIGURE 3 - SCHEMATIC OF IMPACT TEST FIXTURE WITH HYDRAULIC SIMULATION

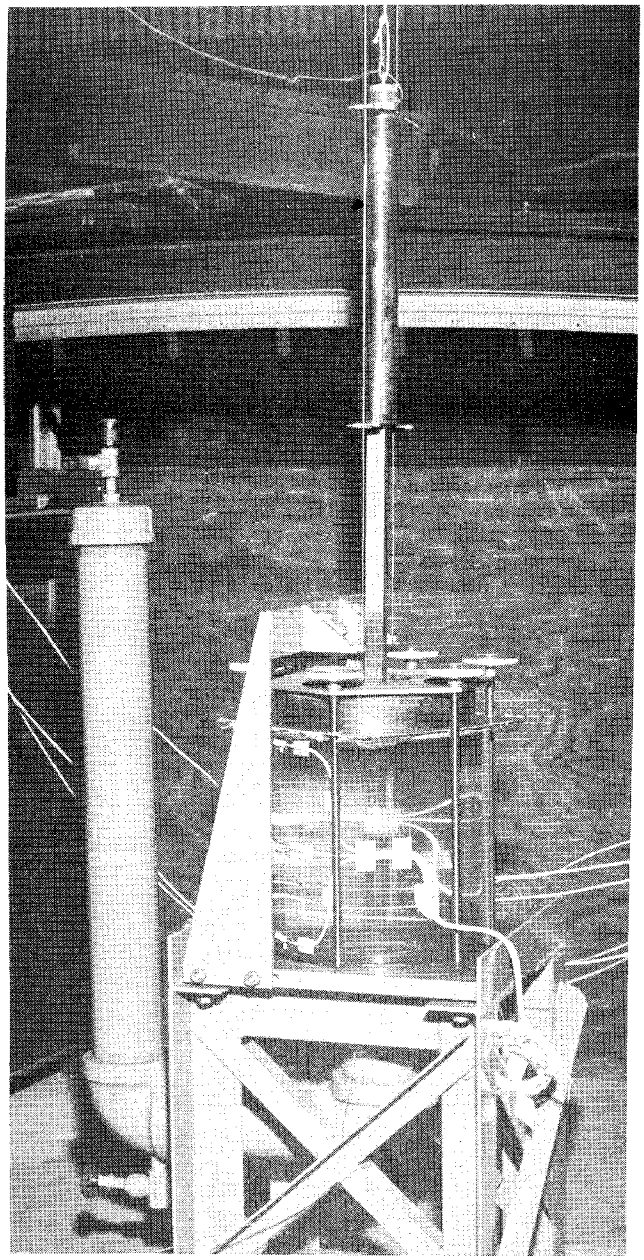


FIGURE 4 - IMPACT TEST FIXTURE
WITH HYDRAULIC SIMULATION

Details of the fixture are given in Figure 3.

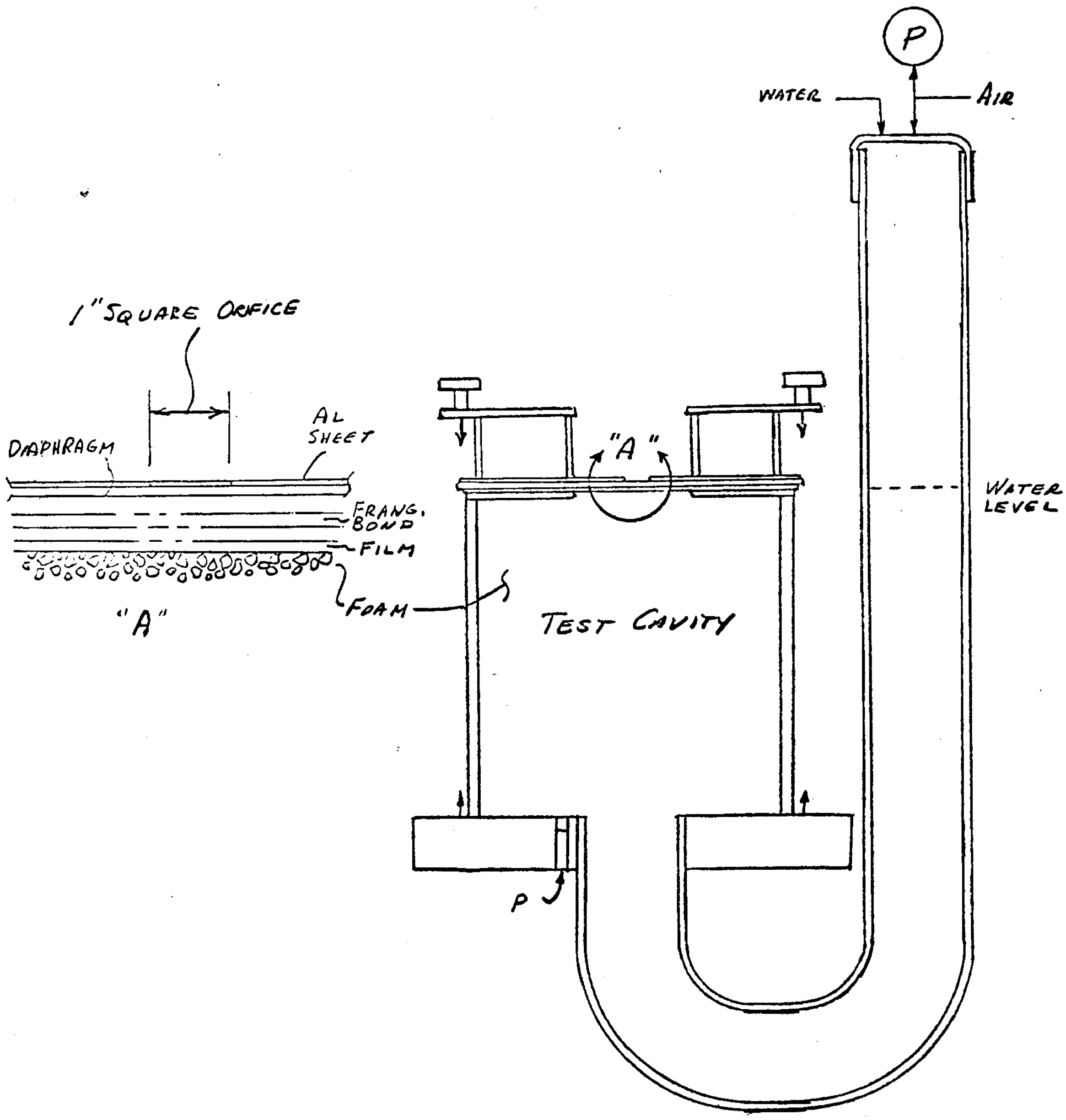


FIGURE 5 - MODIFICATION OF THE IMPACT TEST FIXTURE FOR EXPULSION TESTING

PENETRATION PROTECTION

Bladder cell fabrics. - The investigation and analysis of bladder cell materials and their specifications revealed a vast body of data derived under standard test conditions but a dearth of data under impact environments. Three bladder cell fabric constructions were selected from impact testing, representing light, medium and heavy weight fabric materials. The test fixture is shown in figure 1, page 10. This fixture limits the active fabric area to a circle 4 inches in diameter. The impact energy is determined from the heights of the drop and the weight of the dart. The data obtained show that fabrics fail under low impact loads due to extremely high shear loading at the point of contact. The ability of these fabrics to absorb large amounts of energy in tension is not realized under these load conditions.

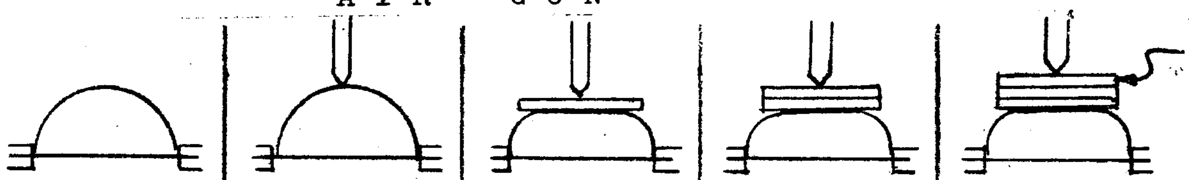
Energy absorbing cushion materials. - The use of cushion materials between the fabric and the dart to reduce the shear load and increase the effective load area of the fabric was evaluated using the same test criteria. Cushion materials evaluated included semi-rigid materials, foams, fabrics and felts. The foams were the least effective, being subject to local shear failure in the legs of the foam structure itself. Felts were the most effective, deforming locally and conforming to the configuration of the dart, then compressing in a conical shape ahead of and in the direction of travel of the dart.

Combinations of cushion materials and bladder cell construction. - Combination of these materials were tested next. The nylon felts combined with semi-rigid materials like Firestone backing board F1-41 (a resin impregnated fibreglas) are highly effective. The nylon felt used for combination testing was 3/16 inches thick and weighed 25 ounces per square yard. The use of heavier felts such as ballistic felts in the same thickness did not provide additional protection under these test conditions. The fuel cell fabric does elongate at impact and does not fail due to shear across the threads but rather in tension of these threads. Data from these tests are given in table I and II, page 16 and 17.

Air gun testing of bladder cell and combination materials. - The bladder cell is designed to drape between its structural supports and thus react to any hydraulic loads imposed upon it. The drape of fabrics under given dynamic conditions has been tested for several years using an air gun, which elongates a circular specimen of the fabric into a section of sphere until it fails (see figure 6, page 18). Air under pressure is introduced into a conical plenum below the ring mounted test specimen. This plenum pressure is recorded. The elongation of the fabric is recorded by high speed photography. The fabric expands until it fails in tension. During a crash, the expanding fabric may contact an object which could cause a localized failure and fuel loss at much lower pressures. The air gun was modified and a chisel added which would contact the expanding fabric at a preset height. The same three fabric constructions were tested in the air gun. The fabric was

Table I

AIR GUN



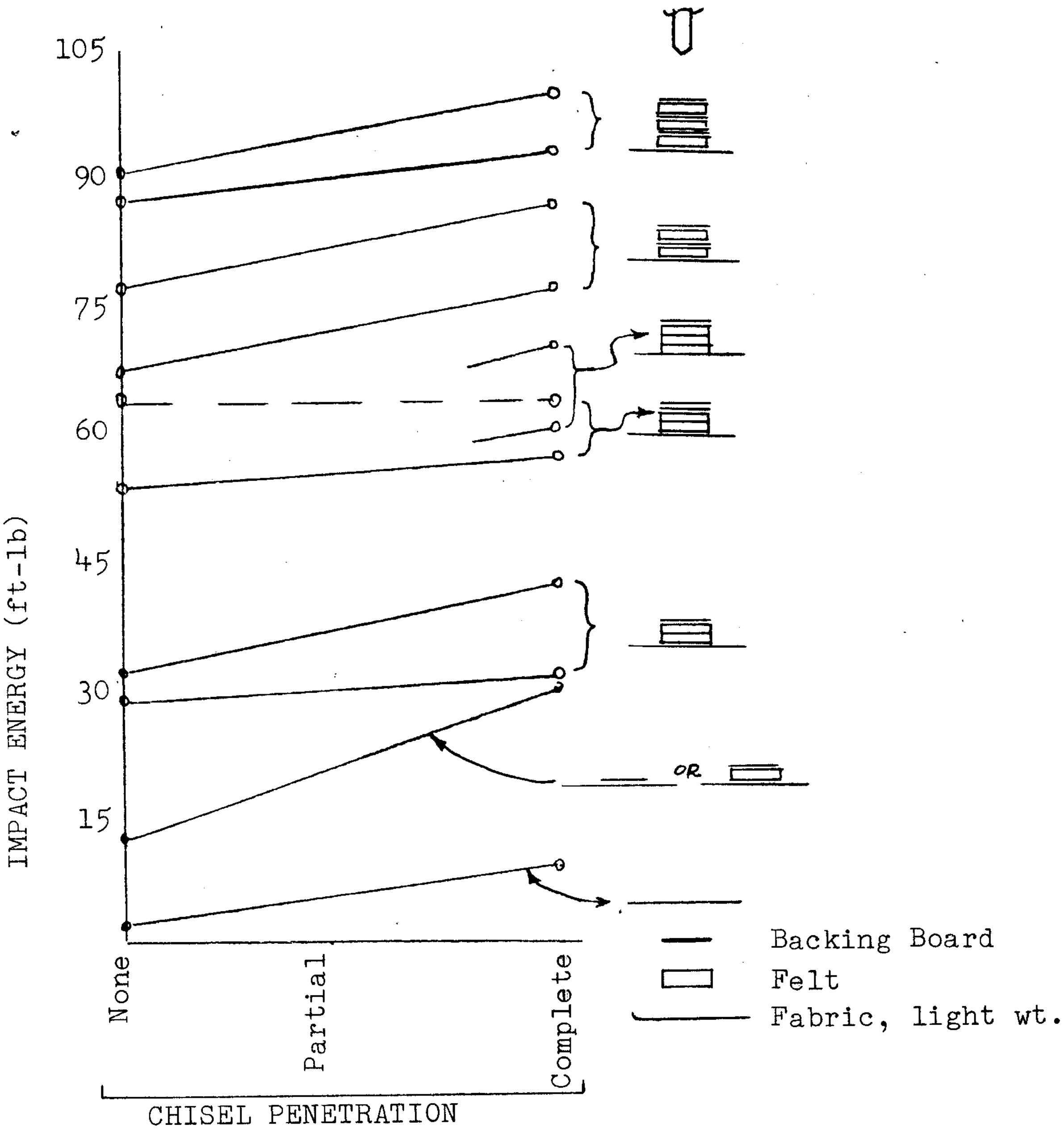
Fabric Contruction						
Light Weight	14.8	5.7	10	15.2		Rupture Pressure (psi)
Medium	21.6	8.4	10.1	16.4		
Heavy	62.7	43.3	52.2	58.9	64.0	

IMPACT CHISEL

Light Weight		6.67	28	71	91	Impact Energy at Failure (ft-lb)
Medium		5.0	40	83.3	105	
Heavy		31.5	150	270	380	

EXTERIOR CUSHIONING MATERIAL

Table II



IMPACT PROTECTION WITH CUSHION MATERIALS IN VARIOUS COMBINATIONS AND THICKNESS

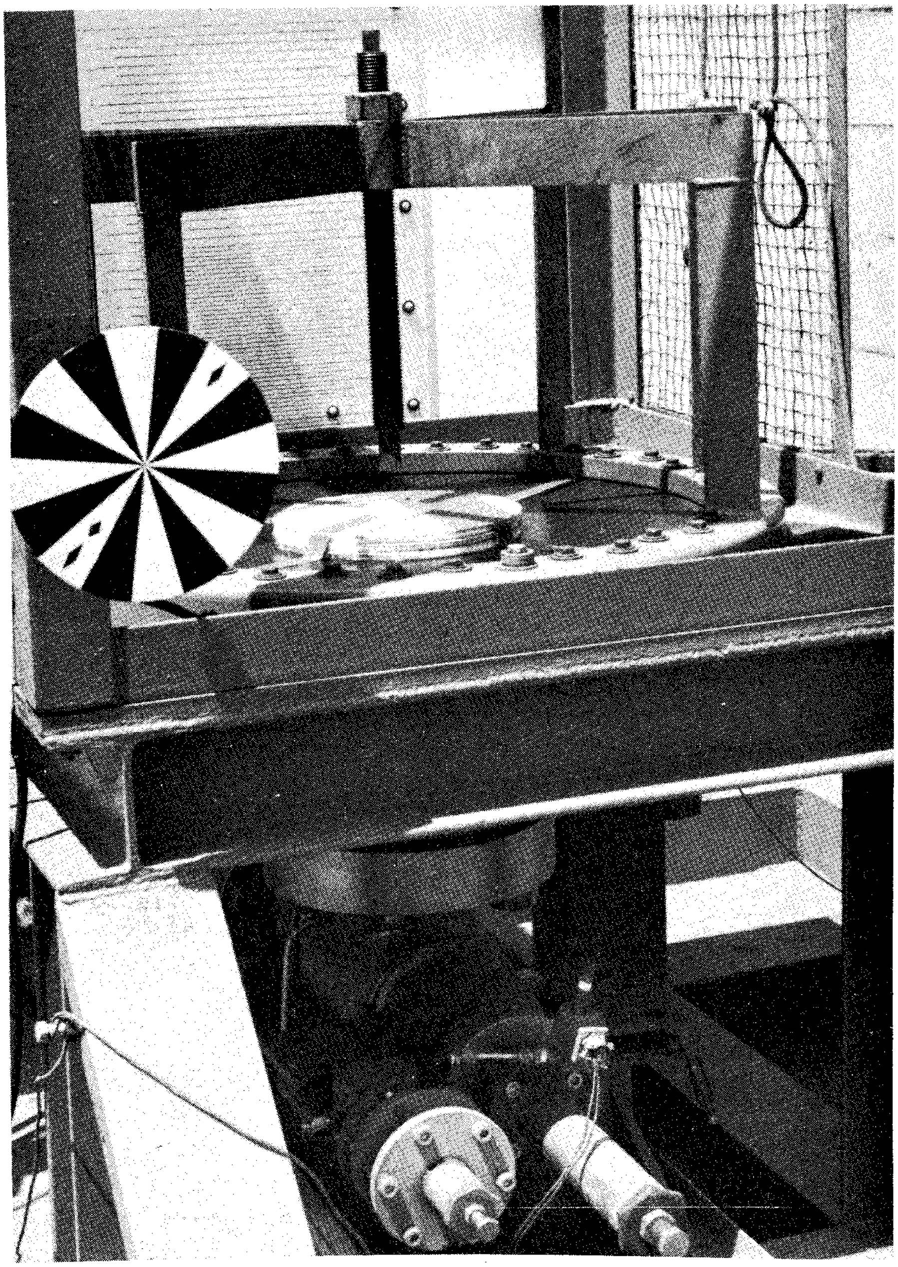


FIGURE 6 - FUEL CELL FABRIC IMPACT PROTECTION

Nylon felt and fibreglas backing board shown in place for test.

first elongated without the chisel to determine the pressure necessary to cause failure. The chisel was then mounted 3 inches above the face of the relaxed fabric. Tests were then run elongating the fabric against the chisel and with multiple layers of felt and backing board between the fabric and chisel. The felt and backing board were 12 inches in diameter and loosely adhered to the fabric. (See figure 6, page 18.) Data from these tests are given in table II. The protection afforded the fabric against the penetration of the chisel is again related to the thickness of the protective material. Tests were continued using additional layers of the felt/fibreglas cushioning material until the pressure at failure was equal to or greater than the pressure required to fail the freely expanding fabric.

<u>The inner-liner approach</u>. - The inner-liner concept discussed earlier in this report was initially evaluated on the original impact device. The test specimen consisted of a 6063T6 al sheet, one foot square, 0.063" thick, on which the film and/or bond to be tested was adhered. This temper and gauge aluminum sheet was used to assure the formation of rough-edged metal petals ahead of the penetrating chisel. The early test program verified the need to know what these petals do as penetration takes place. The test variables recognized in the beginning were (1) inner-liner elongation, (2) liner area available for elongation, (3) rate of elongation, and (4) liner damage at impact. The first test specimens used nylon film, nitrile film and a special high elongation woven nylon fabric. These materials were bonded directly to the aluminum sheet. The specimen was mounted in the test fixture and subjected to a low energy impact which would deform the aluminum surface. This same drop was repeated and the aluminum gradually deformed ahead of the chisel. The films all failed before the wound in the aluminum sheet was 1/8 inch wide. The woven fabric failed at about 3/16 inch width. These materials remained tightly bonded to the aluminum sheet during the tests, severely limiting the film or fabric available for elongation. (See figure 7, page 20.)

<u>Investigation of possible frangible bonds</u>. - Possible use of inner-liners verified the need of a frangible bond, that is, a bond between the inner-liner and its support which would carry the loads of normal aircraft operation but allow the inner-liner to separate from the bond (in shear or peel) as the liner might elongate. An alternative bond might be a "spot" contact between liner and aluminum base. This has the obvious disadvantage when impact occurs at or near the spot contact. The frangible bond could be effective either through the mechanics of a much reduced contact area or a much lower adhesion between materials. Materials tried included such items as glass beads, woven and unwoven fabrics, kapok, foam, flocking, etc. The installation of these materials in an aircraft was considered while the test specimens were fabricated. Flocking, for example, was difficult to use and could not develop a bond strong enough to be capable of carrying flight loads and still retain frangible characteristics. Therefore, it was soon dropped from consideration. Ten ppi foam in ground or sheet and reconstituted sheet, proved effective due to the large reduction in contact area.

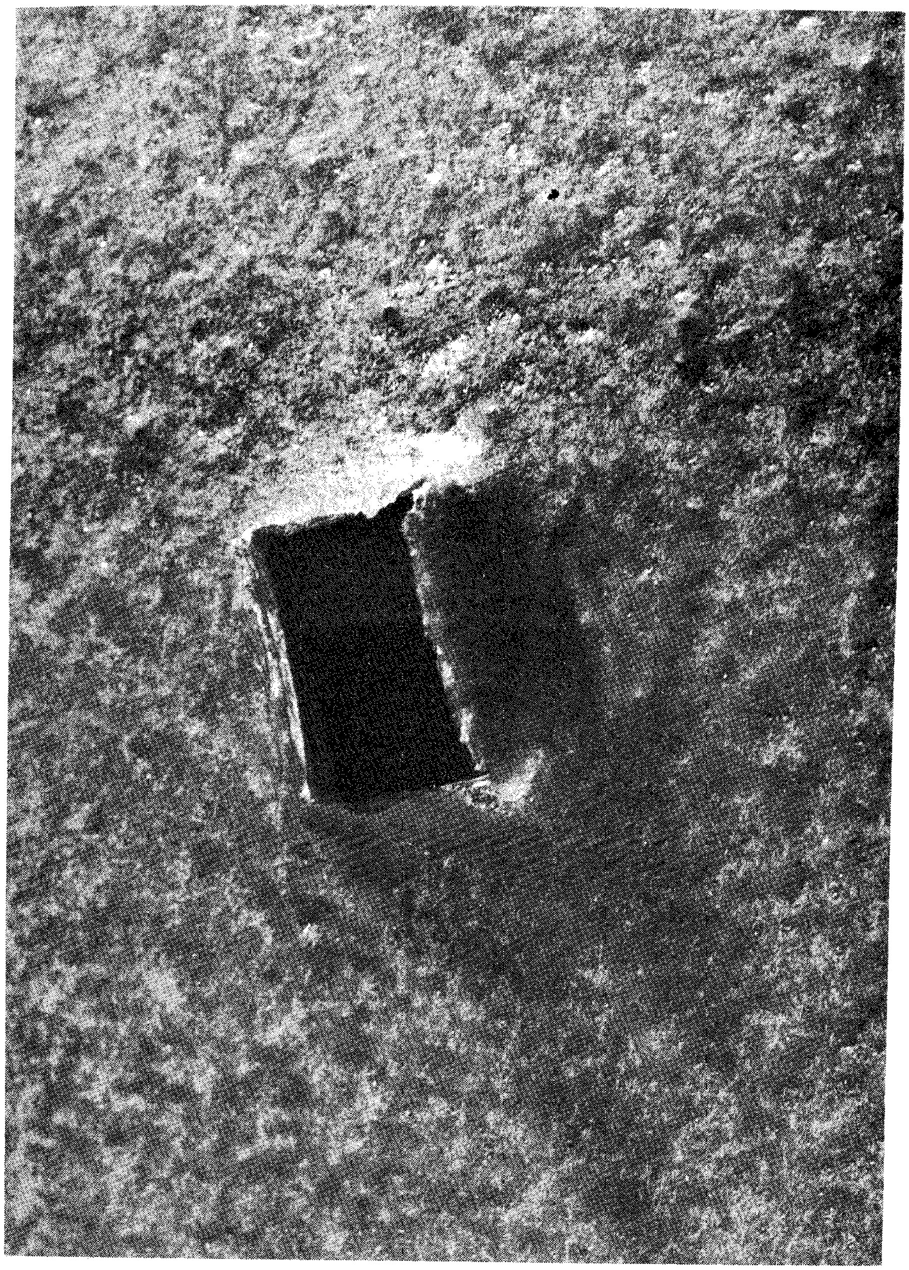


FIGURE 7 - INTEGRAL TANK INNER-LINER
BONDED TO SIMULATED TANK WALL

The bond between these materials did not fail, severely limiting the amount of liner material that could elongate as penetration took place.

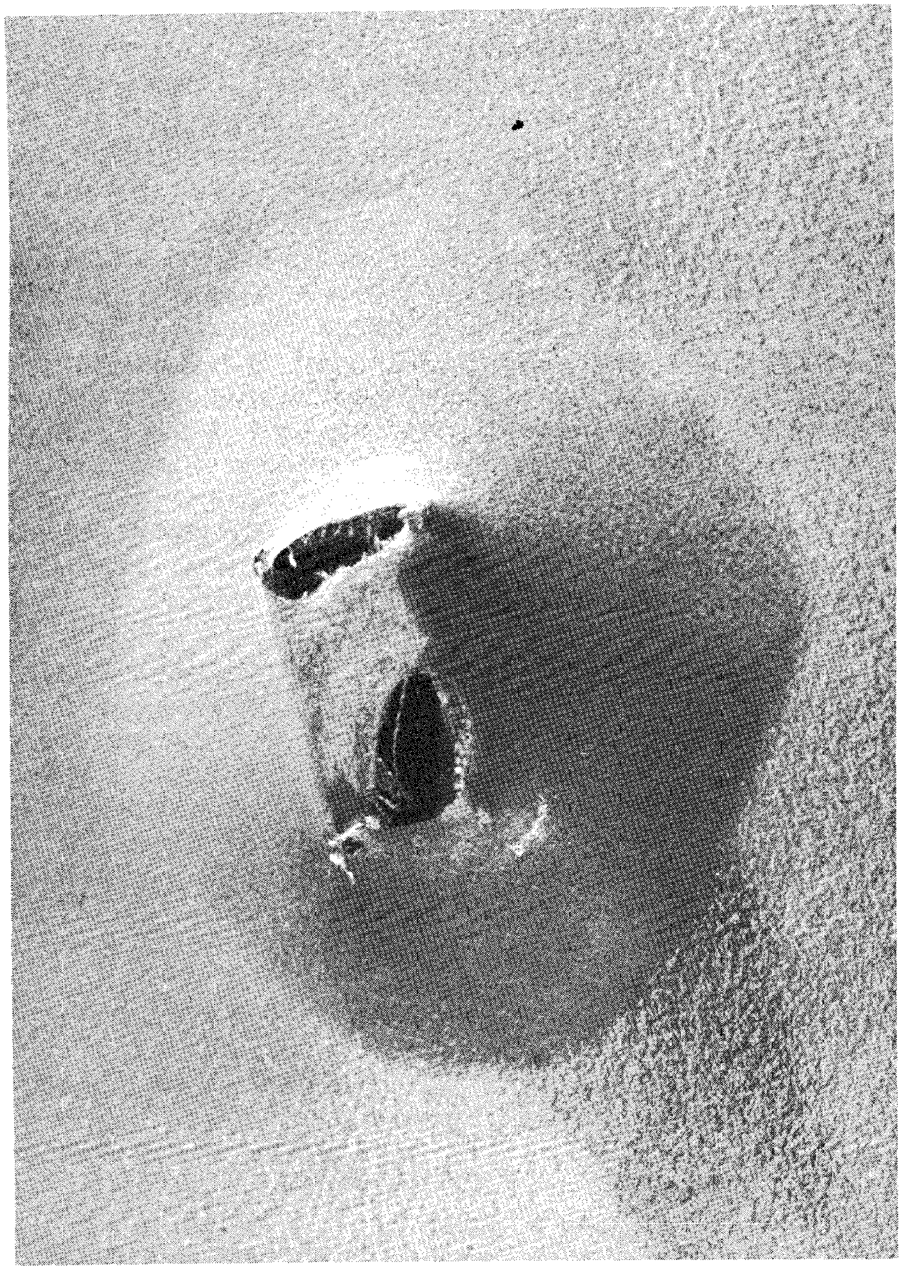


FIGURE 8 - INTEGRAL TANK LINER BONDED TO SIMULATED TANK WALL

The frangible bond concept has allowed the inner-liner to separate and the liner is free to react as petals form and the test chisel penetrates. The liner material has failed due to petal contact and failure to elongate.

The sheet was easiest installed since a bonding agent could be sprayed on the aluminum and the foam gently pressed into the wet cement film. The inner-liner material could be coated with cement and pressed against the other side of the foam sheet or a light spray of cement put on the foam and the inner-liner pressed against this wetted surface. The sheet foam frangible bond did allow the inner-liner to move away from the aluminum surface tending to protect the chisel created petals from contacting the liner. (See figure 8, page 21.) The sheet foam was first tested using 1/4 inch thick material. The frangible bond allowed the breakaway of the inner-liner and provided protection from the petal edge. However, the petal corners did occasionally cause the liner to fail. The depth of penetration would be 1/2 inch or less, in fact failure would occur before the dart had penetrated far enough to be in contact with the inner-liner. The sheet foam thickness was increased to 1/2 inch and tests conducted. More petals were formed by repeated low energy drops and by single drops at higher energies. These tests ultimately resulted in good frangible bonding and proved that this construction protected the liner as the petals were formed if the depth of penetration was enough to put the chisel edge of the dart in contact with the inner film.

Early development of inner-liner films. - The inner-liner films used in the above tests were 0.010 to 0.030 inches thick and capable of elongating 200 to 400%. The failure of this film in these early tests was attributed to localized damage at impact. None of the films tested elongated more than 25%. The inner-liner film must have a high elongation and elongate locally or have less elongation and elongate over a much larger area to encompass a penetrating object as it may go further into the tank. Tests to evaluate this elongation were conducted next. The test specimens used the aluminum panel, 1/2 inch thick foam, frangible bond and the inner-liner film material being evaluated. Each specimen was subjected to a single impact and successive tests using greater energy inputs until the film failed. The frangible bond did prevent petal damage and a small piece of the foam was impinged and retained between the penetrating chisel and the inner-liner. High stress points in the inner-liner developed where the ends of the chisel edge contacted the liner. Ultimate failure was generally at either one or both of these ends or along the entire edge. The area involved in separation from the frangible bond varied with the liner material. Those inner-liner materials with higher modulus of elasticity would cause a bond separation over large areas. None of the materials elongated over 50%, limiting penetration protection to about a one inch depth. The liners would tear further as the chisel continued to move and open the wound at the side of the chisel.

Low tensile, low modulus of elasticity films. - Analysis of the reaction of these liner materials indicated that they must be capable of extreme elongation with low tension loads (strain) or (by definition) the modulus of elasticity must be very low. A compound with a low modulus of elasticity (but not fuel resistant) was selected and specimens prepared using the compound as the inner-liner. Test results were excellent and penetration to the maximum depth of the test fixture was accomplished without damage to the liner. Using this additional information, the laboratory was asked to supply a compound which would have the low modulus and meet the original requirements. The laboratory compounded a nitrile having a low modulus and which has a minimum elongation of 800% in laboratory tests, but also indicated that the fuel characteristics were not known. The test program was expanded in two directions because of the fuel characteristics. First, the laboratory started fuel testing the compound. Second, the feasibility of preventing fuel/extendible film contact was evaluated. The inner fuel barrier concept as used with bladder cells was applied to the highly extendible material and impact tested. When a nylon fuel barrier was sprayed directly on the highly extendible film, the impact elongation displayed by film was drastically reduced and the use of the directly applied barrier was eliminated from our consideration. The tests were repeated using a 2 to 3 mil membrane between the liquid and the extendible film as a fuel barrier interface. These tests were successful. The thin film failed and then opened around the chisel as the chisel and extendible film penetrated and came to rest without damage to the extendible film. Nylon film is recommended if this use is significant. Recent tests of the first requirement (a compound relatively unaffected by fuel) indicate that the second concept is unnecessary and redundant.

Varying the test parameters. - The test program was continued using the new test device referred to earlier. (Figures 3 and 4, pages 12 and 13.)

(A) The initial testing done on the new device was done with the test cavity filled with water, but not pressurized. The test specimen consisting of aluminum sheet, 1/2" 10 ppi frangible bond and the new, highly extendible film 0.109 inches thick. The 20 pound dart was dropped 6 feet and penetrated into the cavity 4.5 inches.

(B) The cavity was then pressurized to 5 psi and the drop height increased in increments until the maximum height of 18-1/2 feet was run. No failures were experienced. (See figure 9, page 25.)

The frangible bond foam performed its functions of reducing contact area, thus decreasing the breakaway load and of preventing direct contact between the forming metal petals and the extendible film. This foam also provided further protection by "chunking" out in a section under the sharp edge of the chisel providing a much larger contact area on the surface of the extendible film. (See figure 10, page 26.)

(C) The internal pressure was increased to 20 psi and the dart dropped from 10 feet. Again, there was no failure.

The frangible bond foam in different pore sizes was then extensively investigated to determine which combination would provide the best "chunk" ahead of the chisel. One and eight tenths pound per cubic foot foam in 10 and 40 pores per inch (ppi), 4 and 6 pounds per cubic foot foam and "foam felt" were tested. The heavier foams and foam felt do provide a "chunk;" however, the 40 ppi foam provided adequate protection in these tests and does not impose the weight penalties of the heavier foams.

(D) Figure II, page 27, is a closeup of the cavity side of the 0.109" gauge extendible film after a test using the 20 pound dart dropped a distance of 18 feet. The internal pressure was 20 psi. The cavity penetration was maximum with some bounce and return out of the cavity.

The broad "H" shape mark **roughly** in the middle, marks localized damage to the film by the chisel edges. The two pits that look like holes (but are not) on the horizontal bar of the "H" are damaged areas at the ends of the chisel edge. This film (and those from other tests) would have failed before this depth of penetration if the chunk of frangible bond foam had not been present. The appearance of a cloth weave on the surface of the film is from the cloth liner used to cure the material. There is no fabric in the film. The circular mark appearing in both figure 10 and 11, page 26 and 27, is from the fixture clamp and marks the boundary of the 4 inch diameter test area on the specimen.

Tests for shock mitigation. - The new test fixture provides an excellent means of obtaining data on the use of foam in a tank for shock mitigation, energy dissipation and flow mitigation if a tank wall is ruptured. The effect was studied under two criteria for best input. The 20-pound dart was used with a 20 psi internal pressure, but with a drop of 12 and 18 feet. The tests were conducted first without foam in the test cavity, but with the hydraulic head. Next the tests were repeated with the cavity completely filled with 10 ppi thermally reticulated polyurethane foam. Finally, the 2" of 10 ppi foam next to the test specimen was removed and 40 ppi foam (same 1.8 pound/ft. density) put in its place and the tests run. This test setup is shown in figure 12, page 29. Some of the data from these tests are reproduced in figure 13, page 30. Tests 1.1.13 and 1.1.21 are control tests, giving data on tests from 12' and 18' without foam in the test cavity. Tests 1.1.19 and 1.1.20 were 18' drops with the two methods of filling the cavity with foam. The initial surge of pressure as measured in container opposite the entry point, was much less in foam-filled test than that of the 12' drop in water or 18' control test. Further, the frequency response in the foam-filled tests was much lower. The penetration of the chisel into the cavity was greatly attenuated, the foam-filled cavity being penetrated to a depth of 6-3/4" from an energy input of 360 foot pounds as compared to the same penetration from an input of 240 foot pounds where no foam was used. Data from these closely controlled tests show that the internal foam is effective in shock mitigation and energy dissipation.

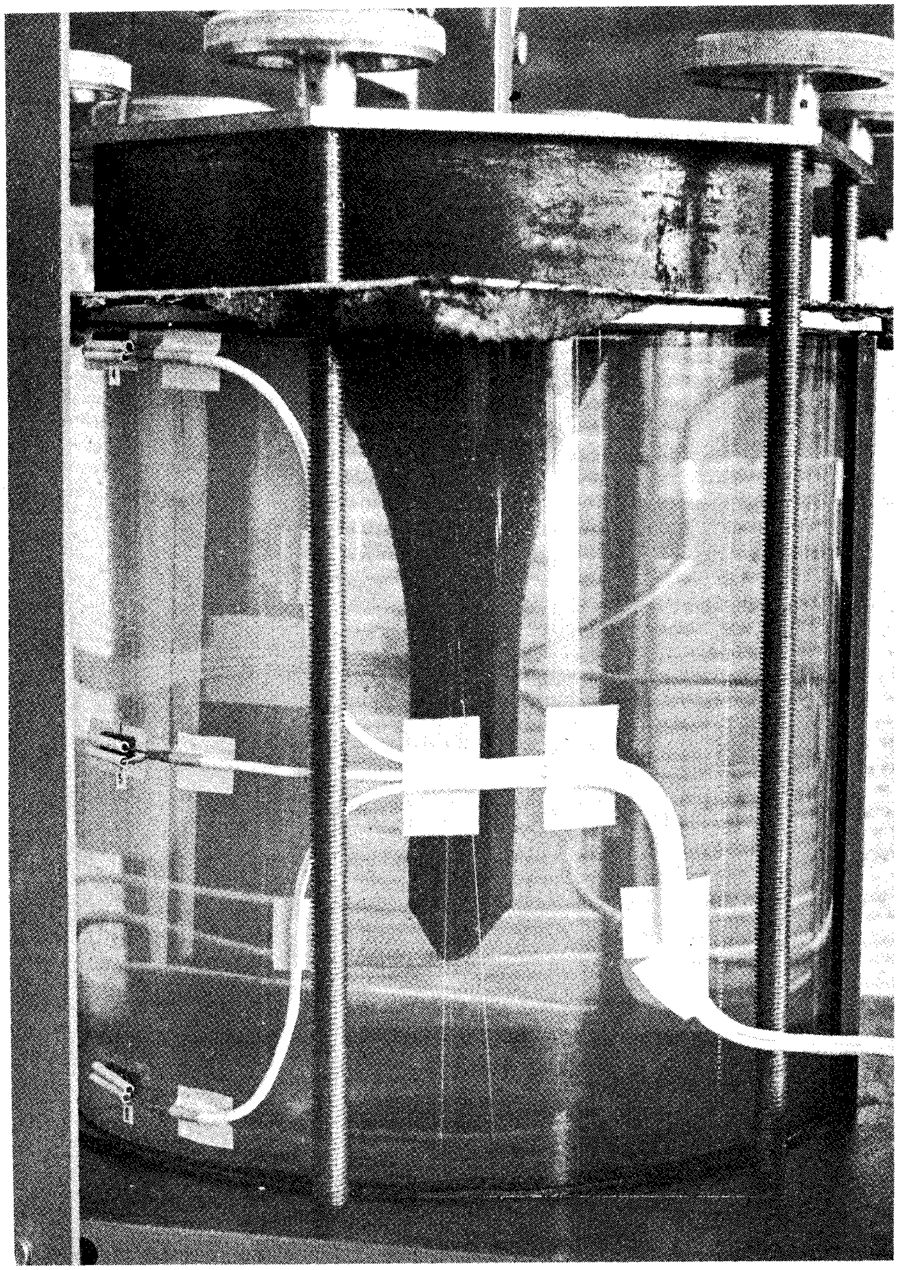


FIGURE 9 - VERIFICATION OF THE INTEGRAL TANK/INNER-LINER CONCEPT

The extendible film completely encompasses the penetrating chisel without loss of liquid integrity. This has been possible due to the frangible bond between the film and simulated tank wall and the extreme extendibility of the film within a very short time frame.

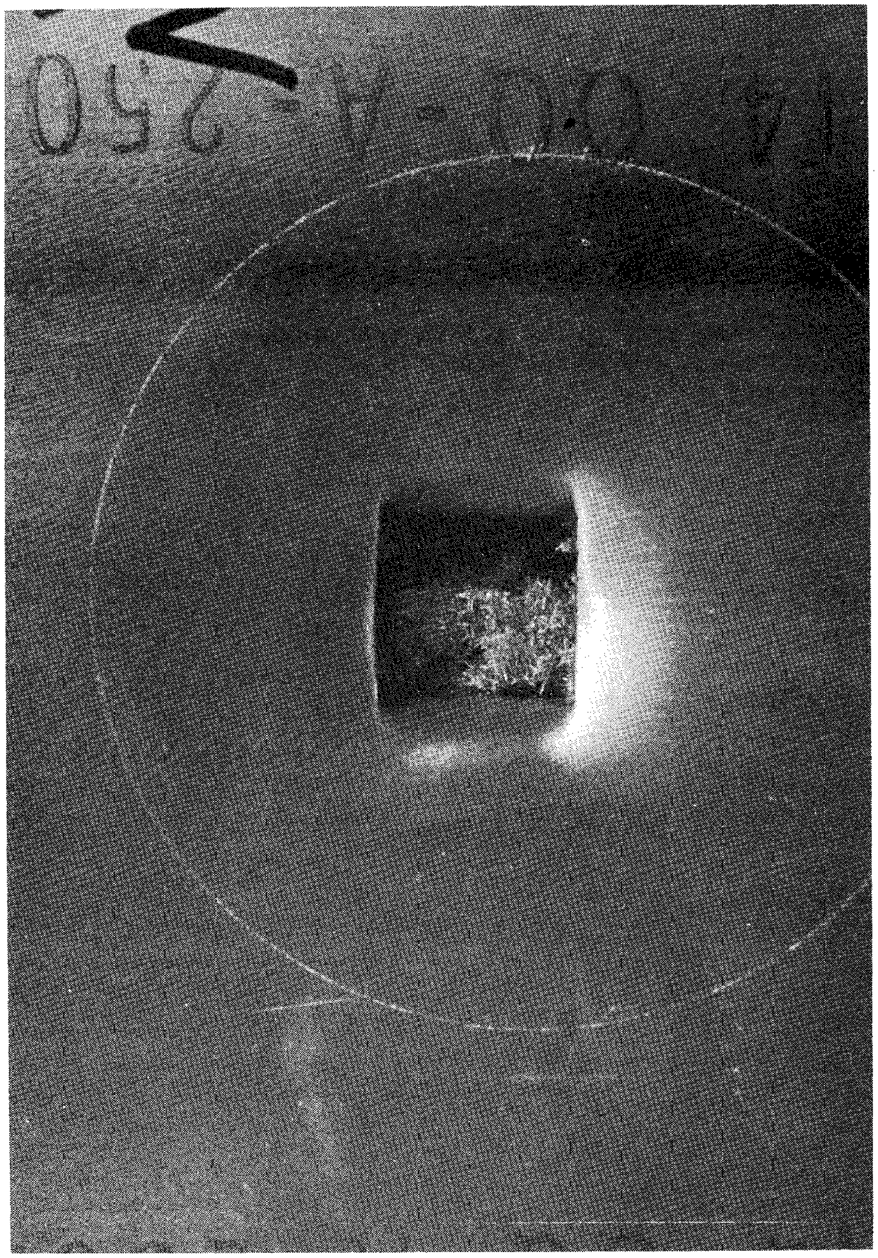


FIGURE 10 - FRANGIBLE BOND FOAM
MATERIAL AFTER TEST

The foam seen in the wound is torn from the 10 pore per inch frangible bond as the chisel penetrates the specimen. This piece of foam is held between the chisel edge and the extendible film (inner-liner) providing excellent protection for the film.

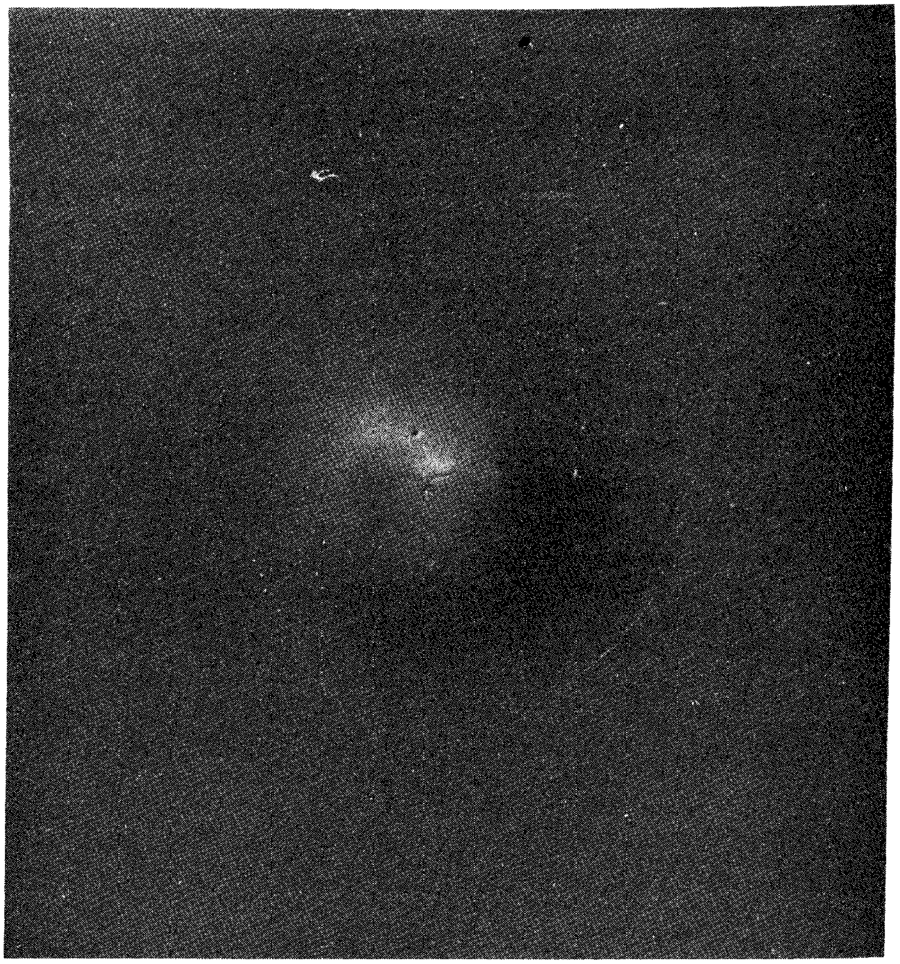


FIGURE 11 - EXTENDIBLE FILM AFTER TEST

The film surrounding the "H" shape has been elongated approximately 900% by a chisel penetration test. The "H" is local damage from the chisel. The two apparent cavities where sections of the "H" join, represent severe damage to but not penetration of the film from the extremely sharp ends of the chisel edge. The fabric weave pattern in the surface is from the liner used to cure the film, there is no fabric in the extendible film.

The effect of varying working area. - The earlier test program limited the active specimen to a circular area 4" in diameter. This is one of the parameters for test equipment used in industry. The new test device allowed observation of the materials when using a circular area 10.5 inches in diameter. Tests were run dropping the chisel from different heights and pressuring the test cavity up to 20 psi. The data obtained were comparable to the data from the previous tests where this area was limited to the 4" diameter circle. The 4" diameter test area was exceeded only when the test cavity was empty and the penetration was 11". The area tests were continued, manually inserting the chisel into a previously impacted specimen free of the test fixture. This allows the chisel to penetrate approximately 16". The extendible film was pulled away from the frangible bond in a circle about 9" in diameter. (See figure 14 and 15.) This is the maximum area to be involved since any internal pressure would act on the surface of the cone, formed by the extendible material, collapsing it. Figure 15, page 32 shows very little distortion in the grid pattern on the surface of the extendible film when viewed along the conical axis. Likewise, figure 14, page 31 graphically displays the elongation in the extendible film at various points on the surface of the cone. This elongation varies from none at the outer edge to approximately 700% at the chisel end.

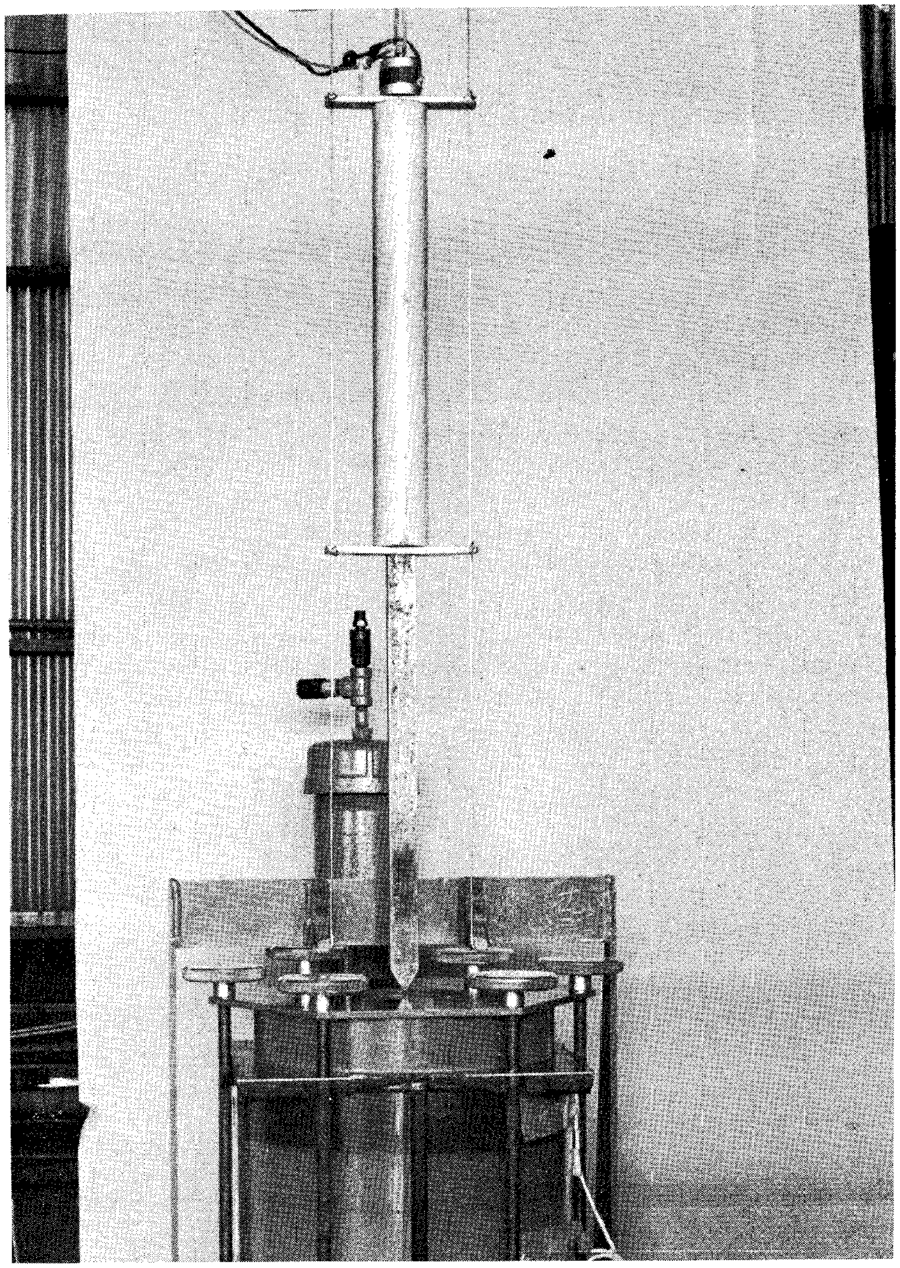
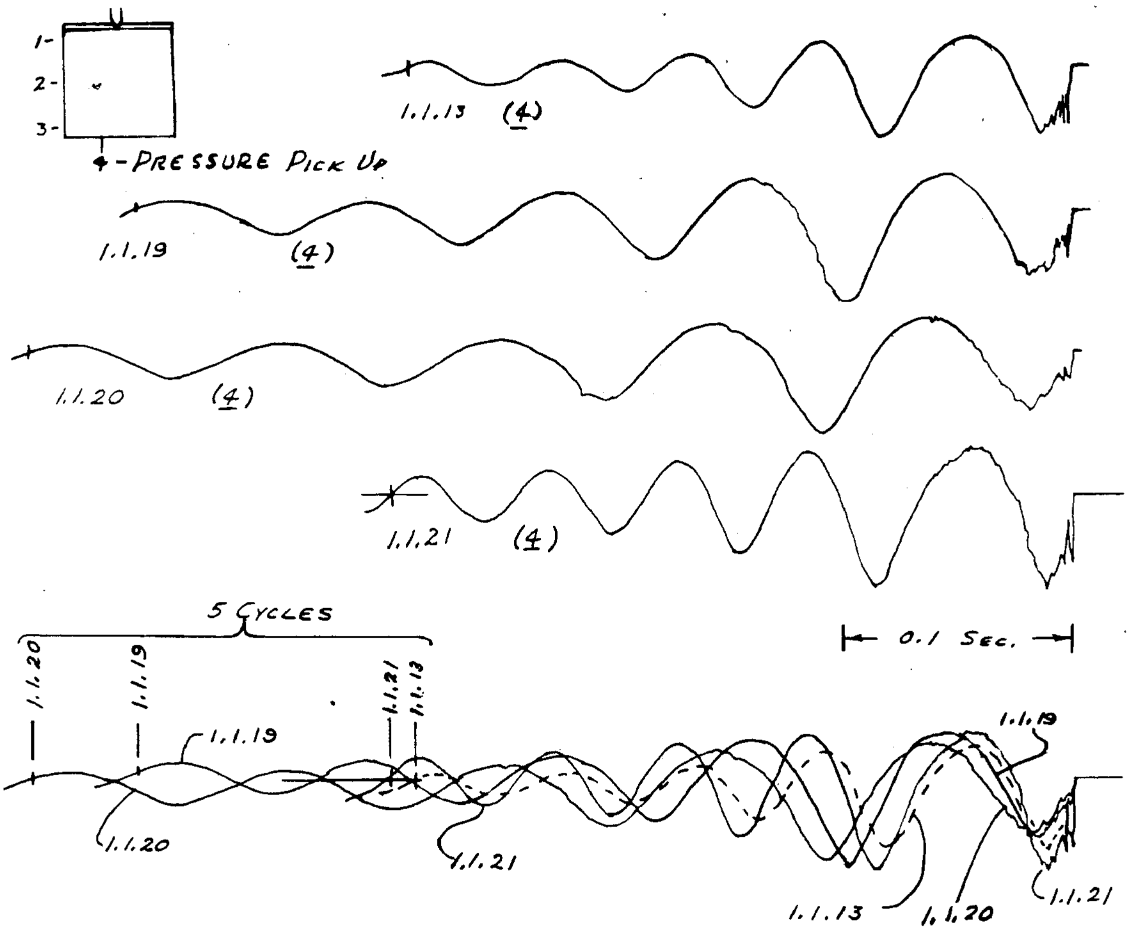


FIGURE 12 - THE DART AND FOAM-FILLED CAVITY

The dart shown in this picture is the twenty-pound dart. The magnetic release is shown at the top of the picture. The cavity was filled with various combinations of 10 pore per inch (grey) and 40 ppi (black) foam for both impact and expulsion tests.



TEST No.	DROP	ENERGY INPUT	FOAM IN CAVITY	CHISEL PENETRATION	(4) PRESSURE TRANSDUCER
1.1.13	12'	240 FT-LB.	NONE	6 3/4 IN	14.4 PSI
1.1.19	18'	360 " "	10 PPI	7 1/4 IN	10.8 PSI
1.1.20	18'	360 " "	40 & 10 PPI	6 3/4 IN	10.8 PSI
1.1.21	18'	360 " "	NONE	9 1/8 IN	25.2 PSI FIRST PEAK

FIGURE 13 - CAVITY PRESSURE AND FREQUENCY ATTENUATION AS FOAM IS INTRODUCED INTO THE TEST CAVITY

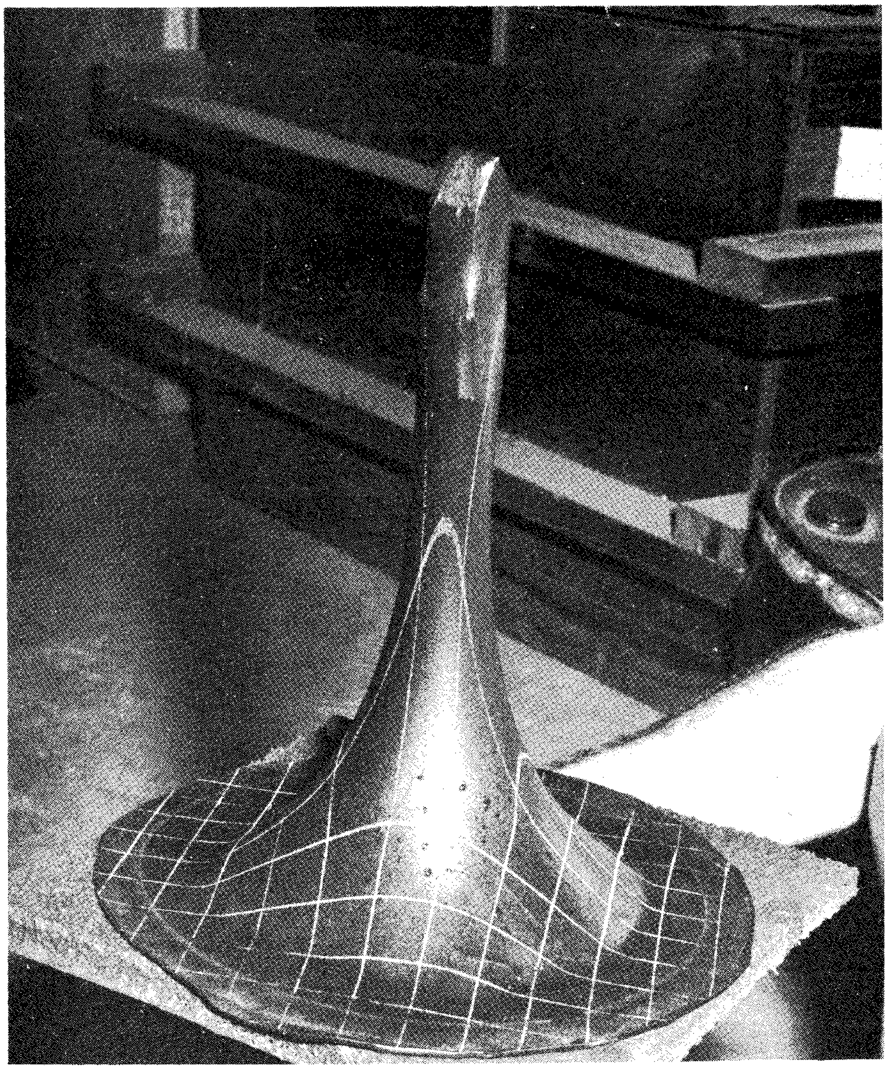


FIGURE 14 - EXTENDIBLE FILM ELONGATED 1200%

The mechanics of elongation in the extendible film are depicted in this picture. A test was made in the fixture, then the dart and specimen removed. The chisel was reinserted in the wound and then penetrated to a depth of 16 inches by hand. The area pulled away from the frangible bond is roughly a circle about nine inches in diameter. The one inch square grid painted on the film shows no distortion at the edge of the specimen and extreme elongation at the end of the chisel. Note the bits of frangible bond foam under the film along the sides and end of the chisel.

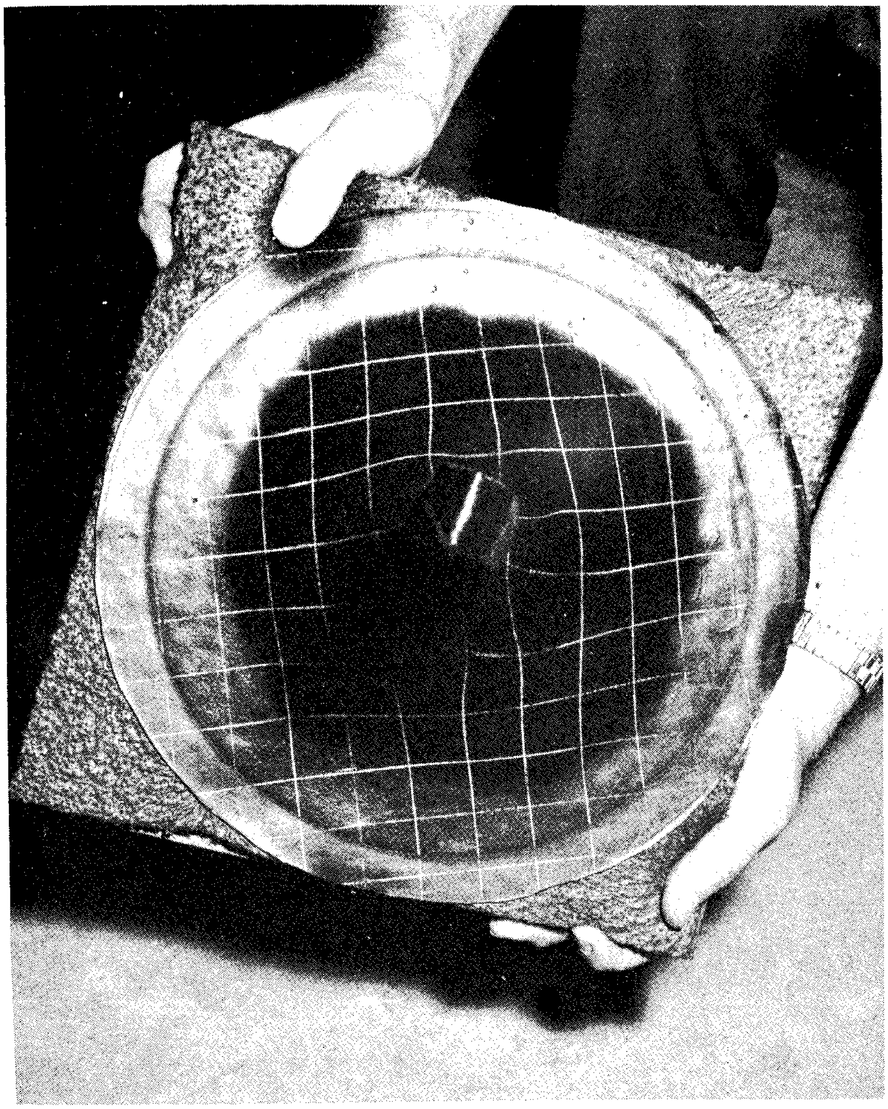


FIGURE 15 - THE SAME TEST AS SHOWN IN FIGURE 14

The one inch grid painted on the extendible film before elongation shows very little distortion on elongation in this view. The area detached from the frangible bond is easily seen in this view.

REDUCTION OF FUEL EXPULSION THROUGH AN OPEN RUPTURE

Assumes failure of integrity systems. - The test program has evaluated crash/fire protective concepts assuming a system which maintains liquid integrity. The following evaluation is of the concept of reducing fuel loss through a tank wall by use of an internal material to reduce internal flow to the wound and/or effectively reduce the wound size by creating pressure losses related to flow velocities.

Preliminary test to establish control comparison. - The first tests of this concept were simply a continuation of the impact test evaluating the frangible bond/extendible film concept. These tests were conducted following the drop of the chisel by first depressuring the cavity and removing the chisel. Then the cavity was repressurized pneumatically as before and the measure increased forcing the extendible film to drape and then elongate through the hole created by the falling chisel. The film was elongated to failure and the flow of water through the open wound observed.

(A) The first test was run with no foam in the cavity. Flow from the cavity through this wound created a roughly spherical cloud of water particles with a 15 foot radius.

(B) The concept was again tested following an impact test where the test fixture cavity was filled with 10 ppi reticulated foam. The same spherical shape was created, this time the radius was only 6 feet.

(C) The next test was run with two inches of 40 ppi foam in the top of the cavity and 10 ppi foam filling the rest of the cavity. Again the spherical cloud appeared; however, its radius was limited to 3 feet.

These tests were indicative of the effect of the concept but the data was not comparable. The pressure at the rupture of the extendible film varied widely due apparently to the aluminum petals. The presence of foam fragments from the frangible bond and possibly some extendible film material would alter flow characteristics through the wound now acting as an orifice. In fact, the highest burst pressure recorded occurred during a test which used 2 inches of 40 ppi foam and created the lowest flow. The mode of testing was modified, removing all the test variables except the foam pore count.

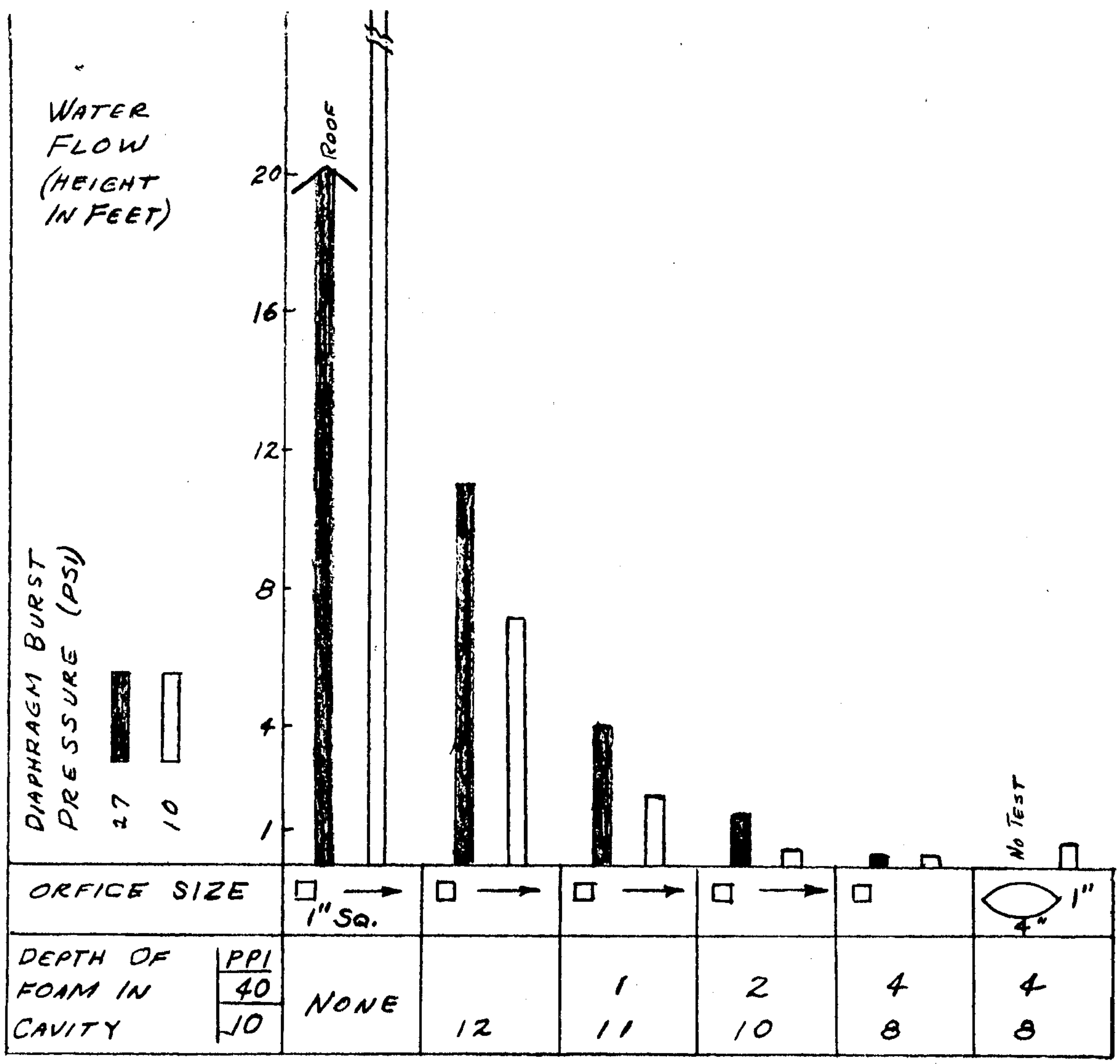
Description of testing procedure. - The impact test specimen was replaced by an aluminum sheet with a one inch square hole in the center and a plastic membrane (mounted beneath the aluminum sheet). The plastic membrane provided a burst diaphragm and the one inch hole a fixed orifice. The diaphragm burst at approximately 27 psi which simulated a high deceleration force in an aircraft tank. Regulated air at 30 psi was introduced into the test fixture plenum chamber. Flow through the air regulator was limited and high flow of water out of the test fixture caused a drop in cavity pressure - again a condition which could simulate changing deceleration of the airframe or a drop in hydraulic head due to flow out of an aircraft tank. Tests were conducted without foam in the cavity, with the cavity filled with 10 ppi foam, then with one, two and four inches of 40 ppi foam at the top of the cavity and the balance of the cavity, in each case, being filled with 10 ppi foam. The 10 ppi foam in these latter tests served to hold the 40 ppi foam in place.

Comparison of pore size and foam thickness. - Data from tests without this supporting foam falls into the same category as those with the foam and where there is no change in the 40 ppi thickness. Data from these tests show the same dramatic attenuation of flow as smaller pore size foam and more foam thickness is introduced in the test. Flow from the test with no foam reached some 40 feet above the orifice. The introduction of 10 ppi foam in the cavity reduced the flow, limiting the height reached to a range of 9 to 13 feet. Replacing a like amount of 10 ppi foam with a one inch thickness of 40 ppi foam reduced the flow further and reduced the spherical cloud of water particles to a 3 to 6 foot radius. A two inch thickness of 40 ppi foam reduced the radius to values from one to one and one-half feet. Four inches of 40 ppi foam eliminated the cloud of particles and flow resembled highly turbulent flow in a channel. These data are tabulated in table III, page 35. The flow during the tests using four inches of 40 ppi foam was so low that the regulated air input was able not only to maintain cavity pressure but increase after the diaphragm burst, approaching the 30 psi limit. This means that flow through the orifice decreased once it was initiated.

Stabilization of test cavity pressure. - The rate of flow through a wound is a function of the pressure. The test plan was changed and a new diaphragm material used which burst at approximately 10 psi. An accumulator was added so the test cavity pressure would be maintained. The test fixture was moved outside to allow uninterrupted flow during the open test and to improve the photography. The data from these tests are also tabulated in table III, page 35. Figures 16 through 19, pages 36 through 39, show the test results.

Variation of wound shape and size. - Flow is also a function of wound size. Also, the action of the internal foam should be different as wound size and configuration changes. The test plan was changed once again. The orifice was changed from the one inch square hole to a football shape having a one inch maximum width and a four inch length. Tests were run using no foam and four inches of 40 ppi foam. Flow through this wound with four inches of 40 ppi foam in the cavity is shown in figure 20, page 40.

TABLE III



EXPULSION FLOW ATTENUATION USING INTERNAL FOAM

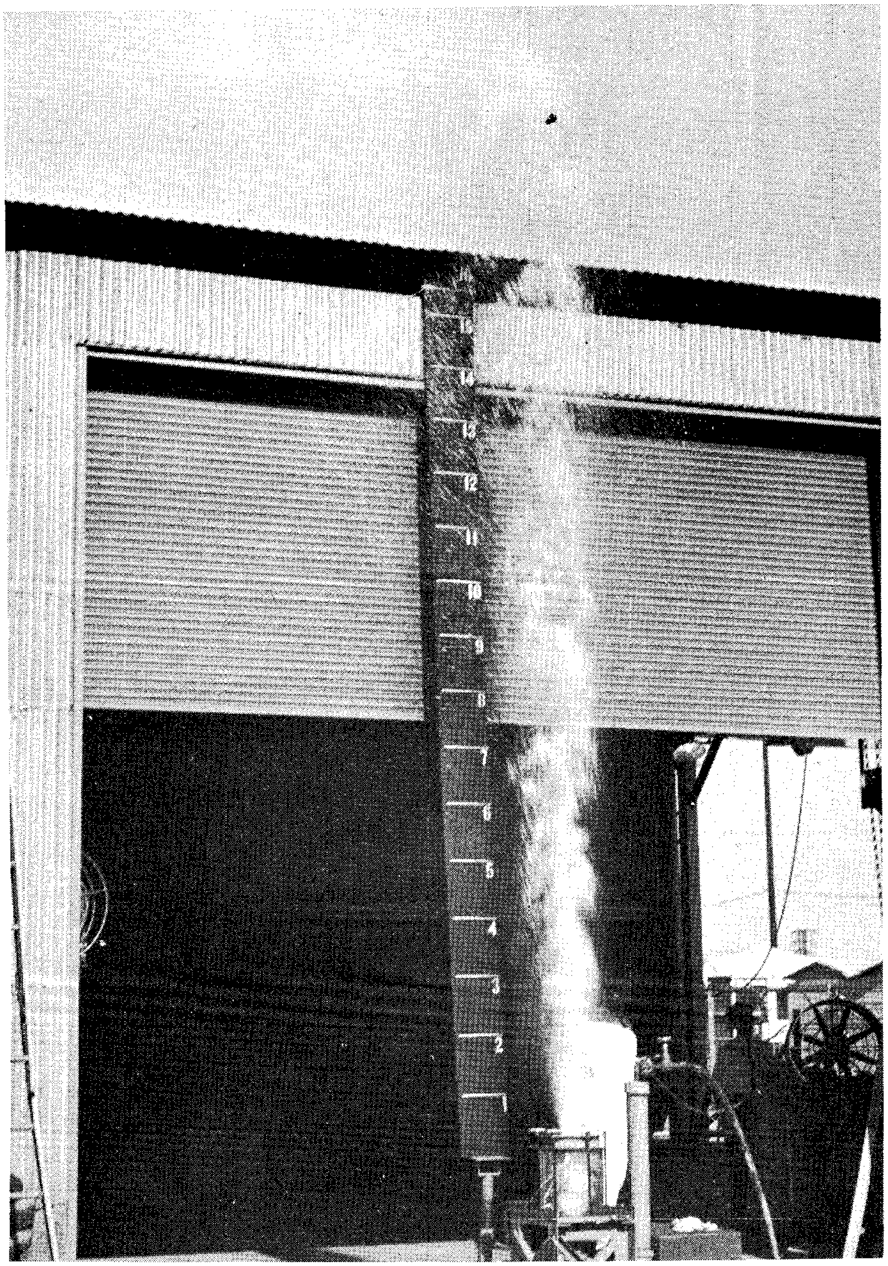


FIGURE 16 - FLUID EXPULSION WITHOUT INTERNAL FOAM

This test is the control for a series of tests to determine the effect on flow through a given wound when foam is used in a tank. Figures 17, 18 and 19 show the reduction in flow in this test series where the only variable is the pore size and layer thickness of the foam in the cavity.

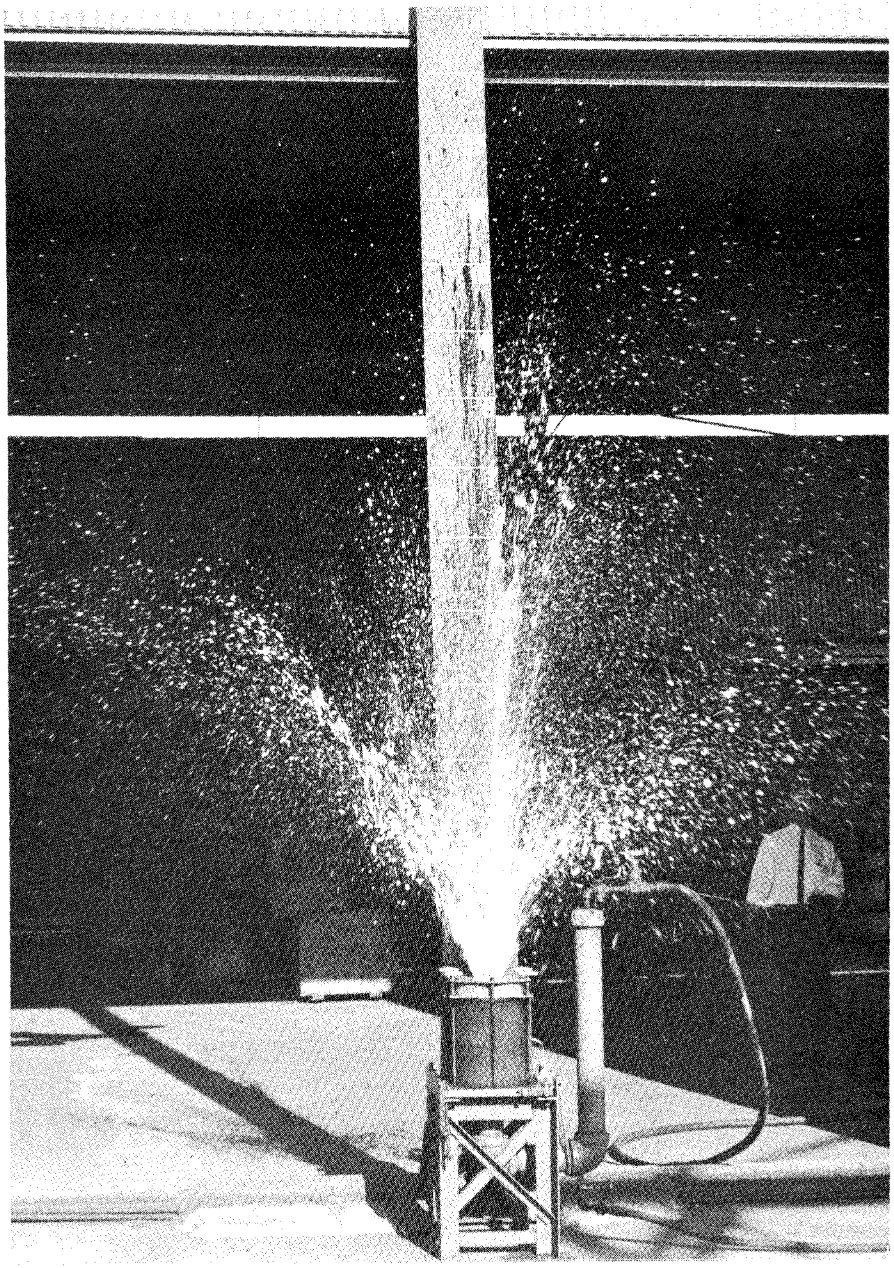


FIGURE 17 - FLUID EXPULSION WITH TEST CAVITY FILLED WITH 10 PORE PER INCH FOAM

The test cavity is filled with 10 ppi foam. The picture shows flow at diaphragm burst, steady flow was about seven feet high. The peak flow in the control test (no foam) reached a height of thirty-five feet, leveling off to approximately twenty feet.

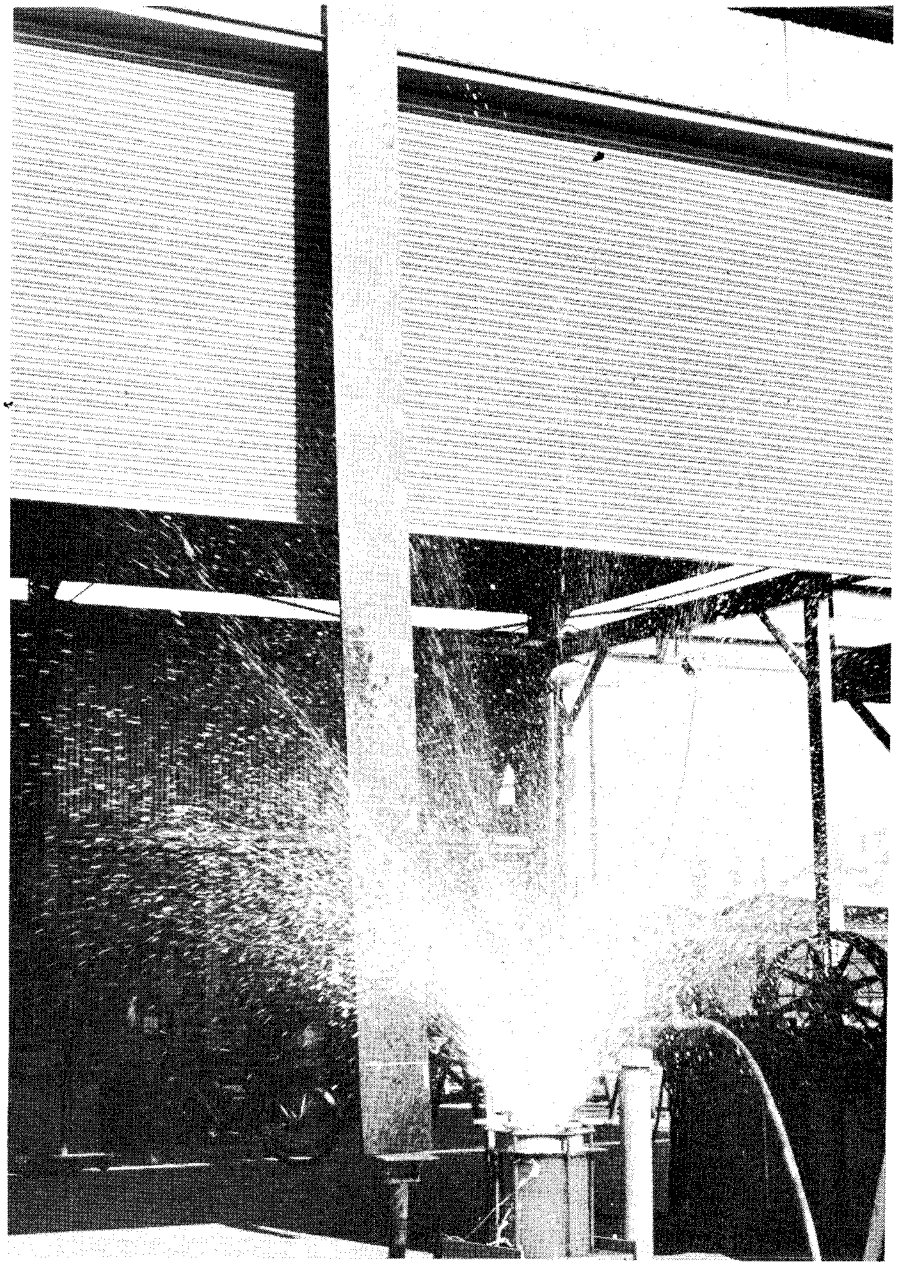


FIGURE 18 - FLUID EXPULSION WITH TEST CAVITY FILLED WITH 10 AND 40 PORE PER INCH FOAM.

The test cavity is filled using a one inch layer of 40 ppi foam (black) and eleven inches of 10 ppi foam (grey). Flow at diaphragm burst is shown. Steady flow was below five feet height.

FIGURE 19 - FLUID EXPULSION WITH TEST CAVITY FILLED WITH ADDITIONAL 40 PORE PER INCH FOAM

The test cavity is filled using a four inch layer of 40 ppi foam (black) and eight inches of 10 ppi foam (grey). Flow at diaphragm burst is shown. Steady flow was three to four inches high.

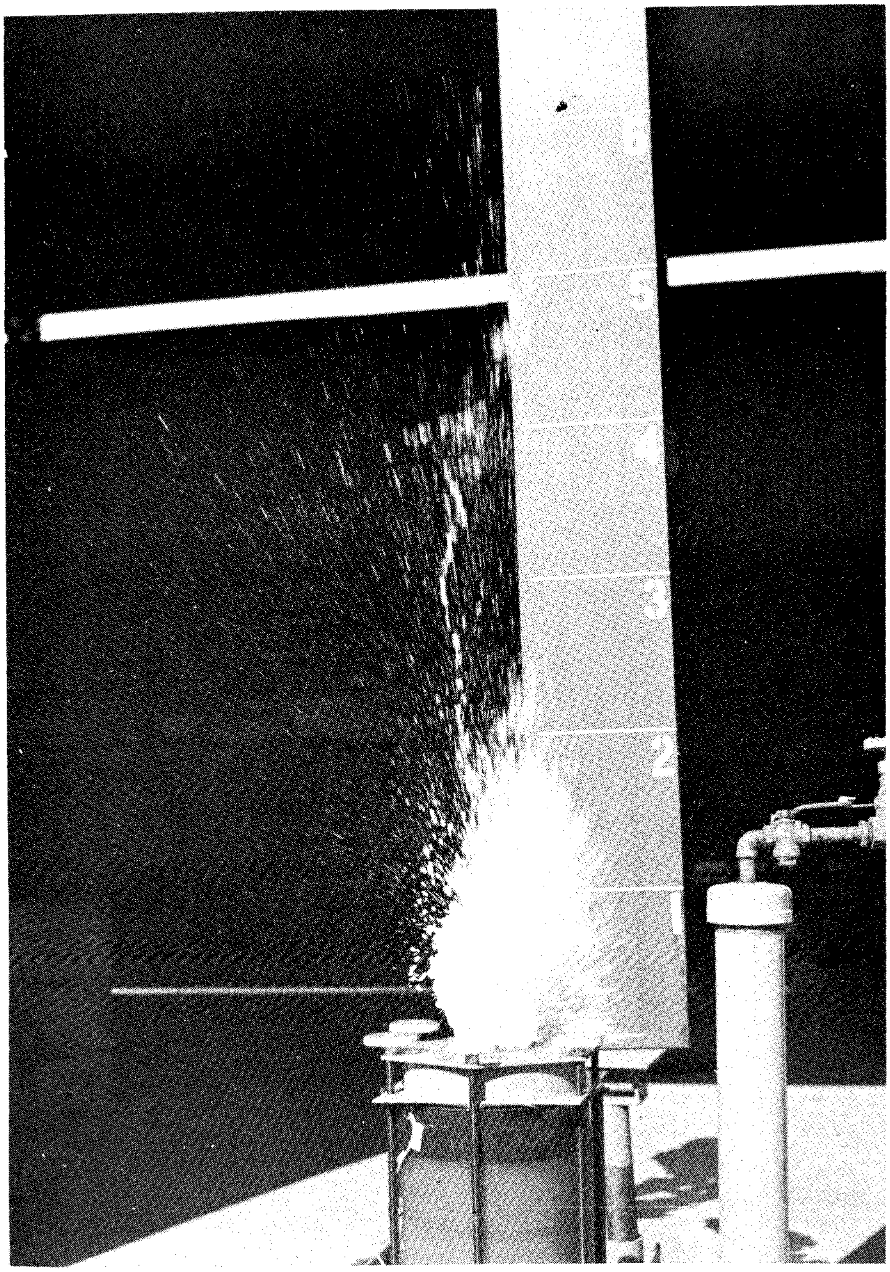


FIGURE 20 - FLUID EXPULSION WITH LONGER ORIFICE

The test cavity is filled using four inches of 40 ppi foam (black) and eight inches of 10 ppi foam (grey). Flow at diaphragm burst is shown. The orifice is a football shape, four inches long and one inch wide.

THE APPLICATION OF PROTECTIVE CONCEPTS TO THE AIRFRAME

Review. - Previously in this report a number of protective concepts have been discussed which may be used in varying degrees and combinations to add relative invulnerability to aircraft fuel tank construction during and following survivable crashes. These included:

(A) The principle of preventing penetration by containment (expandible film).

(B) The principle of preventing penetration by load distribution (fibreglas-nylon felt layers).

(C) The principle of preventing high velocity expulsion of fuel from a penetrated or ruptured tank (40 pore per inch reticulated foam).

The first and third principle interacted in that the foam performed other functions supporting principle (A) without affecting its capability of performing principle (C). For the expandible film to operate effectively, a frangible bond was necessary which was found to be best fabricated of (40 ppi) reticulated foam. This was the same material selected to best perform the function of principle (C). In addition, the thickness of the foam accommodated the metal petaling caused by a foreign object being forced through the tank wall. This accommodation in turn protected the expandible film from sharp edges of tank or supporting structures. Finally, pieces of the foam consistantly impinge themselves upon the point of the penetrating object and remain between it and the expandible film, adding substantially increased protection.

External to the tank, vulnerable areas may be protected with small increase in weight and no attendant fuel displacement by layers of fibreglas and nylon felt, which spread the impact load over a larger area of the tank surface and reduce the probability of certain types of penetration. The results in Table I, page 16, (impact chisel) show that multiple layers of this protective material can reduce the probability of certain types of penetration by as much as 2100% when compared to unprotected typical coated fabric used in fuel cell construction. This protective system is external and does not interfere with internal tank inspection. Materials installed inside fuel tanks require a method of quick removal for inspection and easy, rapid reinstallation. Thus, the following comments relate to factors affecting installation planning.

INSTALLATION OF CURTAIN TYPE COMBINATION ASSEMBLIES

Problems affecting retrofit. - It should be basically assumed that any protective assemblies installed inside a fuel tank, be it of the bladder cell or integral type, makes inspection almost impossible if the accumulation of hydraulic, electrical and fuel lines customarily passing through the tank are not re-routed. This would obviously present an almost insurmountable obstacle for such an installation if retrofit, but must be taken into consideration with respect to design criteria for new aircraft fuel systems. Any future simulated or actual tank crash testing should assume such re-routing.

Extent of protection and probable construction configuration. - Tests have indicated that it is not essential to provide such curtain protection for all internal surfaces of the tank. Therefore, figure 21, page 43, illustrates recommended areas of protection as being the tank bottom, front and a front portion of the top and sides. Figure 22, page 44, illustrates a typical combination of structures which might be found inside an integral tank. It would not be practical to "smooth" all these varying contours into relatively flat surfaces nor would it be necessary. Figure 23, page 45, is intended as an overlay for figure 22, page 44, indicating steps in construction of a curtain assembly. It is not intended that the assembly would be "manufactured" inside the tank, but rather in open structures and forms identical to the tank construction. First, blocks of thermally reticulated polyurethane foam of 40 pore per inch designation and probably of 2 inch thickness may be cut and temporarily adhered to the forms. Figure 24, page 46, is an alternate overlay illustrating that this may also be accomplished with sheet thermally reticulated polyurethane foam. In either case, this foundation assembly will receive a premolded or flat expandible film sheet illustrated by figure 25, page 47, which will be adhered to the foundation by means of a frangible bonding system previously discussed. Preference is felt for the "block" foundation illustrated in figure 23, page 45, over the "roll" foundation in figure 24, page 46, since it is believed that the block system will tend to hold its shape better during removal and inspection and will accommodate flat stock expandible film.

Actual installation. - Following completion of the curtain assembly on forms, it will be removed and turned over exposing the surface to contact the tank walls. At points of attachment, strips of rubberized fabric will be attached to the "outside" of the thermally reticulated polyurethane foam block foundation with a non-frangible bond. This will act as the base for permanently adhering strips of Velcro or equivalent types of fasteners. Some snap type mechanical or plastic fasteners may also be applicable. Velcro is preferred at present due to not being effected by hydrocarbon fuel and due to its accommodation of minor misalignments during installation. All that remains to complete the installation in the aircraft is to adhere the mating Velcro or equivalent component to the surface of the tank structure matching the position of the material adhered to the curtain assembly. Now the entire assembly may be quickly and easily installed and subsequently removed for inspection. Similar protective systems may be installed inside fuel cells without the requirement for Velcro attachment since inspection would not be necessary. In this case, permanent adhesive would be employed.

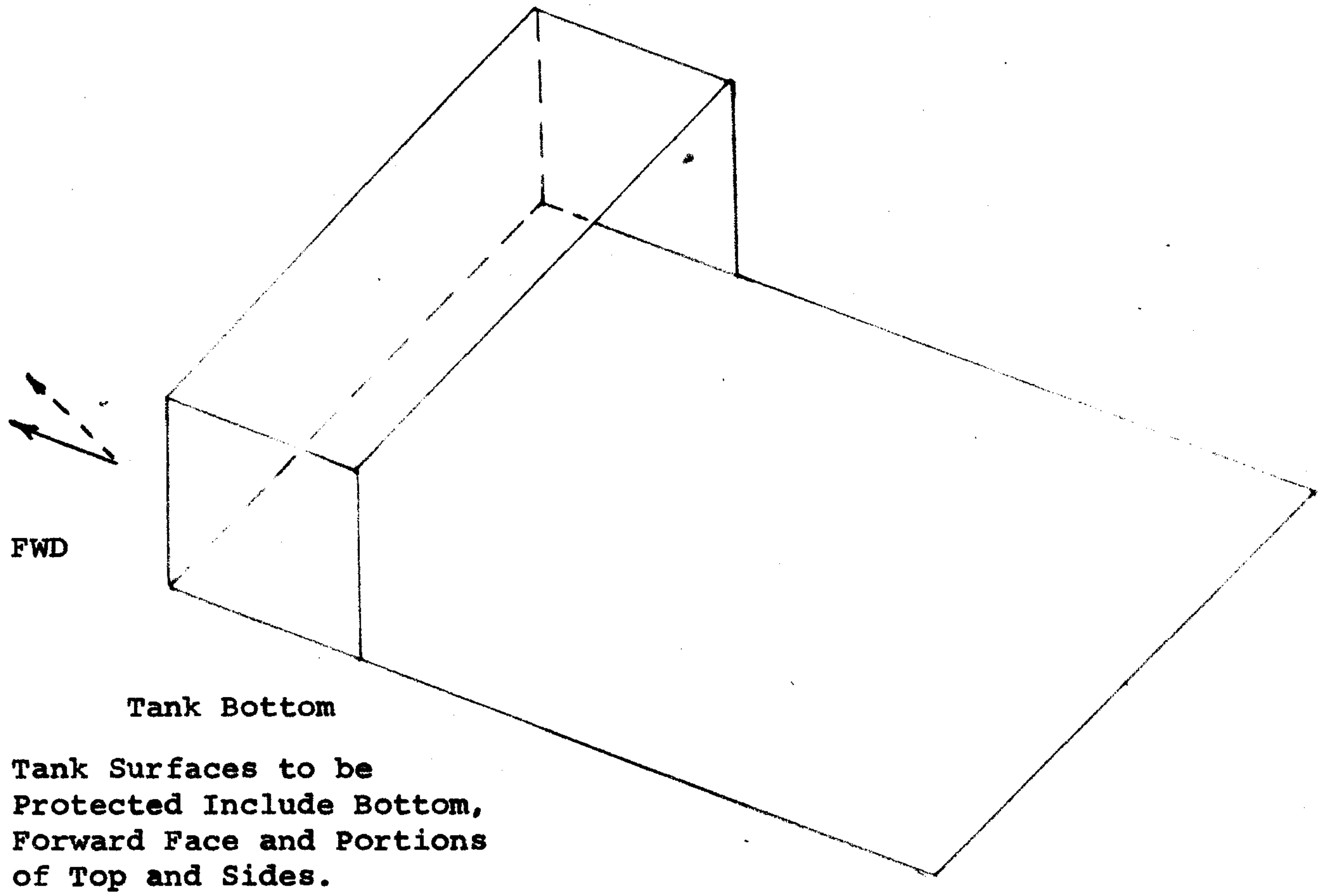


FIGURE 21 - SUGGESTED AREAS OF INTEGRAL TANK PROTECTION.

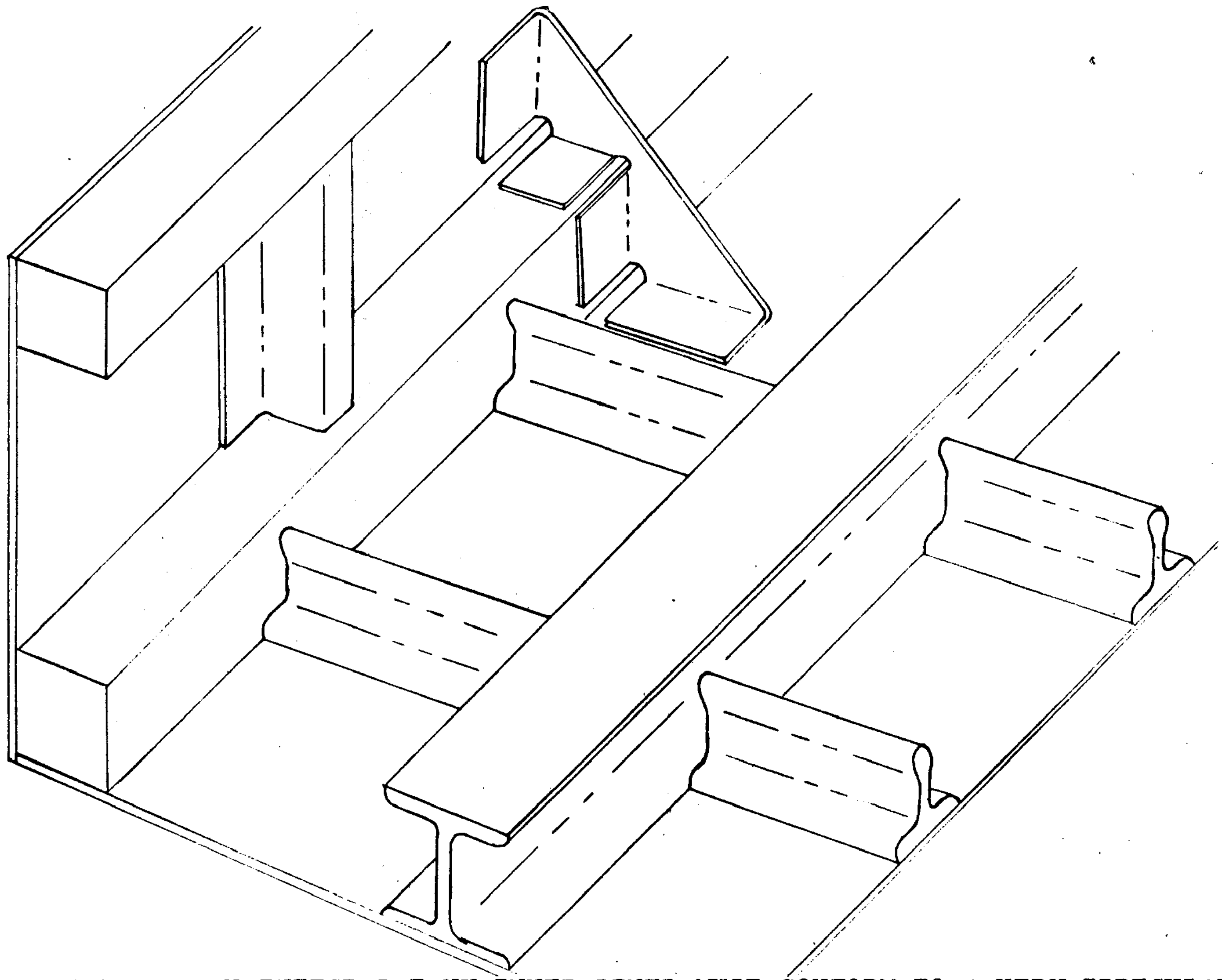


FIGURE 22 - AN INTEGRAL TANK INNER-LINER MUST CONFORM TO A VERY IRREGULAR SURFACE.

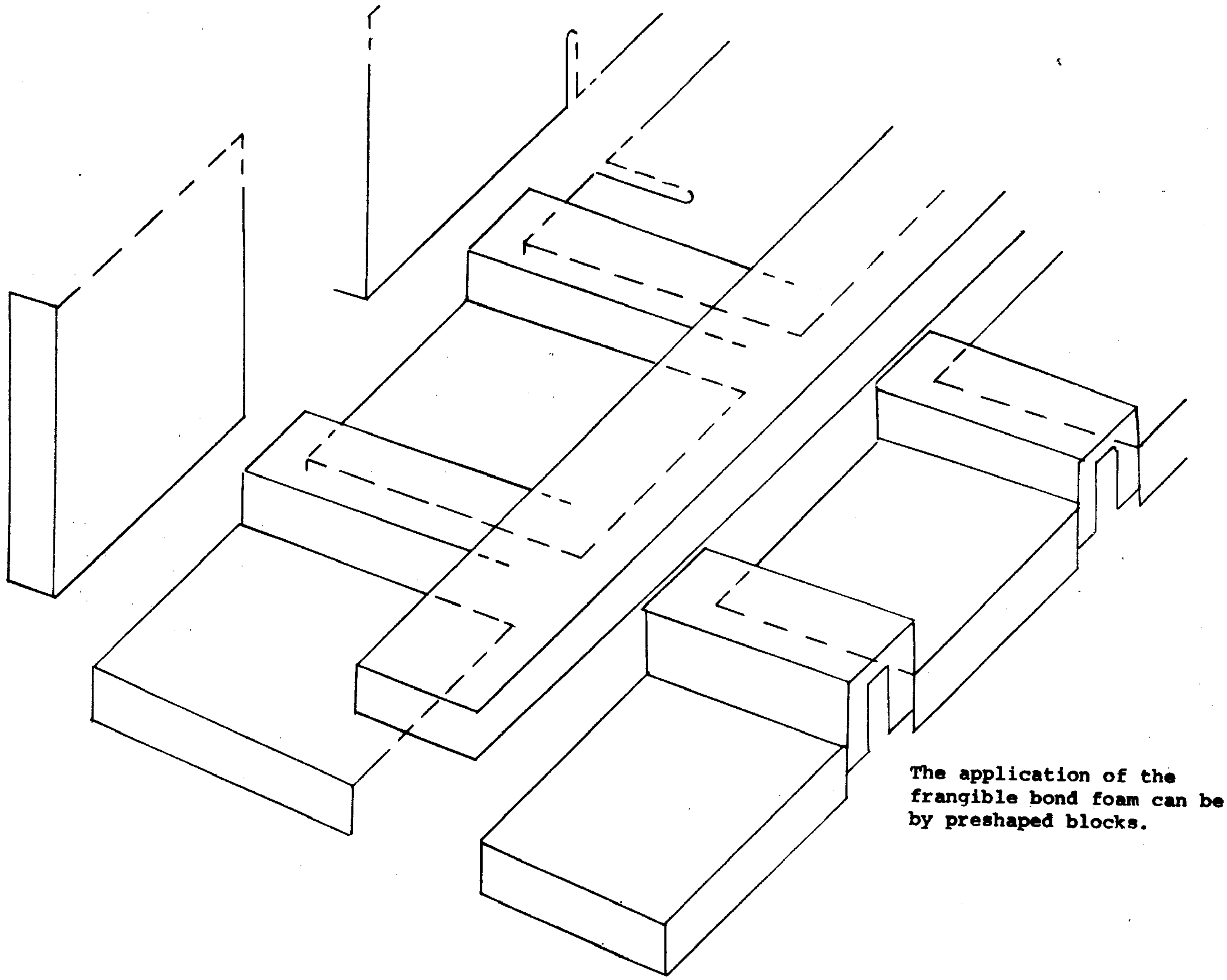


FIGURE 23 - ONE CONCEPT OF FRANGIBLE BOND APPLICATION.

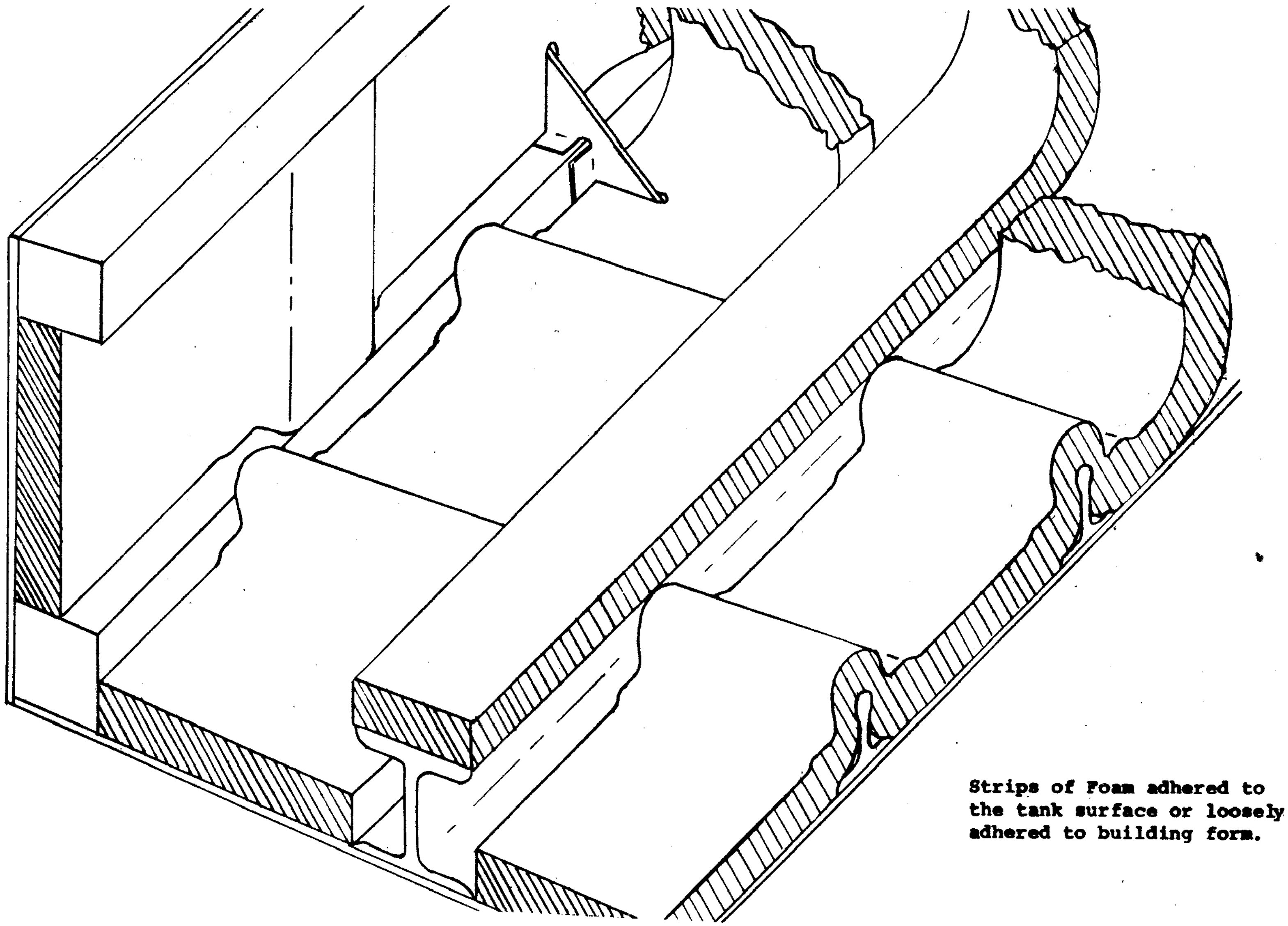
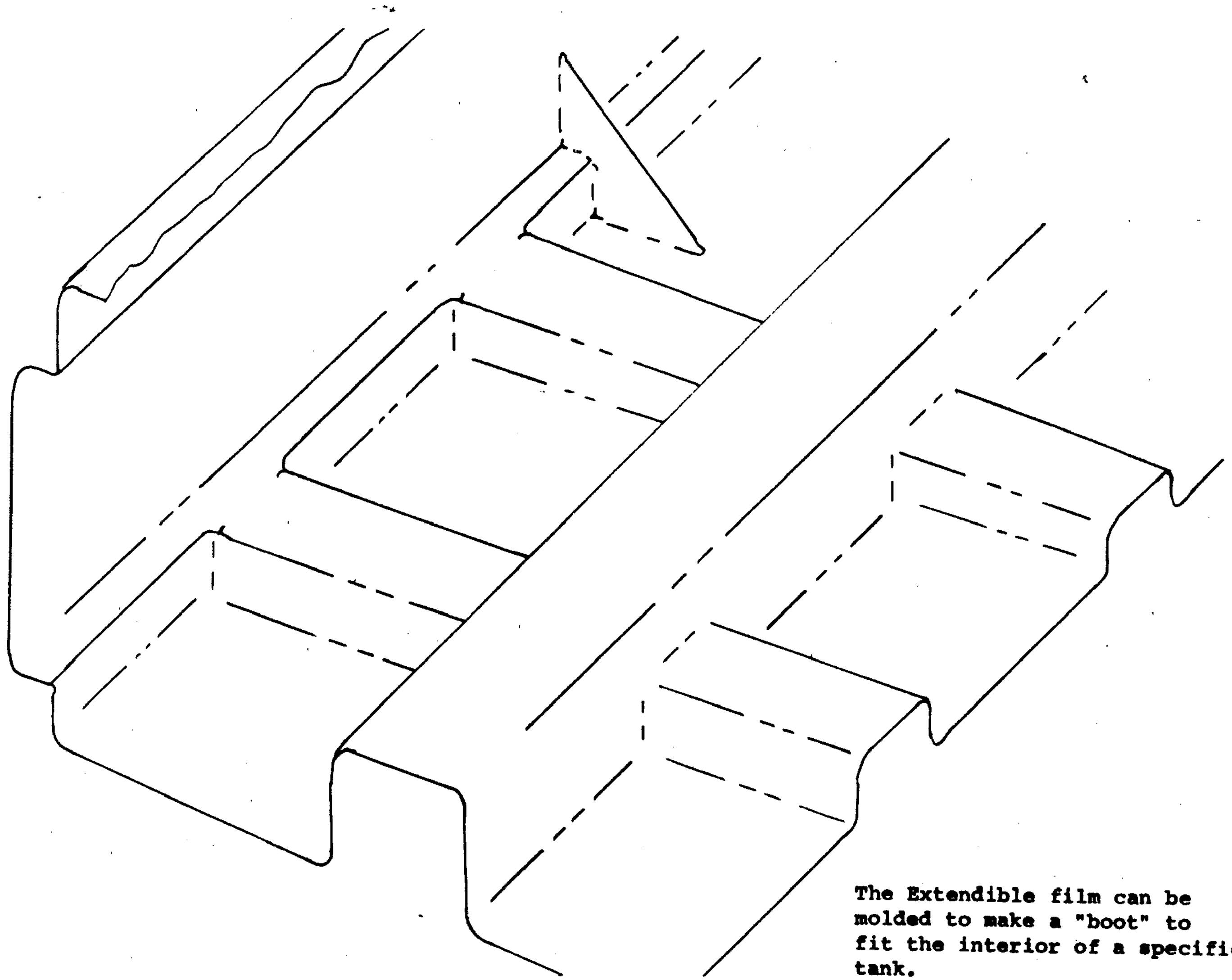


FIGURE 24 - ALTERNATE CONCEPT OF FRANGIBLE BOND APPLICATION.



The Extendible film can be molded to make a "boot" to fit the interior of a specific tank.

FIGURE 25 - EXTENDIBLE FILM APPLICATION CONCEPT.

Installation of fibreglas/nylon felt external protective layers. - In accordance with data developed elsewhere in this report, penetration resistance increases with additional layers of this combination of materials in which the nylon felt component is adjacent to metal structures making up the outside of the tank, and the fibreglas Firestone backing board material is next to the felt. Normally this material is employed in connection with military self-sealing fuel cell systems to provide alignment of the lips of a wound in the cell wall allowing the self-sealing gum rubber to expand, covering the wound. Practically, benefits diminish after three such sandwich layers are combined. With little weight penalty, this treatment may be applied to the entire front of a wing spar for example, which comprises the forward tank wall. It may vary in numbers of layers depending upon proximity and estimated vulnerability to components which might shear off during a crash and be propelled into a tank. In this regard, this system of protection will be particularly useful also on the rear of the rear spar comprising the rear wall of the tank. When bladder cells are used the same form of protection is effective outside the structure containing the cells. Adherence may be made permanent and without sensitivity to hydrocarbon fuel submergence.

CONCLUSIONS

Statement of concepts. - The research described within this report has proven the feasibility of providing crash/fire resistant fuel containment for aircraft during crash environments that are otherwise survivable. The concepts provide for maintaining fuel integrity with a secondary provision for flow attenuation, if liquid integrity is lost. The concepts can be applied to both bladder cell and integral tanks. One concept provides for maintenance of liquid integrity through the application of cushioning materials to the exterior of the tank where aircraft configuration allows this. The inner-liner concept has evolved into a frangible bond/extendible film concept, which can drape wounds and/or elongate and encapsulate an object as it penetrates the tank. The foam which forms the frangible bond can perform a secondary function, dramatically reducing flow through the wound, if the extendible film fails and liquid integrity is lost.

Degrees of protection. - The following crash/fire resistant protective concepts are generally grouped in relation to increasing degrees of criticality or of complexity in solution. It is recognized that it is impossible to condense these to this degree without serious oversimplification. Thus, the intention of this section is to allow the user to grasp a quick perspective of typical problems of vulnerability and available solutions, bearing in mind that the actual application engineering for a specific set of circumstances may be substantially more complex. Some of these solutions are incorporated in aircraft and some have been evaluated in other programs.

Condition A. - During a survivable crash, fuel is expelled from the tank under relatively high pressure and carburets or vaporizes into a hemisphere being rich at source and leaning out towards its periphery. During its expansion and development, an ignition source might be encountered in a portion of the hemisphere which could support combustion or explosion. It would then involve the entire hemisphere which, by this time, might be several times the size of the total wreckage of the aircraft, thus preventing egress of occupants, even though otherwise uninjured.

Solution: Provide minimum of two inches of 40 pore per inch thermally reticulated polyurethane foam on tank interior in vulnerable areas such as the forward tank wall and adjacent areas at bottom, top and sides. This may be attached by various mechanical means if in an integral tank to provide ready removal for metal surface inspection periodically. If loads of as high as 24 psi are anticipated, the thickness should be increased to 4 inches. Regardless of the cause of the wound, such as penetration, wracking, tearing, seam splitting, etc., this solution has been shown to totally eliminate carburetion or vaporizing of fuel during expulsion and to change the nature of fuel flow through a wound to a relatively slow and unpressurized flow of liquid fuel. This flow admittedly may also seek out and find an ignition source, but even so, will probably result in a fire of a localized nature, non-explosive, of low temperature and intensity, slow to propagate and remote from the passenger area. This solution does not self-seal the tank. Pressure loss through the foam tends to draw it into the wound thus increasing differential pressure across the wound to atmosphere which increases sharply with deceleration force.

Condition B. - During a survivable crash, sharp objects in the wreckage may penetrate the tank wall, whether integral or bladder cell, remain in place, fall away or fall inside the tank, exposing a resulting puncture wound.

Solution: - This solution is referred to in the report as a "curtain" assembly. Employ the solution described in "Condition A." Add to this, by frangibly bonding to the inside of the tank, an extendible film with high elongation characteristics and quick response time. Such film has been established as feasible and is under advanced development by Firestone. The film will tear away from the frangible bond, draping over penetrating object. Usually the 2 to 4 inches of 40 ppi thermally reticulated polyurethane foam will "chunk" out on the point or front of the penetrating object tending to blunt its penetration and cushion contact with the extendible film. This film will extend 800% in a few milli-seconds, tightly encompassing the penetrant. Even if the film is cut by possible contact, it will continue to tightly grasp the penetrating object rather than tear, thus maintaining liquid integrity in the tank. The thickness of thermally reticulated polyurethane foam (2 to 4 inches) also absorbs or buries metal petaling and superficial tank surface irregularities preventing damage of the extendible film. Application of the film to thermally reticulated polyurethane foam may be such that edges are open, allowing fuel to permeate thermally reticulated polyurethane foam bulk, thus reducing fuel displacement and allowing a quick response as described in Condition A. This total solution may be readily applied to any type tank.

Condition C. - The anticipated wound may involve substantial open areas of such size that portions of the foam in the solution described in Condition A may simply be torn away and expelled, allowing the problem to remain unabated.

Solution: Either between the tank wall and 40 ppi thermally reticulated polyurethane foam, as in Condition A, or preferably attached to the inside surface of the thermally reticulated poly-urethane foam, then carrying a frangible bond for the film as in Condition B, use a layer of light weight fuel cell rubberized nylon fabric such as Firestone E-1367 weighing between 4 and 5 ounces per square yard. This would effectively drape the wound, forcing fuel to laterally traverse adjacent areas of 40 ppi reticulated foam.

Condition D. - It is anticipated that the tank is vulnerable to external, heavy components such as electric motors, hydraulic pumps, etc., close to tank walls which may shear off their mountings during a crash and be projected into the tank.

Solution: Firestone has experimented extensively with use of layers of Firestone backing board identified as F1-41, which is a heavy weave of long filament fibreglas permeated with resin and 3/16 inch nylon felt between the fibreglas and exterior tank wall. Tables I and II, pages 16 and 17, indicate the increasing capability of absorbing and distributing foot pounds of energy with single, double and triple plies of this "sandwich" when applied externally to the fuel tanks, but inside the airframe. One, two, or three layers of this construction may be applied to the tank surface, thus exposed to this hazard, to the component package or disposed somewhere in between.

Description of a practical, low weight, low cost, high protection level tank incorporating the most useful of the features described in the foregoing. - Protect the entire forward surface of the tank plus adjacent bottom, top and side areas with a "curtain assembly" consisting of two inches of thermally reticulated polyurethane foam, 40 ppi, with frangible bonded extendible film attached to the inside surface. If an integral tank, apply with Velcro or other mechanical attachment to allow removal of curtain assembly for metal surface inspection. If a bladder cell, curtain assembly may be permanently bonded. Provide added protection of 4 inches of 40 ppi thermally reticulated polyurethane foam in areas of breather connection. Protect front and rear of tank exterior metal structure from penetration by use of 3 layers of backing board and 5/16 inch nylon felt. If a bladder cell installation, apply backing board and nylon felt externally to the structure containing the bladder cell.

RECOMMENDATIONS

It is recommended that: The Government continue this investigation on crash/fire resistant tanks by implementing the following program:

(A) Apply the frangible bond/extendible film concept to representative integral tanks in existing airframes to verify:

1. The proposed method of application during aircraft fabrication.

2. The ability to remove the installed materials for aircraft structural inspection and their subsequent re-application.

3. The laboratory test results obtained in this program by impact testing the concept. This testing to include falling dart, pendulum and sled tests. The criteria for these tests should simulate or reproduce the crash environment that may be experienced in a survivable crash.

(B) The flow characteristics through an open wound as attenuated by internal foam have been evaluated under laboratory conditions. The effectiveness of this concept when the wound is an irregular shape and distorted structural components hold the foam away from the wound, is not known. These flow characteristics should be evaluated as a part of the program suggested in (A) above.