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AIRCRAFT FUEL TANK DESIGN CRITERIA

By

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James W. Turnbow

March 1966

U. S. ARMY AVIATION MATERIEL LABORATORIES
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This report was prepared by Aviation Safety Engineering and Research (AvSER), a division of the Flight Safety Foundation, Inc., under the terms of Contract DA 44-177-AMC-254(T). This effort consisted of the investigation through dynamic testing of the factors which must be considered in the design and fabrication of new materials for crashworthy fuel tanks.

Views expressed in the report have not been reviewed, or approved, by the Department of the Army; however, conclusions and recommendations contained herein are concurred in by this command.

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Technical Report
AvSER 65-17

by
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SUMMARY

Accident statistics indicate that postcrash fire is the most serious threat to human life in aircraft crashes. Several methods are available to reduce this hazard; however, the simplest and most effective immediate method is through control of the fuel spillage.

Accident investigation reveals that fuel tanks developed to current crash resistant fuel tank specifications fail even under relatively moderate crash conditions. A discussion of the factors which must be considered when establishing specifications that will result in a crashworthy fuel tank is presented.

Experiments were conducted with fuel tank material specimens and with experimental fuel tanks subjected to actual aircraft crashes. Results indicate that fuel tanks can be built today that are capable of preventing fluid spillage during accidents involving decelerative loading above the human survival range.

Evaluation of the test data indicates that additional analysis is needed in order to understand fully why certain materials function as excellent tank materials and others do not. Two types of materials, "Fuzzy Wall" and "Tough Wall", are shown to have demonstrated good crash resistant characteristics.

FOREWORD

This report provides basic information needed for use in rewriting military specifications governing crash resistant fuel tank design.

Sincere appreciation is extended to Mr. Richard L. Cook, Plastic Engineering Division of Goodyear Aerospace Corporation, for his consistent effort in developing and furnishing new materials and ideas which have been greatly influential in this study.

Appreciation is also extended to the following companies for their contributions to this fuel tank study:

Hexcel Products, Inc.
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Chem Seal Corporation of America
Firestone Tire & Rubber Company

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*Reg. T.M., Goodyear Aerospace Company, Litchfield Park, Arizona.

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SYMBOLS

p	pressure (lbs/in.^{2})
w	weight density of fuel (lbs/inch^3)
n	design load (G's)
h	pressure head of fuel (inches)
F	force (lbs)
M_s	load per unit length (lbs/inch)
ϵ	strain (inches/inch)
r	radius (inches)
L	1/2 width of opening in structure (inches)
a	length of opening in structure (inches)
θ	angular width of opening in structure (radians)
D	diagonal length of opening (inches)
A	area of opening (inches^2)

INTRODUCTION

Studies of accident histories involving both fixed-wing aircraft of all classes and helicopters reveal that the greatest number of fatalities occur in accidents involving postcrash fire. These studies have also indicated that the postcrash fire problem in helicopters is significantly more serious than in fixed-wing aircraft with respect to the incidence of fire and fatalities (References 1 through 6).

An examination of the evidence available on those accidents followed by fire reveals that once ignition has occurred in the presence of significant quantities of uncontained fuel, chances of survival are greatly reduced, even when crash fire equipment is immediately available. The evidence also indicates a significantly increased survival rate had the fires not occurred. One study[3] indicated that 9.5 percent of the accidents resulted in postcrash fire and that 65 percent of all fatalities occurred in these accidents. Of 168 fatalities occurring during the tabulated accidents, 88 occurred in the fire accidents. Of 390 total injuries, in the same accidents, 150 occurred as a result of fire. This gives a death rate of 0.98 per fire accident and an injury rate of 1.67 per fire accident. Data on fire causation indicates that ruptured fuel cells and lines are the predominant factor in 78 percent of the crash fire cases. The spread of this fuel through the occupiable area contributed heavily to the 88 deaths in 90 accidents. In addition, almost every fire accident resulted in the total loss of the airframe and the equipment aboard.

The general conclusions reached as a result of the accident studies and some of the postcrash fire research conducted to date are that (1) escape time from a cargo- or transport-type fixed-wing fuselage is considerably longer than that from a helicopter in the event of a fire; (2) improvements in existing ground fire-fighting systems will provide little, if any, improvement in escape time from crashed helicopters in which the crash forces result in fuel tank burst and postcrash fire; and (3) more emphasis should be placed on "built-in protection" in the aircraft themselves. This would lead to a reduction in the percentages of fire experienced and a savings in human life.

Research has been conducted in four crash fire prevention areas which fall under the heading of "built-in protection". The specific areas in which research has been or is being conducted at this time are (1) fire inerting systems, (2) breakaway fuel tanks, (3) fuel solidification, and (4) fuel containment. Following is a brief discussion of each of these areas.

FIRE INERTING SYSTEMS

This approach involves methods and techniques for eliminating potential ignition sources between the time of impact and the time that combustibles come in contact with these potential ignition sources. Inerting systems have been demonstrated as being feasible both by NASA, in their crash fire research program conducted with large fixed-wing aircraft in the early 1950's, and by AvSER, who developed experimental inerting systems for military helicopters. Even though the systems developed by the previously mentioned agencies functioned as designed, it is not possible to develop a system which is capable of inerting every conceivable ignition source. It is certain, however, that a significant percentage of fires could be eliminated by inerting the two most common ignition sources: the hot engine components and the electrical system of the aircraft. The experimental inerting systems developed by NASA and AvSER during their research programs demonstrated that these two most common ignition sources could be inerted properly and within the very short time period required. The weight penalties associated with this concept, the problems associated with automatic activating systems, and the fact that other ignition sources will continue to exist (even though the main sources have been inerted) greatly reduce the probability of this concept's being utilized.

BREAKAWAY FUEL TANKS

This concept involves fuel tanks designed and installed in a manner permitting them to break free of the aircraft and tumble clear of the wreckage during a crash. Breakaway systems have been demonstrated in experimental testing, and several light fixed-wing aircraft are equipped with breakaway fuel tanks. An examination of the results of some accidents involving aircraft equipped with breakaway tanks indicates some measure of success. Breakaway systems will result in some slight weight increase to the aircraft but no increase in fuel costs. Utilization of this concept, however, is presently limited to small fixed-wing aircraft and helicopters.

FUEL SOLIDIFICATION AND EMULSIONS

This concept involves the injection or mixing of chemicals into the fuel to form a "gelatin-like mass". The concept is one which would prevent the release of large quantities of fuel in a pure liquid state, thereby preventing the rapid vaporization such as occurs under impact conditions when fuel tanks are ruptured. This is a new concept, and further theoretical and experimental work is required before all problems associated with the concept are resolved. At present, solidification will result in a weight increase due to the chemical additives. In addition, there are problems of actuating mechanisms and mixing systems, which will undoubtedly result in additional weight and cost. Some of the above factors may be reduced by carrying the fuel in a solidified or emulsified state at all times, converting it to a liquid at the point of usage or injecting it directly into the engine. These factors are all a part of the research presently being conducted.

FUEL CONTAINMENT

This concept involves the use of new fuel tank materials and new methods and techniques in fuel tank design and construction to improve the ability of the fuel systems to contain fuel under crash impact conditions. Crash resistant tanks developed in accordance with present military specifications have been tested but have been found to fail under minimal crash conditions owing to their inability to withstand penetration of surrounding structure. The results of recent research conducted with new materials which offer excellent resistance to penetration indicate that sufficient knowledge now exists for achieving significant gains in fuel containment in the immediate future. Improved fuel containment can now be obtained with minimal weight increases and with no increase in fuel costs. This concept offers immediate promise in reducing the incidence of postcrash fire in the immediate future and is the subject of the balance of this report.

During the past four years, AvSER, under U. S. Army contracts, has been actively engaged in postcrash fire research in all of the four areas discussed earlier in this report. Because effective fuel containment appeared to offer the greatest immediate results in reducing the incidence of postcrash fire, the 1965 effort was focused on fuel tank studies involving fixed-wing fuel tanks, fuel tanks carried inside helicopter fuselages above the floor (CH-21 helicopter arrangement), and fuel tanks carried under the floor of helicopters (CH-34 helicopter arrangement). The study further focused its attention on the fuel bladder or flexible bag concept.

Since 1956, considerable work has been devoted to the development of crash resistant fuel tanks. A review of the previous work was made, including an analysis of the results from the many test crashes performed by NASA and AvSER. In addition, selected actual aircraft crashes involving fire were investigated. While some of the efforts have produced favorable results, there still is not a satisfactory crash resistant fuel tank in operation today.

The containment problem was then redefined and a plan of action was formulated. New requirements for the fuel tank materials were specified and specimens were obtained from various manufacturers. These specimens were in the form of diaphragms, which were drop tested from various heights for comparison. When certain specimens demonstrated the capability to perform as desired, actual fuel tanks were constructed and tested in full-scale instrumented aircraft crashes. These test tanks were then evaluated, and the information obtained was applied to the new generation of materials and tests were conducted until a total of 6 test crashes were performed, containing a total of 36 experimental fuel tanks.

FUEL SYSTEM DESIGN CRITERIA

GENERAL

Fuel tanks designed to current specifications are incapable of providing postcrash fire protection in moderate and severe aircraft crashes. The problem is primarily one of inadequate fuel system design from the standpoint of resistance to the crash environment. Some failures are directly associated with the tank itself, while others are associated with related systems, including boost pumps, vent systems, filler necks, tank-to-structure attachments, and fuel transfer lines.

In the following paragraphs, a discussion of certain critical factors concerning the fuel system design is presented. Few of these factors lend themselves to a quantitative analysis. Further, there is, at present, insufficient experimental data to allow the establishment of an accurate boundary between the failure and no-failure regions. Fortunately, however, there is sufficient information to allow large improvements to be made without establishing such boundaries and without introducing large weight penalties or other adverse effects.

The actual crashworthiness of a fuel system is dependent upon the dynamic behavior of not only the fuel tank and its related equipment but also the behavior of the aircraft structure surrounding the tank. It is the intent of the following discussion to present those factors which must be considered when establishing the specifications that will ultimately result in crashworthy fuel systems.

PROPERTIES OF FUEL TANK MATERIALS

The existing specification covering crash resistant fuel tanks of the flexible type is MIL-T-27422A, dated 25 March 1964. This specification establishes the design loads or G factor at 35G longitudinal and 35G vertical, and the minimum material strength measured in pounds per lineal inch, using the 35G design load.

Equation (1) of MIL-T-27422A specifies for fuselage tanks and condition "(a)"* for wing tanks that the strength of flexible tank walls shall be not less than

$$M_s = \frac{0.00292\,nhw \times 1.6}{D/A} .$$

*Reference 13 gives full specifications for wing tanks.

For a CH-21 installation, the values of the constants would be as follows, assuming the tank to be 30 inches high (actual value, 43-inch maximum) by 64 inches wide (Figure 1, MIL-T-27422A, Reference 13):

$$D/A = \frac{30^2 + 64^2}{30 \times 64} = 0.037$$

and

$h = 2.5$ feet = Head of fuel

$w = 48.6$ pounds per cubic foot = Density of fuel;

then

$$M_s = \frac{(0.00292)(35.0)(2.5)(48.6)(1.6)}{0.037} \qquad (1)$$

$M_s = 540$ pounds per inch.

In the CH-21 tests described in Appendix I, the crash resistant fuel tank used was constructed to Specifications MIL-T-27422A and MIL-T-6396A. The tank wall material had an actual strength of $M_s = 475$ pounds per inch. The results of the tests indicate the inadequacy of the tank, as installed, to withstand the impact conditions imposed. The reasons for the failure were: (1) the acceleration environment, particularly with respect to vertical acceleration, is considerably more severe than the arbitrary design load of 35G; and (2) high tensile strength alone is not assurance that the cell will be crashworthy.

Equally important with adequate tensile strength (to resist inertia and squashing pressures) is the resistance to penetration and tear propagation. Neither MIL-T-27422A nor MIL-T-6396A contains requirements for resistance to tear propagation. An additional parameter of significance appears to be the ultimate strain for the tank material, and perhaps more specifically the strain at maximum load. This property affects both resistance to penetration and resistance to pressure forces. To illustrate, consider the following example. A long crack of width 2L is assumed to be opened in the tank supporting structure wall. It is desired that the flexible bladder bridge the gap and carry the pressure load through tension in the bladder wall. It is assumed that only that portion of the bladder covering the crack deflects (effective width of crack = 2L). The load diagram is shown in Figure 1.

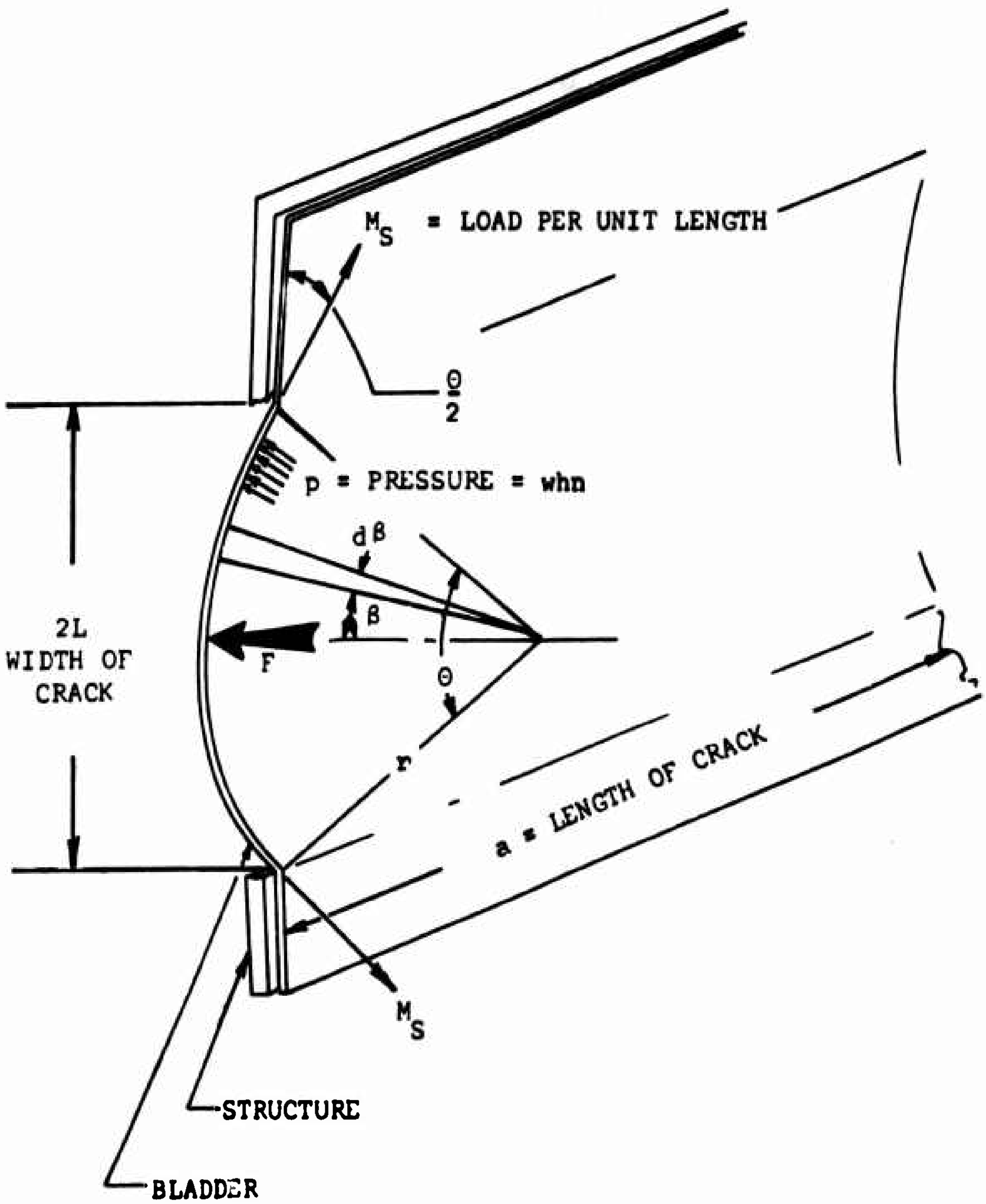

Figure 1. Bridging the Gap in Structure by Fuel Bladder.

The pressure is given by

$$p = whn$$

where

w = Weight density of the fuel

h = Head of fuel

n = Design G load (example, 35G).

The total force on the tank wall is then

$$F = 2a \int_0^{\theta/2} (whn) r \cos \beta \, d\beta$$

$$F = 2a(whn) r \sin \frac{\theta}{2}, \qquad (2)$$

and for equilibrium,

$$2M_s a \sin \frac{\theta}{2} = 2a(whn) r \sin \frac{\theta}{2}$$

$$M_s = (whn) r. \qquad (3)$$

The strain is given by

$$\epsilon = \frac{r\theta - 2r \sin \theta/2}{2r \sin \theta/2}$$

$$\epsilon = \left[\frac{\theta}{2 \sin \theta/2} - 1 \right]. \qquad (4)$$

The radius, r, is related to the crack width, 2L, by the relation

$$r = \frac{L}{\sin \theta/2} \qquad (5)$$

Therefore,

$$M_s = \frac{(whn)L}{\sin \theta/2} \qquad (6a)$$

$$\epsilon = \left[\frac{\theta}{2 \sin \theta/2} - 1 \right]. \qquad (6b)$$

Since equation (6b) implies that θ is a function of ϵ, then M_s is also a function of ϵ; that is, the design strength of the tank material is dependent upon the ultimate strain capable of being sustained by the material. Equation (6b) is a transcendental equation and not readily solvable for θ as a function of ϵ. It can be solved numerically for any given value of ϵ.

As an example, consider a 20-inch-wide crack in the structure and let

$$n = 35G$$

$h = 30$ inches*

$w = 48.6/1728$ pounds per cubic inch

$L = 10$ inches

$\epsilon = 0.20 = 20$ percent.

From equation (6b), $\theta/2$ is computed to be 1.03 radians $= 59^{o}$.

$$M_s = \frac{48.6 \times 30 \times 35 \times 10}{1728 \qquad \text{Sin } 59^{o}}$$

$$M_s = 344 \text{ pounds per inch}$$

This value includes no factor of safety. If ϵ is reduced to 10-percent, the corresponding value of M_s is 435 pounds per inch, or about 26-percent increase. Thus, specification of tensile strength alone may not accomplish the desired objective.

The real advantage of having the capability of sustaining large strains in the bladder material lies in the ability of the material to deform to the extreme contours required in crashes resulting in large structural distortions and breaks in the tank area. This capability, coupled with resistance to tear propagation, will offset a considerable reduction in ultimate strength. Obviously, there is a minimum ultimate strength which must be met, particularly for tanks located in areas where squashing (compressive loads) may be sustained. Similarly, there is a minimum elongation (strain) which the material should be capable of undergoing while still carrying near maximum load. However, with only the data presently available concerning all of the factors affecting fuel tank design, it is impossible to fix definite numerical values for strength and elongation in a manner to be completely comprehensive with respect to crashworthy fuel tank design. In fact, it appears that there are other material properties which may be equally important in determining the resistance of the material to the crash-induced environment; for example, (1) flexural rigidity and (2) failure mechanisms. The best available evaluation of the overall value of these material properties lies in the results of experimental tests and actual crashes discussed in following sections of this report.

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*Units of all constants in equations (6a) and (6b) must be consistent. Here the pound-inch system is used.

TANK LOCATION

The location of the fuel tank is of considerable importance in minimizing the postcrash fire hazard of a proposed tank installation. The location must be considered with respect to occupants, ignition sources, and probable impact areas. In the event of postcrash fire, greater distances between occupants and the (ruptured) fuel supply tend to increase the escape time. Installing fuel tanks as far as possible from the engine (a primary ignition source) can reduce the incidence of postcrash fire considerably. Another important consideration is the location of fuel tanks with respect to probable impact damage. Landing-gear failures occurring in moderate impact accidents have repeatedly resulted in fuel tank ruptures and postcrash fires. Obviously, the required crash resistance of the tank must depend on the probable mode of failure of such landing gear and/or its supporting structure.

The location of fuel tanks under the floor of helicopters poses a serious threat, since many accidents with these aircraft occur in near level flight attitude and at high sinking speeds. It is obvious that low-mounted fuel tanks will contact the ground early in the crash sequence and will be subjected to penetrations from rocks, stumps, and other ground irregularities. Thus, it is good design technique to locate fuel tanks higher in the structure. As much aircraft structure as possible should be allowed to crush before the tanks themselves are exposed to direct contact with obstructions. This concept applies to impacts against both the tank support structure by blades and large internal masses such as transmissions, engines and cargo.

Fuel tank volume reduction is another factor that must be considered. If the fuel tank is nearly full and located in an area where large-scale structural collapse occurs, the fuel tank may not only experience pressures far beyond normal fuel tank strength but could also be exposed to torn and jagged metal which may puncture the tank. Expansion areas should be provided in appropriate regions of the structure surrounding the tank if it can be visualized that the structure may collapse and compress the tank in other regions owing to compressive loads during a crash. Finally, if the tank or any other portion of the fuel system fails, spillage should be prevented from entering the occupiable area or areas of high potential ignition sources.

TANK-TO-STRUCTURE ATTACHMENTS

The method of fuel tank attachment to the surrounding structure is responsible for many fuel tank failures. Military Specification MIL-T-27422A states that attachments between the fuel tank and aircraft structure should be designed so that the tank will separate from the aircraft structure before the tank fails. Accident investigations have indicated many instances where these attachments have remained with the aircraft structure and have torn large holes in the flexible cloth bladder. The bayonet-type cell attachment is particularly susceptible to this type of failure. This attachment functions as designed when loads are applied parallel to the bayonet lug; however, when shear loads are applied, the release is not effected, resulting in tears occurring in the fuel cell.

This problem is also present with all of the commonly used attachments at filler necks, fuel pumps, quantity indicators, fuel drains, vents, and cell interconnects. Figure 2 illustrates this typical failure in a MIL-T-27422A crash resistant fuel tank (1965 accident of a large troop-carrying helicopter).

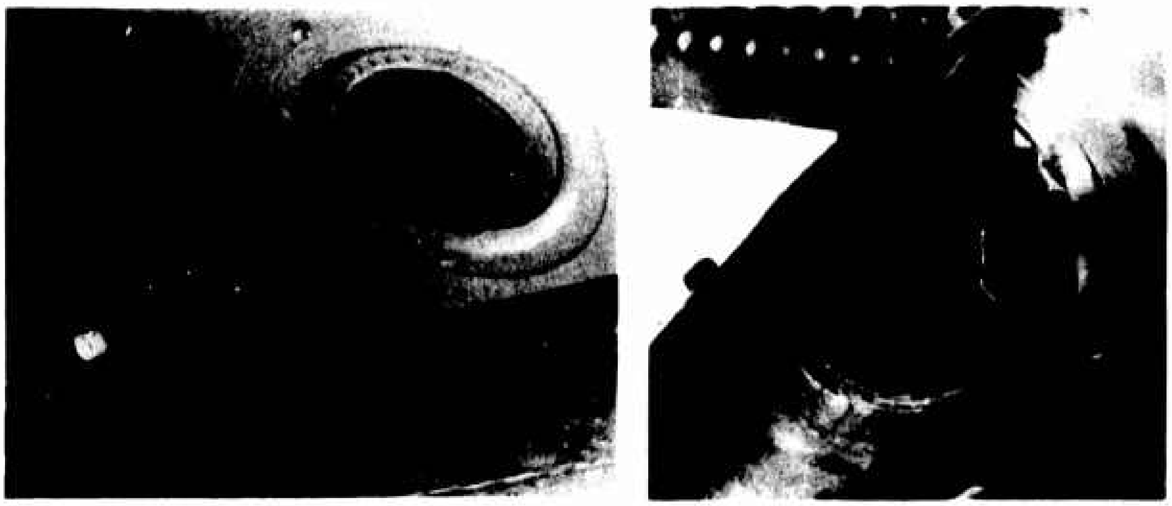


Figure 2. Rigid Attachment Failures.

The two photographs in Figure 2 clearly indicate the typical failures associated with rigid attachments. In the left-hand photograph the tank-to-aircraft filler neck fitting can be seen still attached to the aircraft. The tank failure resulting from the filler neck attachment ring's being torn free is shown on the right.

It is essential that <u>all</u> such connections be designed so as to allow the tank and aircraft structure to separate positively under both tensile and shear loadings without fuel spillage.

VENT SYSTEMS

Vent systems should be designed to eliminate the problem referred to above; that is, spillage due to vent line and/or tank failure at tank-structure connections. In addition, vent systems should be arranged to prevent spillage in accidents in which the aircraft comes to rest in other than normal flight attitude.

FUEL TRANSFER SYSTEMS

Electrically-driven boost pumps should be eliminated in all new designs. Alternate solutions now in operation include (1) air-driven boost pumps and (2) at least one installation in which no boost pump at all is utilized. This installation uses a suction system with a positive displacement engine-driven pump.

When air-driven boost pumps are used, the pump preferably should be installed in the fuel line in a position removed from the tank. The fuel line itself should be of the flexible type attached to the tank through self-sealing breakaway fittings. These fittings should function under both tension and shearing loads in a manner to eliminate the type of failure illustrated in Figure 2.

Insofar as possible, all lines and connections should enter and exit the tank from one central location. The generally preferred location is at a protected point at the top of the tank. This arrangement reduces the number of attachment points between the tank and the structure. As previously noted, these attachment points must provide for separation without fuel spillage.

When crossover connections, drains, and outlet lines must be located in the lower regions of the tank, self-sealing breakaway fittings must be used. All fuel lines should be of extra length and flexible nature to allow for large misalignments due to structural displacements.

In order to eliminate fuel spillage due to severed fuel lines, these lines may be armored or protected by hydraulic fuses similar to those now employed in hydraulic systems.

Careful attention to the routing of lines through structure and providing extra length lines will also reduce the likelihood of line severance and/or disconnect. The holes in the structure through which fuel lines pass should be large (up to ten times the diameter of the fuel lines). The fuel lines can be stabilized by the use of frangible attachments, but these should fail easily and allow the fuel line to shift with the structure during deformation.

OTHER CONSIDERATIONS

When designing fuel tanks, several other factors must be considered. For example, when fuel baffles are required, they must be designed so as to allow the tank to rearrange its volume without causing tank wall failure due to tearing or puncture.

The long, rigid, tubular probes used in some fuel quantity sensing systems function as bayonets to punch holes in the tank wall. Alternate solutions are possible, including fuel counters with low-fuel warning lights, flexible probes, curved probes of low flexural rigidity, tank-bottom pressure indicators, and others.

Another factor which must be considered is tank geometry. Every effort should be made to reduce the number and extent of any protuberances or discontinuities which can cause portions of the tank to be caught in the structure while other portions are being displaced. Where tanks would deviate greatly from the regular spherical or rectangular parallelepiped shapes, consideration should be given to using separate tanks. Inside corners (as in a 90-degree elbow) should be greatly curved (6-inch radius minimum), and even exterior corners should be rounded with at least a 1-inch radius to avoid snagging.

SYNOPSIS

The ideal fuel system is one which completely contains its contents both during and after an accident of such severity as to be beyond the boundary of any conceivable survivable accident for the aircraft under consideration. Fuel containment must be maintained no matter how the basic structure fails and regardless of the magnitude of the displacements of the fuel system components with respect to the structure. Similarly, all possible crushing loads, penetration loads, and inertia loads must be carried without leakage.

While this ideal system may not be achieved, it has been demonstrated that it can be approached in actual crash tests, which will be described later in this report. To approach this ideal goal, the system must have definite characteristics. It should be so located in the aircraft as to take advantage of the inherent structural protection afforded by the aircraft structure against impact with obstacles. The location should be removed from large masses, rotor blades, and occupiable areas. The tank should be of compact shape and constructed of tough materials to allow it to withstand impact exposure to jagged metal.

It should be capable of greatly increasing and rearranging its volume without jeopardizing its structural integrity. If a penetration occurs, the tank must be resistant to further tear. The tank should be free floating in the aircraft structure rather than rigidly attached at various locations.

It should contain a suction fuel transfer system. Fuel quantity probes must be incapable of puncturing any portion of the tank. The aircraft structure surrounding the tank should be designed so that if the structure is compressed in one area it will fail in another area so as to provide space for the tank while its volume is being rearranged. The interconnecting lines should be the flexible type and loose enough to allow for large displacements without disconnect or leakage. All lines should be attached to the tank with self-sealing breakaway fittings.

While the tanks tested in this study weighed nearly twice as much as present-day tanks, it should be pointed out that if these tanks are installed as this report suggests, that is, minus the rigid attach points and the boost pump, the overall fuel-tank system will weigh approximately the same as the old system. If the tanks can be made to function as self-sealing and/or if the "tank liner" can be eliminated, there even can be a considerable weight reduction.

TEST PROGRAM

In a search for materials for use in tank construction which would meet the requirements suggested by the crash environment problems previously discussed, a materials testing program was initiated. A lead to this study was observed in a previous full-scale CH-21 crash test conducted in late 1963 (Appendix I). It had been noted that a laminated nylon liner placed between the crash resistant fuel cell and the supporting aircraft structure was not damaged during the crash. This suggested that a fuel tank constructed of this material might be an excellent crash resistant tank. Several companies were contacted to determine their interest in providing the test materials and participating in the test program. The Goodyear Aerospace Corporation and Chem Seal Corporation of America agreed to furnish sample materials and to participate in the testing program. The tests were conducted in two overlapping phases. First, specimens of materials of reasonable weight appearing to have good potential resistance to impact and penetration were evaluated in laboratory tests. As high-promise materials were discovered, actual tanks were constructed and proof-tested in full-scale crash tests in conjunction with other AvSER programs.

MATERIAL TESTS

Initially, a large group of materials estimated to have the characteristics suitable for tank wall construction were assembled and evaluated for impact resistance by AvSER. The most promising of these materials were later tested by Goodyear for penetration, impact resistance, and tear resistance.

The two types of materials which indicated the best overall performances were:

1. "Tough Wall" Materials: These materials (Goodyear code, ARM 018; Chem Seal code, A34) were all similar in nature to the nylon liner used in Test 13. Basically, they were laminated from several layers of nylon cloth with the weave oriented at various angles and bonded together with a resin. Their thickness ranged from 0.070 to 0.100 inch. These materials are listed in Table I, which gives the composition, specimen identification, and other data.

2. "Fuzzy Wall" Materials: These materials (Goodyear code, ARM 019) consisted of a combination of a 3/8-inch

TABLE I
MATERIALS TESTED

Specimen Type Identity	Manufacturers' Designation	Composition	Wt. /Sq. Ft. Approximate (lb.)	Thickness Approximate (in.)	Supplier
A	ARM-018	3-Ply Nylon, 90^{o} Weave Orientation, Epoxy Bond	0.49	0.0760	Goodyear
B	ARM-018	3-Ply Nylon, 90^{o} Weave Orientation, Polyurethane Bond	0.45	0.0800	Goodyear
C	Wing-Board	3-Ply Nylon, 90^{o} Weave Orientation, Nylon Bond	0.45	0.0750	Swedlow
D	A34-10-D	3-Ply Nylon, 90^{o} Weave Orientation, Polyurethane Bond	0.60	0.1000	Chem-Seal
E	ARM-018	3-Ply Nylon, 90^{o} Weave Orientation, Polyurethane Bond	0.39	0.0710	Goodyear
F	ARM-018	3-Ply Nylon, 90^{o} Weave Orientation, Polyurethane Bond	0.49	0.0850	Goodyear
G	ARM-019	Nylon Felt Pad, Neoprene Membrane Sealant	0.49	0.3766	Goodyear
H	ARM-018	4-Ply Nylon, 45^{o} Weave Orientation, Polyurethane Bond	0.45	0.0850	Goodyear
I	ARM-019	Nylon Felt Pad, Crinkl-Core Sealant	0.49	0.3760	Goodyear
J	ARM-018	3-Ply Nylon, 60^{o} Weave Orientation, Polyurethane Bond	0.45	0.0800	Goodyear
K	6061-T4	Aluminum	0.93	0.0630	Alcoa

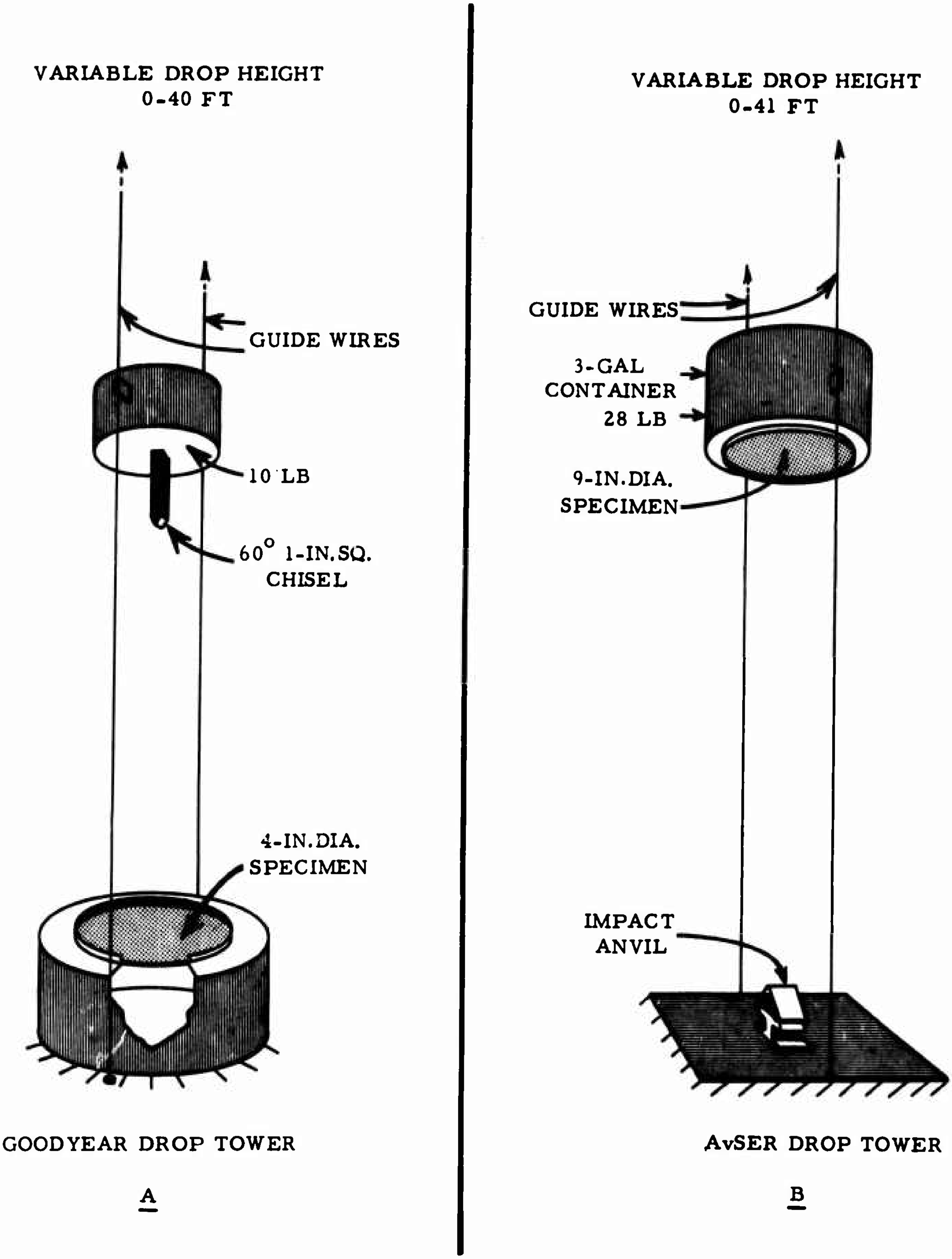


Figure 3. Drop Tower Test Methods.

nylon felt pad ("Fuzzy Wall") and a variety of "inner" membrane sealing films or layers. The felt pad itself is not capable of retaining fuel but is highly resistant to impact, penetration, and tear. The addition of a light, inner layer of material impervious to the fuel is required, in order to take advantage of the high elongation of the pad (200 percent). A material referred to as "Crinkl-Core" was developed by Goodyear as a sealant. This material is a pleated layer of thermoplastic film capable of in excess of 300-percent elongation. Neoprene and other sealing layers were used but did not perform as well as the "Crinkl-Core".

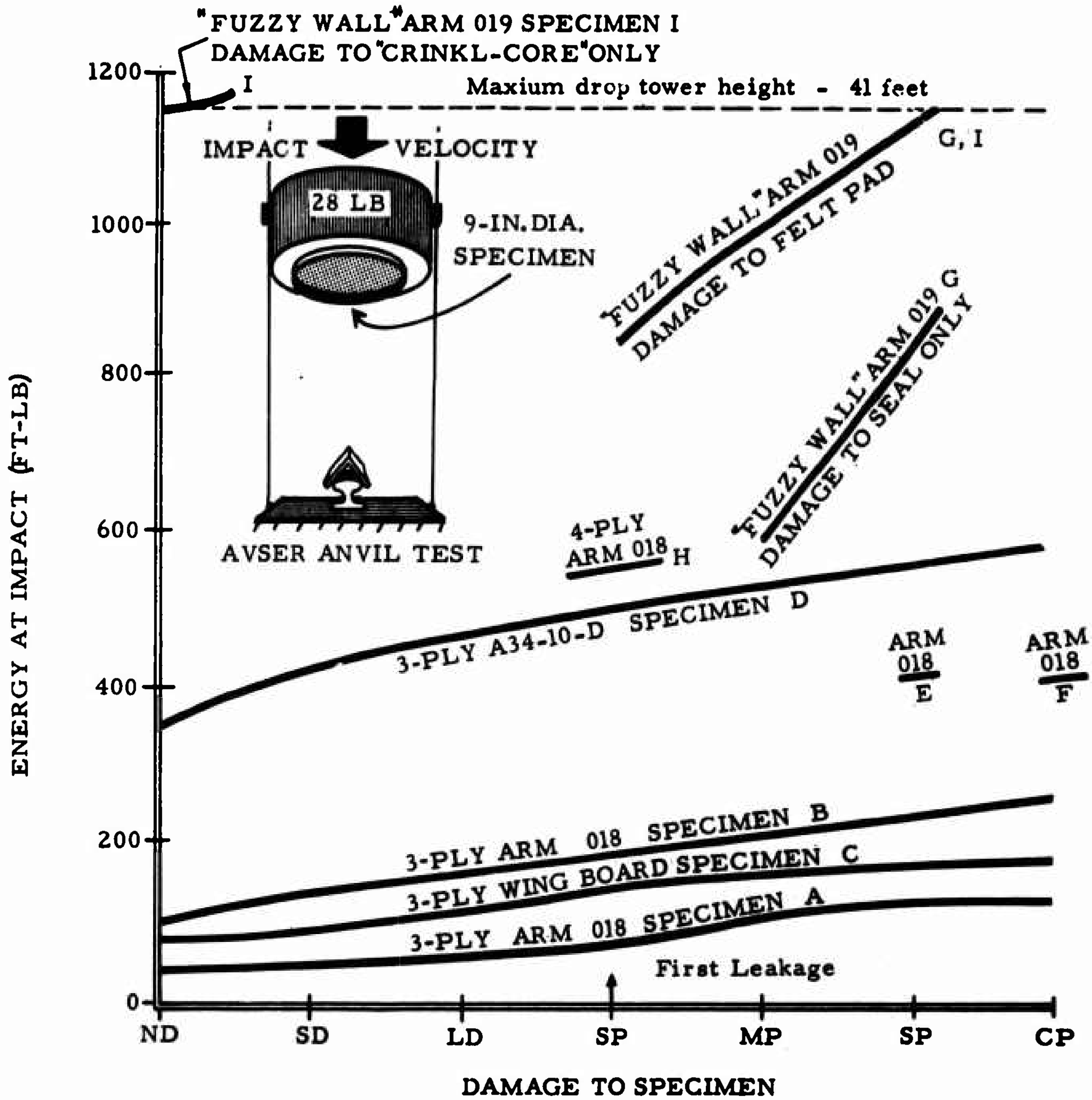
The AvSER impact resistance tests were conducted as shown in Figure 3. The fluid-filled container (28 pounds) was dropped with a 9-inch diaphragm of the selected material onto a 4.25-inch-long anvil made from a steel angle section (2 x 2 x 1/4 inch) as illustrated in the figure.

The Goodyear drop tests were conducted as shown in Figure 3. The specimen diamater was 4 inches. The impact end of the chisel was a 1-inch-square bar with a 60-degree chamfer on the end.

The results from the AvSER test series are given in Figure 4, which shows the correlation between impact energy and degree of damage to the specimen. The results clearly indicate that the "Fuzzy Wall" combinations were capable of sustaining the most energy prior to failure. For example, this material with the Goodyear "Crinkl-Core" sealing layer (Specimen I) took 1140 foot-pounds without leakage occurring.

Failure of the felt pad did occur; however, the sealing layer expanded so as to bridge the opening, as shown in Figure 5. The next best material was the four-ply ARM 018 (Specimen H), which took 575 feet per pound with only a small penetration (equivalent to approximately a 1/8-inch-diameter hole). The three-ply A34-10-D (Specimen D) was almost as good but was 12 percent thicker and 27 percent heavier than the four-ply ARM 018 (see Table I).

The results of the Goodyear drop tests, using the 1-inch-square, 60-degree chisel, are shown in Figure 6. These data indicate the degree of penetration of the chisel as a function of impact energy. While the AvSER drop test more nearly simulates the impact environment associated with the forcing of small objects (fuel pumps, fittings, etc.) into the tank, the Goodyear test best simulates puncture due to broken stringers, bolts, and other structure. It provides a check on the resistance both to impact (rapid loading) and to penetration. The chisel impact test results of Figure 6 are in good agreement with the AvSER tests; that is, the results for the materials tested show the energy for failure to be in about the same relative ratios for both tests. For example, the "Fuzzy



ND - no damage
SD - small delamination
LD - large delamination
SP - small puncture (seepage)
MP - moderate puncture (1 in. P < 3 in.)
LP - large puncture (P > 3 in.)
CP - complete penetration

Figure 4. Impact Resistance - Anvil Test. (Damage to 9-inch Diameter Specimen as a Function of Impact Energy. See Table I for Specimen Identity.)

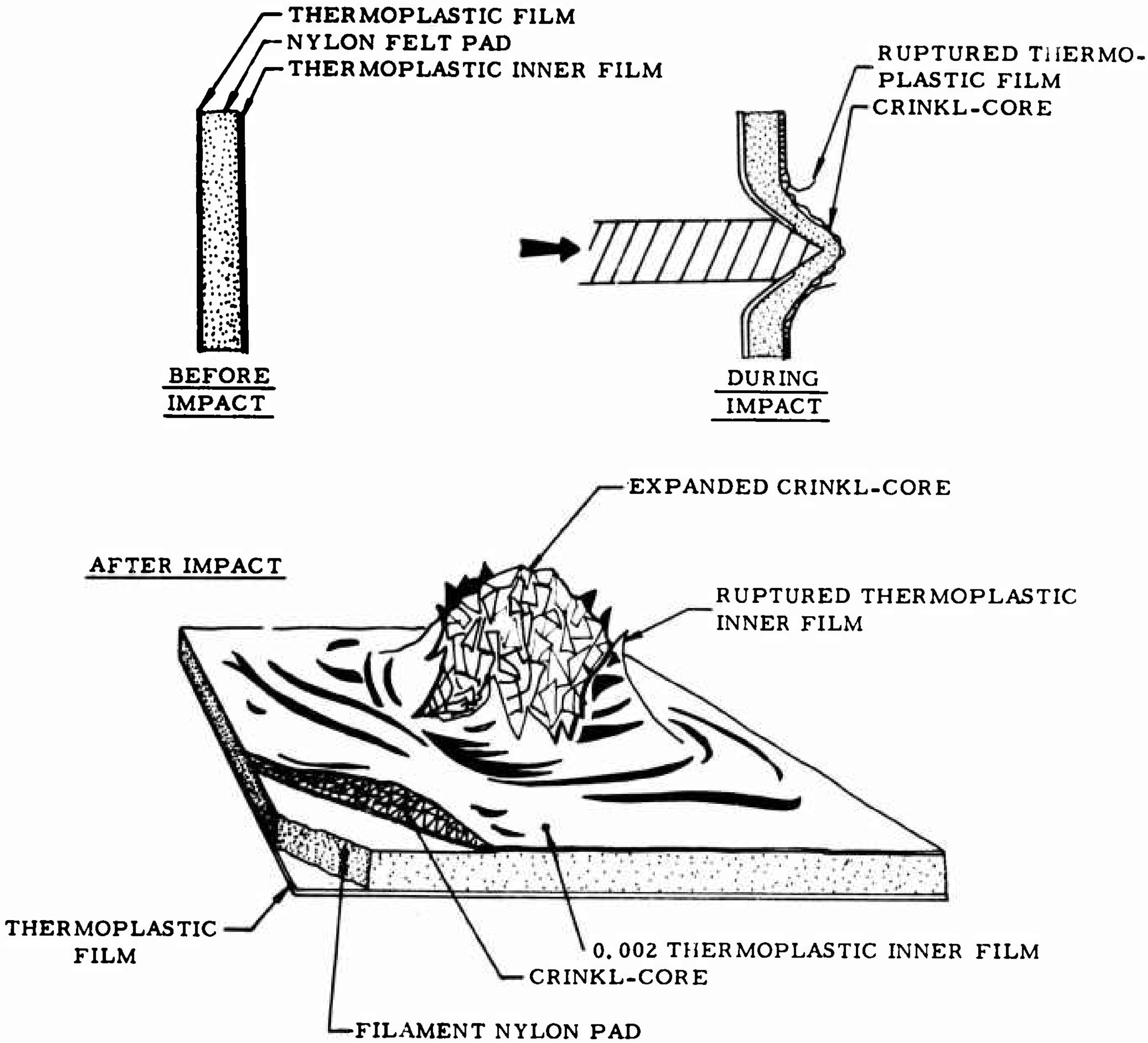
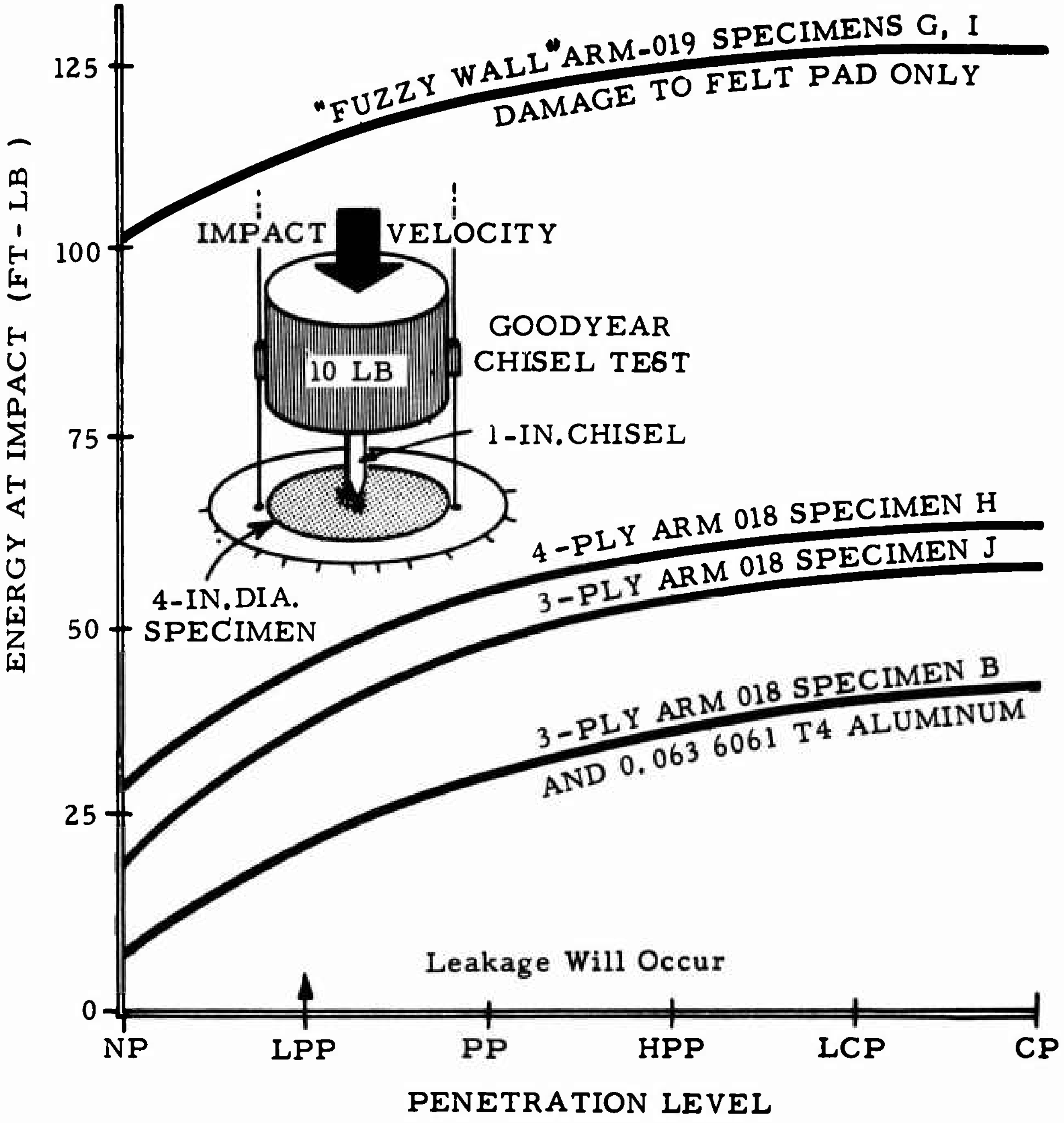


Figure 5. Operational Principle of Crinkl-Core.

Wall" material appears to absorb about two times the energy of the next best material ("Tough Wall", four-ply, ARM 018, Specimen H). It is interesting to note, however, that in static tensile load-carrying capacity, the "Fuzzy Wall" is only about one-fifth as strong as the four-ply, ARM 018 (575 pounds per inch versus 3050 pounds per inch).

In Figure 6, it should be noted that the top curve shows the penetration of the chisel into the "Fuzzy Wall" felt pad only. The "Crinkl-Core" was not penetrated even when complete penetration of the pad itself occurred.



NP - no penetration
LPP - low partial penetration
PP - partial penetration
HPP - high partial penetration
LCP - low complete penetration
CP - complete penetration

Figure 6. Resistance of Tank Materials to Penetration.

Obviously, penetration of the "Crinkl-Core" would ultimately occur if the point of the penetrator passes sufficiently far beyond the inner surfaces of "Fuzzy Wall" material. Note that the lower curve in Figure 6 applies to two materials, including 0.063-inch 6061-T4 aluminum alloy. Aluminum tanks in light aircraft have conventionally been of 0.040-inch material. On the basis of this test, the penetration resistance of the "Fuzzy Wall" material is about five times (for first leakage) that of 0.063 aluminum. Also, the aluminum weighs about twice as much as the "Fuzzy Wall" pad.

The tear resistance of "Tough Wall", "Fuzzy Wall", and aluminum was obtained by the test setup shown in Figure 7.

The 3- by 7-inch specimens were pulled at 20 inches per minute as illustrated, and load deflection curves were obtained. The results are shown in Figure 8 for "Fuzzy Wall", three-ply ARM 018 "Tough Wall", and 0.063-inch 6061-T4 aluminum.

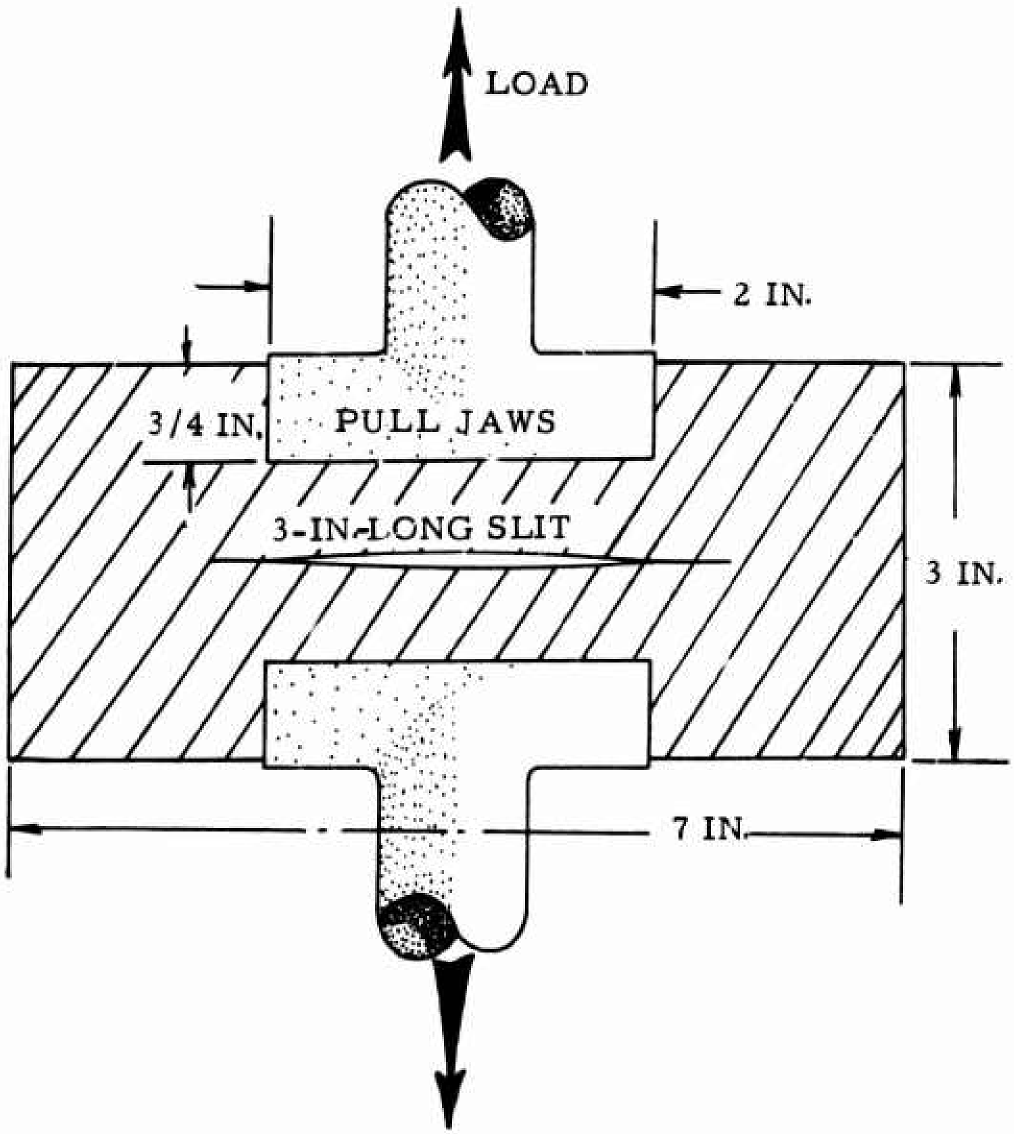


Figure 7. Slit Test for Obtaining Resistance to Tear Propagation.

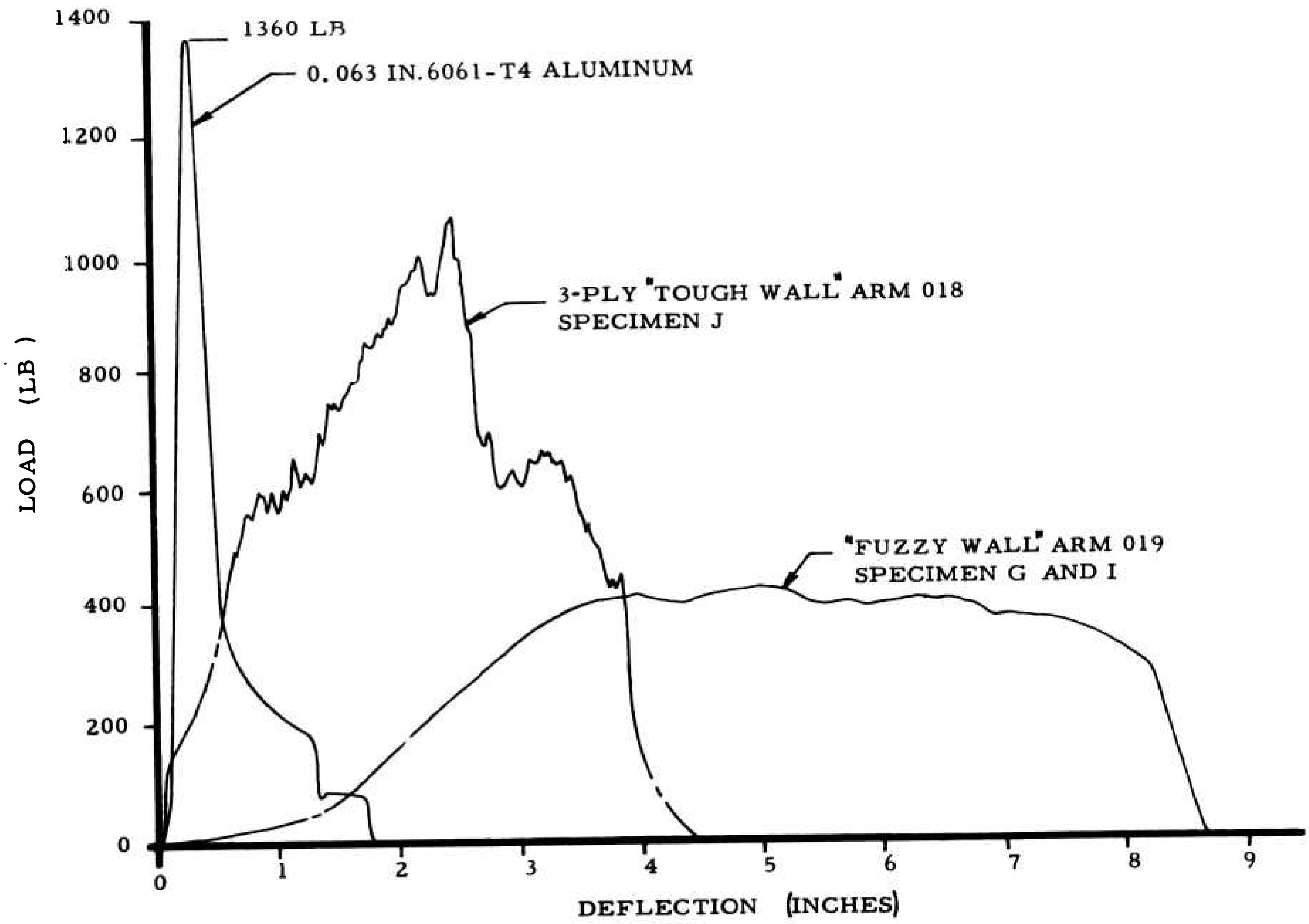


Figure 8. Resistance to Tear for Tank Materials.

The area under these curves represents the energy required to fail the specimen completely. The three materials are compared numerically in Table II.

TABLE II
TEAR RESISTANCE OF THREE MATERIALS

Material	Load To Propagate Tear (lb)	Maximum Load (lb)	Energy To Complete Failure (ft-lb)
"Fuzzy Wall"	400	428	206
3-Ply "Tough Wall"	600	1060	214
0.063-Inch Aluminum	1360	1360	50

Even though the load to propagate the slit in the "Fuzzy Wall" pad is only 400 pounds, or about one-fourth that for aluminum, the energy required to completely fail the 7-inch specimen is about four times that for aluminum.

The energy requirements for the "Fuzzy Wall" and the three-ply "Tough Wall" are approximately the same at slow loading rates, with the "Tough Wall" carrying about two and a half times the maximum load of the nylon felt pad. The large energy-absorption capacity of the pad is due to its high elongation (200 percent). (Impact tests indicate that the performance of the nylon felt is better at high-speed loading.)

FULL-SCALE CRASH TESTS

Concurrently with the materials testing program described earlier in this report, full-scale tanks were constructed of the most promising materials. These tanks were then installed in one of the three different types of crash test aircraft involved, which were then subjected to typical crash conditions. The test aircraft utilized were the C-45 (commercial Beech D-18) fixed wing and the CH-34 and CH-21 rotary wing. The C-45 provided a vehicle for testing fixed-wing tank installations, the CH-34 permitted testing of underfloor tank installations, and the CH-21 permitted testing of a fuselage tank installation. Six crash tests were conducted with full-scale experimental tanks aboard, including three

C-45 tests, two CH-34 tests, and one CH-21 test. These aircraft carried a variety of other experiments on board, in addition to the experimental fuel tanks. These tests are described in detail in Appendix II.

A total of 36 tanks of 10 different types were involved in the tests. Their capacities ranged from 13 gallons (CH-34 self-sealing) to 286 gallons (CH-21). All of the tests involved "survival limit" accidents with one exception. This was a minor impact in a CH-21 drop, Test 12. The results of the experiment are shown in Table III.

The wing tank tests included (1) direct pole impacts into the tank area and (2) wing-tip impacts with a 30-degree sloping earth barrier. Tanks installed in wings involving the wing-tip impact were the least damaged, and thus it can be assumed that they were exposed to the least severe crash environments.

The "Fuzzy Wall" and "Tough Wall" tanks demonstrated good crashworthy characteristics during the severe pole impacts. Minor failures in the form of seepage (less than 1 quart per minute) were experienced by two of the three "Tough Wall" tanks.

The fuselage tanks in six CH-21 tests (five tests performed in earlier studies) showed failures for all tanks. Four of the failures would be considered in the catastrophic category. These involved the three pliocell bags and a MIL-T-27422A tank. A second MIL-T-27422A tank failed to a lesser degree in the minor impact in Test 12. The hollow "Tough Wall" tank, tested in a survival limit test in a CH-21, failed because of exposure to jagged metal. Minor cuts up to 2 inches in length were experienced. However, the degree of fuel spillage was very greatly reduced as compared to the pliocell and MIL-T-27422A tanks. This tank was of the "Tough Wall" B type (see Figures 4 and 6). Had the tank been made of the later developed type H material, the spillage would probably have been reduced considerably. A study of the results of the underfloor tank tests in Table III is quite conclusive in that only the "Tough Wall", the net, and the "Fuzzy Wall" tanks approached surviving this type of environment. Of all the experiments conducted, the second CH-34 underfloor tank tests were the most severe from the standpoint of tank environment. In fact, both of the "Tough Wall" (Specimen D) tanks experienced some degree of failure. The hollow tank failed over a large area, and the honeycomb-cored tank sustained a separation (delamination) which allowed a leakage of approximately 2 quarts per minute. The hollow tank, however, was confined below the floor line by a modification made to the floor to restrain the wheeled loads used in a "cargo" experiment aboard the aircraft. The failure was thus induced by the inability of the tank to expand into another area.

TABLE III
SUMMARY OF TEST RESULTS - FULL-SCALE CRASH TESTS

	LOCATION									
	WING				FUSELAGE		UNDERFLOOR			
Tank Type	No. Tests	Pole Impact	No. Tests	Wing-Tip Impact	No. Tests		No. Tests	No Cargo	No. Tests	1000-lb. Cargo
"Pliocell"	0	-	0	-	3	3 Failed****	3	3 Failed	0	-
Crash Resistant***	0	-	0	-	2	2 Failed	0	-	0	-
Aluminum	2	2 Failed	2	1 Failed	0	-	1	1 Failed	0	-
Exp. Tank (A)**	0	-	1	No Failure	0	-	0	-	1	Failed
Exp. Tank (B)**	0	-	0	-	0	-	0	-	1	Failed
Exp. Tank (C)**	0	-	0	-	0	-	0	-	1	Failed
Self-Sealing	0	-	0	-	0	-	4	4 Failed	0	-
Net Tank	0	-	0	-	0	-	0	-	1	Failed*****
"Tough Wall" Hollow	2	No Failure*	2	No Failure	1	1 Failed	1	No Failure	1	Failed
"Tough Wall"/Honeycomb	1	No Failure*	1	No Failure	0	-	2	No Failure*	1	No Failure*
"Fuzzy Wall"	1	No Failure	0	-	0	-	0	-	1	No Failure

*Minor Seepage - One Tank
** Firestone Experimental Tanks
*** MIL Specification T27422A
**** Previous CH-21 Tests by AvSER
***** Spillage Approximately 1 gal./min.

IMPLICATIONS OF TEST RESULTS

The tests made in the performance of this study were conducted to allow the selection of materials which would greatly improve fuel containment without introducing unacceptable compromises involving weight, complexity, and cost.

A combination of tests was conducted. First, tanks of promising materials were used in several full-scale tests to obtain proof of their capacity for fuel containment. Second, laboratory tests were conducted to approximate the impact, penetration, and tear resistance of these materials in a manner to allow a comparison and selection of other materials which would perform similarly. These laboratory tests could form the basis for a new specification for fuel tanks.

A comparison of the test results for four materials is shown in Table IV. Clearly, the aluminum and MIL-T-27422A materials are unsatisfactory, while the "Fuzzy Wall" and "Tough Wall" materials show good promise.

While no positive proof is presented, it is believed that the 1-inch chisel drop test and the tear test, as described in this report, if met by a proposed tank wall material, would insure a large improvement in fuel containment.

It should be noted that the conclusions reached in this study are applicable only to relatively small (200-gallon) tanks consistent with those now in service in Army aircraft. No extrapolation has been or should be made to larger tanks at this time because of insufficient data.

IMPACT-PENETRATION TEST REQUIREMENT

The proposed material should withstand the chisel test as described elsewhere in this report. The minimum acceptable performance should be:

Energy Level: (a) 45 foot-pounds without leakage

(b) 60 foot-pounds without complete penetration of the chisel

Chisel Size: 1.0-inch-square bar with a tip having a 1.0-inch edge rounded to 1/32-inch-radius edge and a 60-degree included angle

TABLE IV
A COMPARISON OF THE CRASH RESISTANCE OF SELECTED TANK MATERIALS

Material	(lb/in.)	Maximum Strain (Pct)	Tear Resistance (ft-lb)	Puncture Resistance (Condition to Produce Leakage)	Impact Resistance (Condition to Produce Leakage)	Performance In Crash Tests
1. MIL-T-27422A Crash Resistant Fuel Tank, CH-21 Installation	475	20	-	Per MIL-T-6396A (15-lb load on 0.312-in.x 0.031-in. screwdriver point)	Per MIL-T 6396A (1/2-lb steel ball dropped 10 feet) Energy = 5 ft-lb	Extremely Poor
2. "Fuzzy Wall" 3/8-in.* (Goodyear Code ARM-019)	200	200	206	110 ft-lb on 1-in.** 60° Chisel	850 ft-lb on 4-1/4-in. 90° Anvil	Excellent
3. 3-Ply "Tough Wall" (Goodyear Code ARM-018 Specimen J)	2286	23	214	35 ft-lb on 1-in. 60° Chisel	450 ft-lb on 4-1/4-in. 90° Anvil	Fair to Excellent
4. Sheet Aluminum 0.063-in.6061-T4	1320	22	50	20 ft-lb on 1-in.60° Chisel	No Data	Poor

* Material requires a sealant layer in addition to the basic ARM-019 tank wall material.
** Loads thus indicated produced small punctures in "Fuzzy Wall" proper but did <u>not</u> fail Crinkl-Core Liner. See Figures 4, 5, and 6.

Specimen Size:	4.0-inch-diameter working area fixed rigidly around the periphery

TEAR TEST REQUIREMENT

The proposed material should withstand the pull tear test described elsewhere in this report. The minimum acceptable performance should be:

Minimum Load To Propagate Tear:	400 pounds
Minimum Energy for Complete Separation:	200 foot-pounds
Specimen Size:	3 inches x 7 inches with 3-inch slit perpendicular to direction of pull (Figure 6)
Jaw Size:	As shown in Figure 6

CONCLUSIONS

1. Fuel tanks built to current specifications, MIL-T-27422A and MIL-T-6396A, have not demonstrated a capability to withstand the environment typical of "survival limit" accidents.

2. Fuel containment can be achieved under extremely severe conditions ("survival limit" accidents) with tanks of reasonable weight. It is believed that approximate optimization of the system will lead to installations carrying little or no weight penalty.

3. It is a very complex engineering problem to define all the factors leading to the optimization of the crash resistance of fuel systems. However, there is sufficient information now available to allow large improvements to be made in fuel system design without accurately determining all the factors and/or their effects.

4. The threat of postcrash fire will be appreciably reduced if the specifications for the design of crash resistant fuel systems are changed in accordance with the recommendation presented in this report.

5. Although the proper selection of tank wall materials plays a vital role in fuel containment, it is equally important to integrate the fuel cell with the overall structure and all other components of the fuel system if crashworthiness is to be achieved.

6. Of the two types of materials, "Fuzzy Wall" and "Tough Wall", showing good performance in this study, the "Fuzzy Wall" is estimated to be potentially much superior in overall crash resistance.

RECOMMENDATIONS

1. Until additional data are available, the appropriate military specifications should be rewritten to reflect the results of this study.

2. Pending the modifications of the specifications, fuel systems for U. S. Army aircraft currently in the design phase should be required to meet the criteria as defined herein, including the requirements set forth for (1) the tank and (2) all of the other related components.

3. Immediate effort should be made to further current research which has produced excellent early results in providing a self-sealing capability for the "Tough Wall" and "Fuzzy Wall" materials against ballistic impact.

4. Analytical and experimental studies to further the basic understanding of the effect of environmental conditions, tank material properties, and design configurations on the crash resistance of fuel systems should be vigorously pursued.

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APPENDIX I

DYNAMIC TESTS OF A CRASH RESISTANT FUEL TANK INSTALLED IN A CH-21A HELICOPTER

INTRODUCTION

In October 1963, two dynamic helicopter crash tests were conducted that included a crash resistant fuel cell among the test articles. The same test vehicle, a CH-21A helicopter, was first used in a controlled drone crash and then in a dynamic crane drop. Subjecting the same fuel cell to two separate crashes of dissimilar force and acceleration magnitude provided data upon which to base an evaluation of significant value.

The fuel cell was manufactured by the Goodyear Tire and Rubber Company, Akron, Ohio, and furnished by that firm for test installation by the Aviation Safety Engineering and Research Division of the Flight Safety Foundation.

The objective of the tests was to determine the crashworthiness of a crash resistant fuel cell installed in a CH-21A helicopter subjected to full-scale dynamic crashes. The determination was to be governed primarily by rupture tendencies and fuel spillage characteristics as directly related to the force and acceleration environment.

The crash resistant fuel cell was manufactured in accordance with Government Specification MIL-T-6396A. This specification for crash resistant fuel cells resulted from research conducted by the CAA in Indianapolis some years ago. The specific design used in these tests is presently being used in Army CH-21 helicopters in lieu of the thin-walled pliocell cells previously installed. The change resulted in a slight weight penalty, but gained increased cell wall thickness, strengthened seam structure, and improved materials composition.

The first crash established an environment of deceleration and forces well within the design limitations of the cell, yet demonstrated vulnerability to puncture damage, a separate consideration. The last test incorporated a protective liner around the cell to minimize the puncture probability, thus creating a situation whereby the tank might be able to contain the fuel during and after the crash.

Results of the tests are significant in that the normal hazards, pertinent to bladder fuel cells, were produced for detailed observation and evaluation. The effects of jagged metal punctures and impact rupture on a rubber-like cell material are recorded for further study and testing.

Further, the validity of protecting fuel cells with the liner material used is explored.

This appendix is an account of the test methods and results, with photographic and accelerometer records of impact conditions and environment.

DESCRIPTION OF TEST ARTICLE

The crash resistant fuel cell involved in these tests was designed for installation in Vertol CH-21B and C model helicopters. Material composition is nitrile rubber and nylon cloth. It was designed to withstand a 25G vertical impact with a 1.75 stress safety margin incorporated in the manufacturer's design standard to produce a possible 43.75G capability. Weight is 29.8 pounds, an increase of 12 pounds over the standard pliocell tanks it replaced. The cell has no self-sealing properties. General measurements of the cell are shown in Figure 9.

A total of 393 of these cells were produced for installations in CH-21B and C model helicopters. The CH-21A chamber structure in which the cell was installed is designed for 8G horizontal and vertical loads, and 3G lateral loads.

The Goodyear Company also furnished a nylon liner that was mounted on the interior surfaces of the chamber to serve as additional protection for the bladder cell during the second test. The liner is referred to as "wingboard" (Swedlow S3N) and is composed of three sheets of laminated nylon cloth impregnated with nylon resin.

The two tests involved the use of a CH-21A model helicopter. Since the bladder cell was designed for B and C models, minor modifications were necessary in order to properly install the bladder cell in the aircraft fuel cell chamber. The modifications consisted of the following:

1. Reorienting two hanger fittings on the top of the bladder cell to conform to existing suspension points.

2. Improvising a means of suspending the main bladder cell access hole closure plate 6 inches to the left of the existent A model plate opening. This was accomplished by drilling and bolting through the metal top of the fuel cell chamber, picking up the new access plate and the nut plate thereunder, and closing off the old fuel cell chamber access hole by a series of bolts interconnecting the new and old plates.

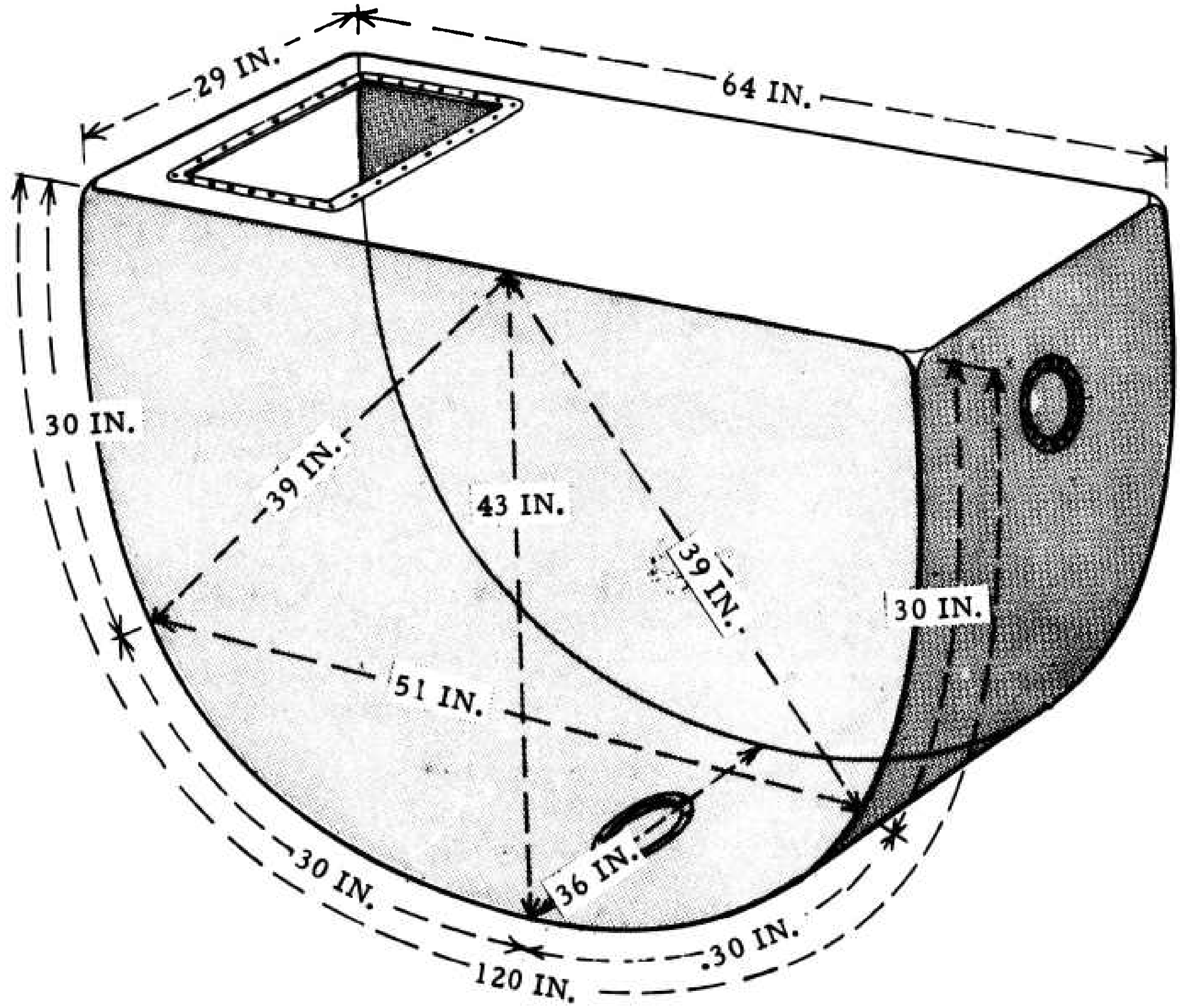


Figure 9. Dimensional Cutaway of Fuel Cell.

During both crash tests, the bladder cell was filled with 212 gallons of dye-colored water to simulate a full load of 286 gallons of fuel. Approximate weight involved was 1750 pounds.

TEST PROCEDURE

The test vehicle for both tests was a Vertol CH-21A helicopter, shown in Figure 10.

Figure 10. CH-21A Test Helicopter (Fuel Cell Chamber Area Painted Dark Amidships).

The first test, designated T-12, was conducted on 5 October 1963. The helicopter was flown and crashed by a radio link remote control system that permitted ground control of the aircraft through a predetermined flight path.

For T 2, the bladder cell was installed in the cell chamber as it would be in normal maintenance replacement. Considerable effort was involved in securing the cell to the chamber walls. The installer had to enter the cell and work blind to attach the studs on the cell exterior to the female fittings mounted on the chamber walls. There were 31 fittings involved.

A relatively mild impact resulted from T-12. Overall structural damage to the fuselage was minor, as shown in Figure 11.

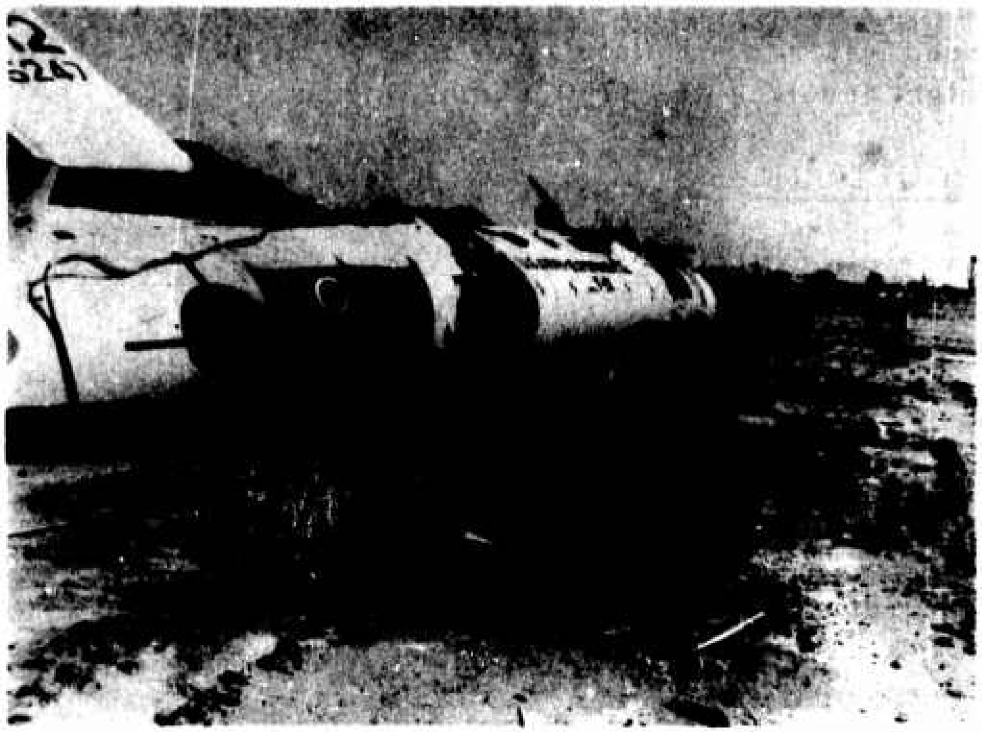


Figure 11. Condition of Helicopter After T-12 Crash.

Figure 12 reveals that the structure directly beneath the fuel cell chamber was disfigured considerably. The chamber area deformed forward, and the metal on the bottom and half way up each side was torn and malformed considerably.

Figure 12. Structure Damage Beneath Fuel Cell Chamber From T-12.

The second test, T-13, was conducted on 22 October 1963 and involved the same test vehicle, the CH-21A shown in Figure 10. The fuselage was separated at the firewall aft of the fuel cell chamber, and the test vehicle for T-13 evolved as approximately two-thirds of the fuselage used in T-12. The fuselage section was dropped from a mobile crane to simulate a crash of greater severity than T-12, the drone flight crash. The test vehicle and crane hookup are shown in Figure 13.

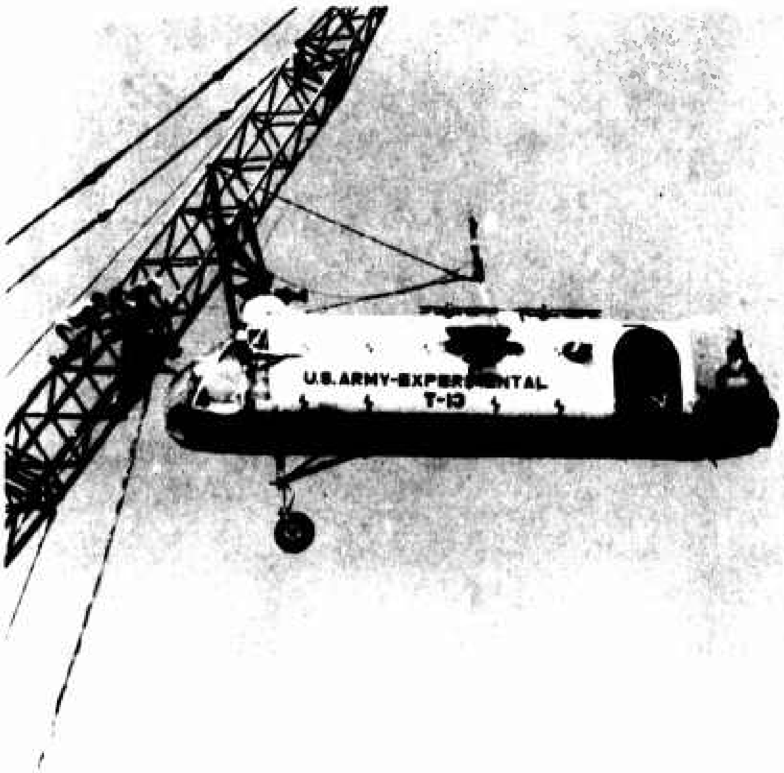


Figure 13. T-13 Helicopter Section and Crane Hookup.

To restore the structural integrity associated with the original cell installation to the T-13 test vehicle, considerable reconfiguration work was involved. The majority of the crumpled and jagged metal around the chamber area was removed. All salvable parts were repaired and/or refastened. The chamber bottom and sides were secured with six longitudinal braces (aluminum angle), and the chamber bottom and sides were replaced with new aluminum sheeting.

Once the chamber was essentially restored, the nylon liner was installed. Separate liner pieces for the top and the fore and aft walls, and one large piece for both sides and bottom, were cut from the 4-foot by 12-foot sheet stock provided. The pieces were fastened to the chamber interior with blind rivets. The rivets passed through washers, which served as load distributors. All seams were closed with pressure sensitive tape, and openings were cut in the liner for the hanger fittings that secure the bladder cell to the fuel cell chamber walls. Figures 14, 15, and 16 provide overall views of the liner installation.

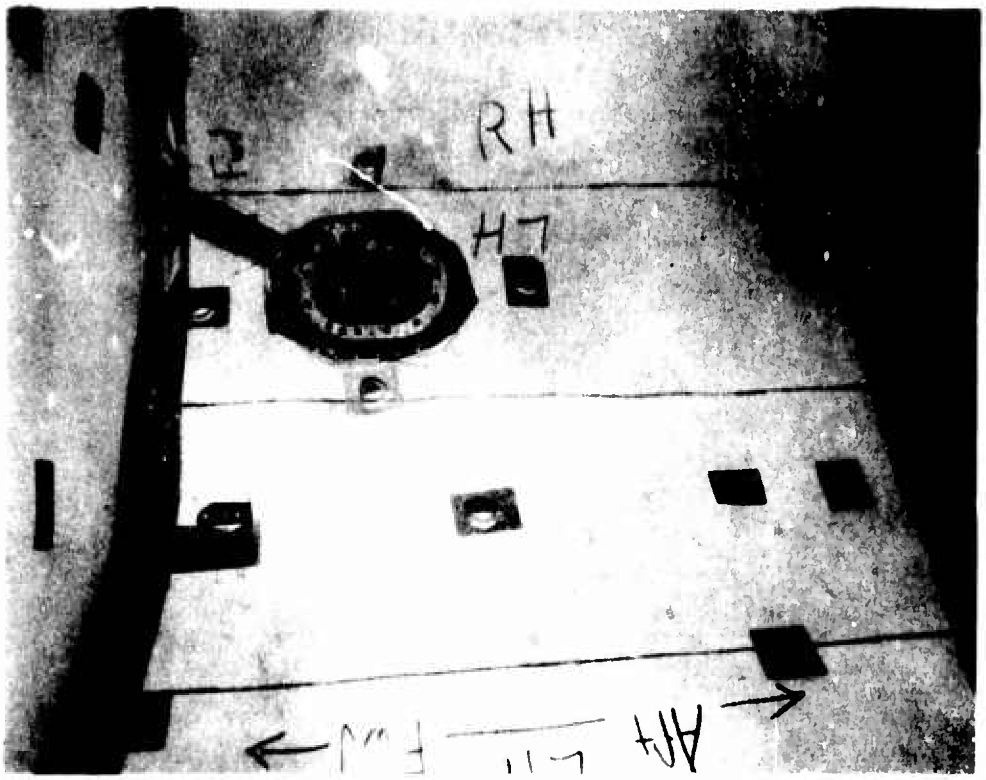


Figure 14. Chamber Bottom Liner Installation.

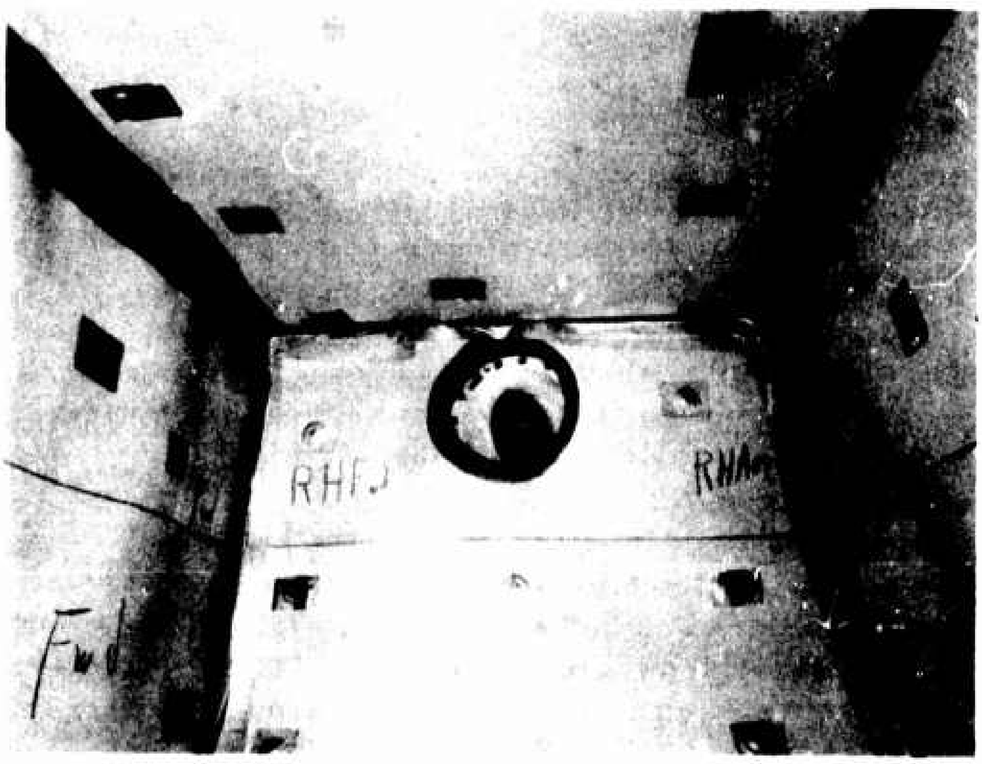


Figure 15. Right Side View of Liner Installation.

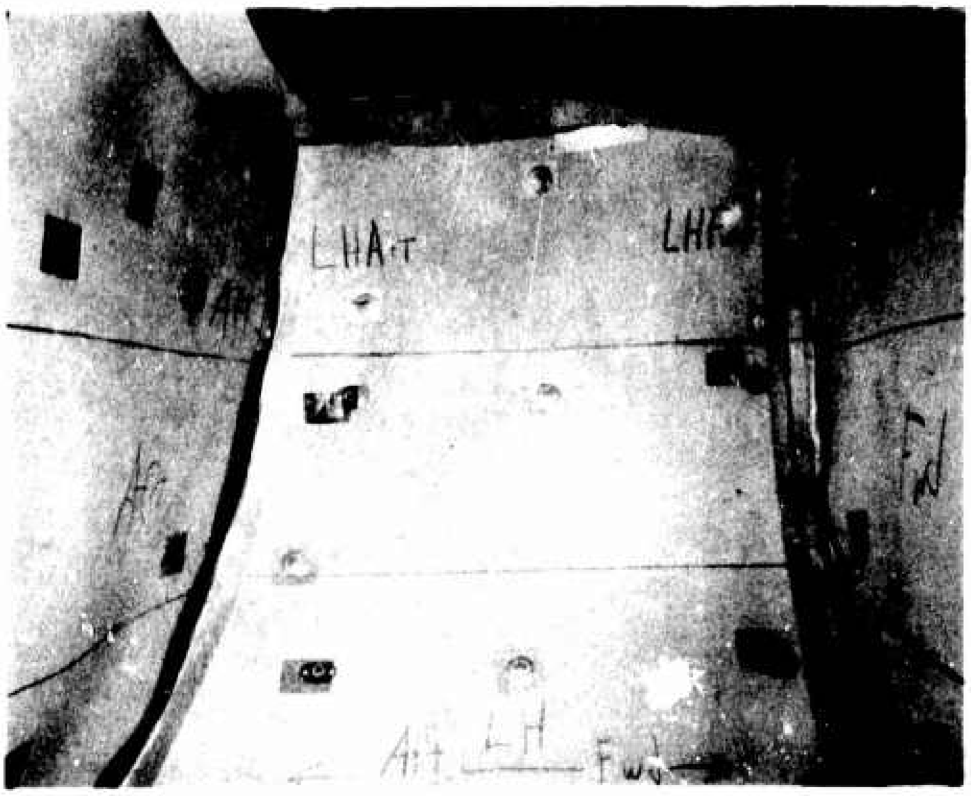


Figure 16. Left Side View of Liner Installation.

The fuel cell was installed after the liner, but structural deformation and the liner installation precluded securing 5 of the 31 fasteners to the chamber top and upper sides.

INSTRUMENTATION

Instrumentation installation was accomplished by fabricating a liquid-tight aluminum housing in the bottom of the bladder cell. All fuel service lines and pumps were removed, and the instrumentation housing was installed in the cavity normally occupied by the booster pump, as seen in Figure 17. Connecting wires to the instruments were run through a 6-foot rubber hose that attached to the top of the instrument housing and exited through the vent installation opening on top of the fuel cell chamber. Sufficient slack was allowed in the hose to prevent line rupture from liquid impact surges.

TEST RESULTS

T-12, Drone Flight, Fuel Cell Without Nylon Liner

The helicopter crashed from an approximate height of 11 feet in a typical descent pattern. Upon impact, the aircraft skidded 28 feet and came to rest lying partially on the left side (see Figure 11). A small flash fire of low magnitude occurred for about 2 minutes and was

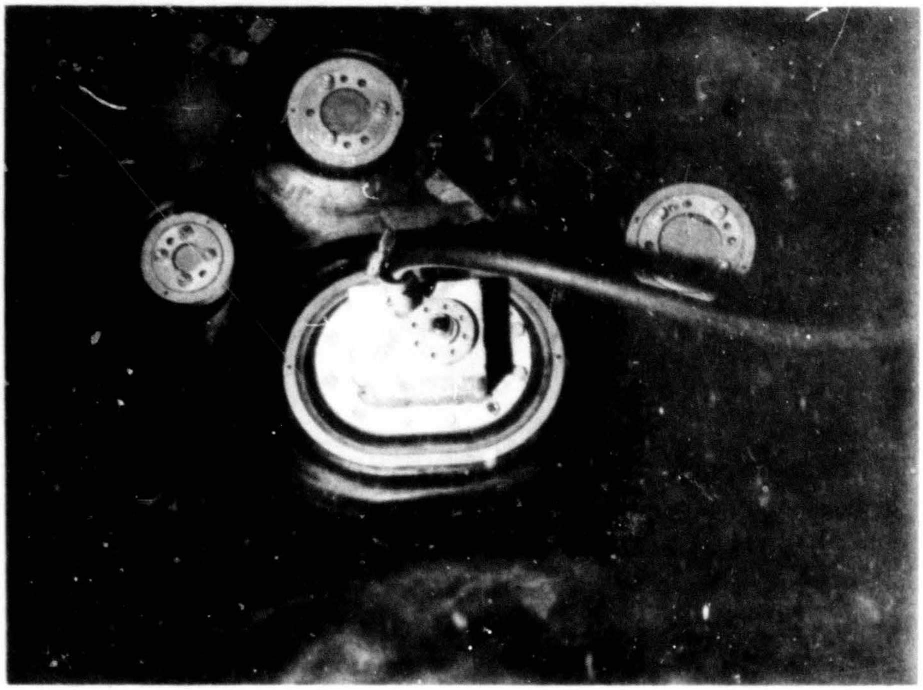


Figure 17. Instrumentation Mounting in Fuel Cell.

attributed to hot lubricant loss from the internally damaged engine that "ran wild" briefly after the crash. The most significant overall damage occurred to the fuselage structure beneath the fuel cell chamber, which deformed inward approximately 16 inches.

Descent and impact data are shown below:

Horizontal velocity:	38.5 feet per second
Vertical velocity:	11 feet per second
Acceleration - vertical:	30G peak of short duration; other accelerations in the 20G range maintained for 2 to 5 milliseconds

The fuel cell sustained only two small slit-like perforations, 6 inches apart on the bottom, 1 foot from the instrumentation housing. These are shown in Figures 18 and 19. The perforations measured 1/2 and 1 inch, respectively, and occurred when the longitudinals, shown exposed in Figure 20, sheared upward. Figure 21 depicts the jagged metal that punctured the fuel cell bottom.

Figure 18. Fuel Cell After T-12 Crash (Perforations Outlined in Tape).

Figure 19. Close-up of T-12 Perforations.

Figure 20. Deformation of Fuel Cell Chamber, Left Side, From T-12.

Figure 21. Interior View of Cell Chamber Showing Area Where Fuel Cell Was Punctured.

As the fuel cell expanded under the decelerative impact force, the metal sides of the cell chamber deformed forward and separated along the seams. This is apparent in Figures 20 and 21. The leakage from the perforations shown in Figures 18 and 19 was sufficient in rate and volume to have resulted in a fire under actual crash conditions.

During the crash deformation, the fuel cell fittings that secured the cell to the chamber walls remained engaged and the bladder was retained in the position installed in the chamber.

The two perforations were repaired prior to reuse of the fuel cell in the second test, T-13.

T-13 Crane Drop, With Nylon Liner

Descent and impact data for this test are presented below:

Height of drop:	29 feet 10 inches
Vertical velocity (at impact):	36.8 feet per second
Horizontal velocity (at impact):	38.6 feet per second
Acceleration - vertical:	147G peak for a sharp G buildup in the first 13/100 second

Upon impact, the fuel cell ruptured in a manner that can be aptly termed an explosion. Figures 22 through 25 depict the crash test sequence and show the manner in which the fuel erupted from the rear of the test vehicle when the fuel cell burst.

The cell ruptured upon impact, and the fuel was forced from the cell initially in a cloud of spray. Figure 23 catches this instant.

In Figure 24, the spray cloud has dissipated and the fuel, now in liquid state, appears in the passenger compartment door and outside the fuselage behind the door. The height of the liquid mass, in excess of 12 inches, in the door serves to illustrate the volume of the flow.

Fuel spillage, as seen in Figure 25, subsided to ground level, spread, and soaked the impact area in the pattern shown in Figure 26.

The interior of the aircraft was extensively wetted from the surface and airborne liquid; the dummies, seats, and other test articles were saturated. Motion photography recorded a torrential flow of liquid along

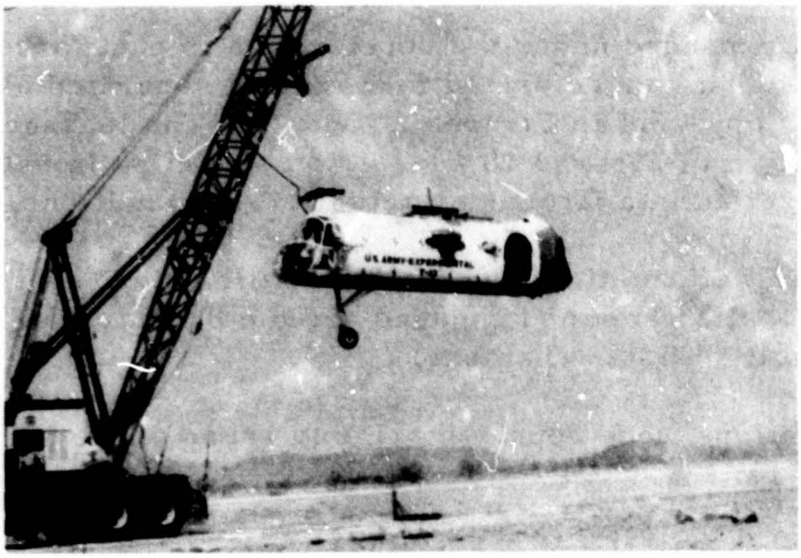


Figure 22. T-13 Helicopter Section During Descent.

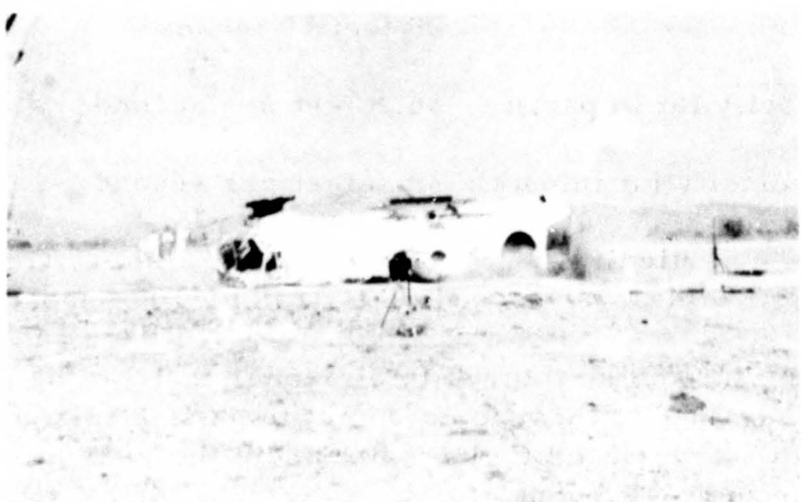


Figure 23. Impact

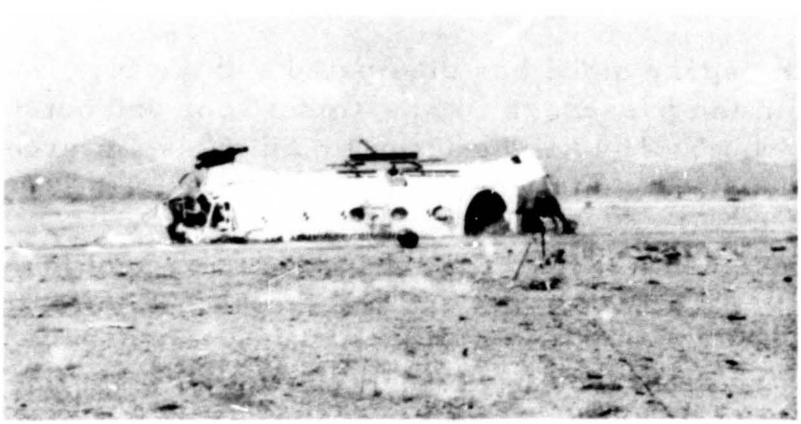


Figure 24. Helicopter Section Skidding After Impact.

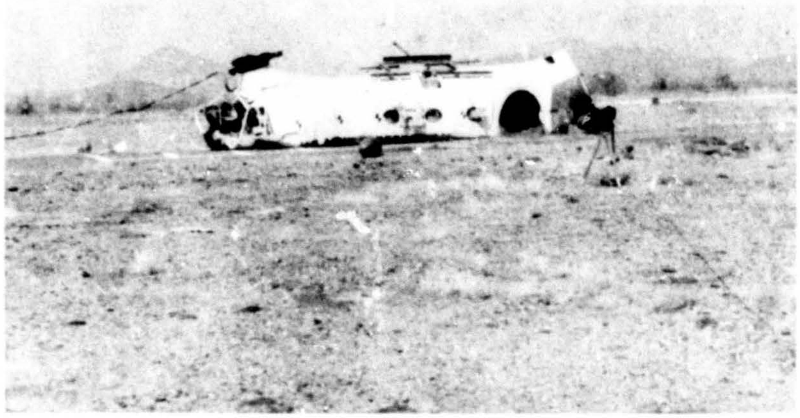


Figure 25. Helicopter Section at Rest After Skid.

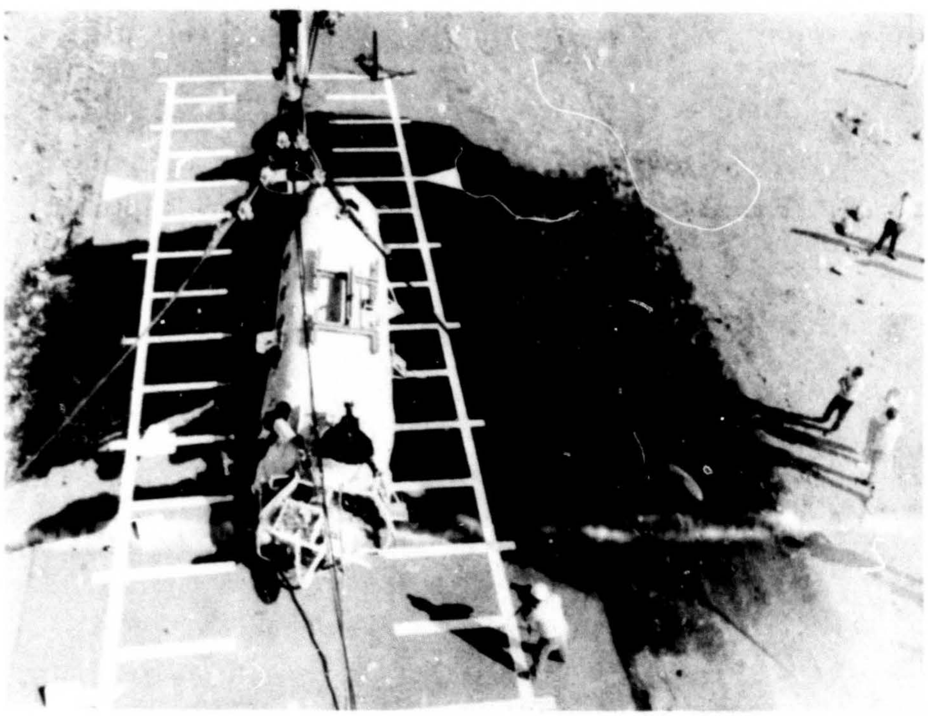


Figure 26. T-13 Exterior Fuel Spillage Pattern.

the interior decking of at least 1-inch depth in some places. Saturation of the aircraft, inside and outside, is due to the manner in which the cell ruptured over half its circumferential length on the left side and forward seam. The opening is shown in Figures 27, 28, and 29.

Damage to the fuel cell chamber structure was extensive and severe. Almost complete loss of structural integrity is shown in Figures 30, 31, and 32. These pictures also indicate that the pressure surge was primarily in a forward and left direction.

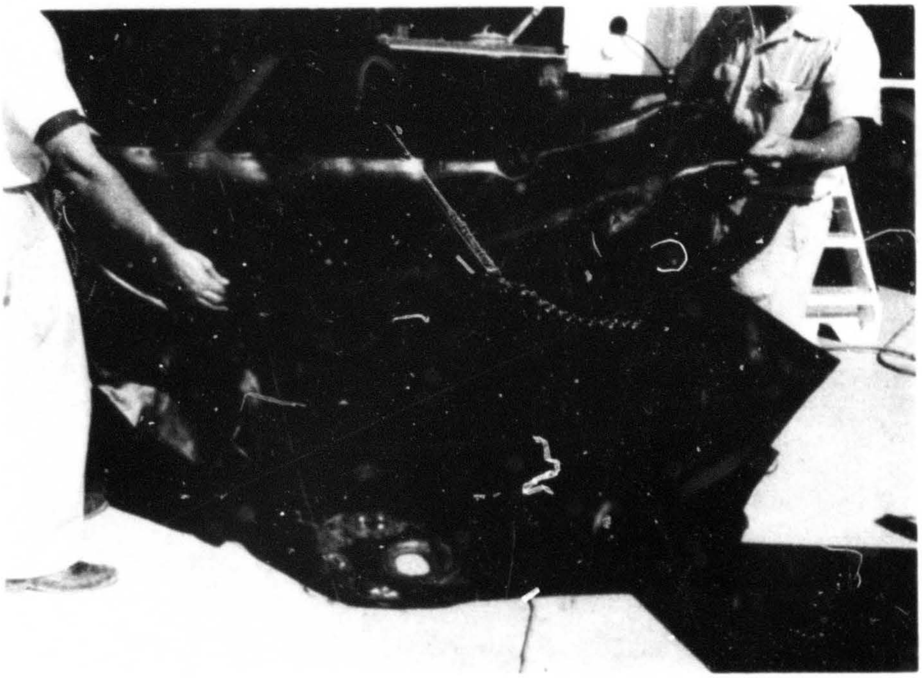


Figure 27. Front Side Showing Length of Seam Rupture.

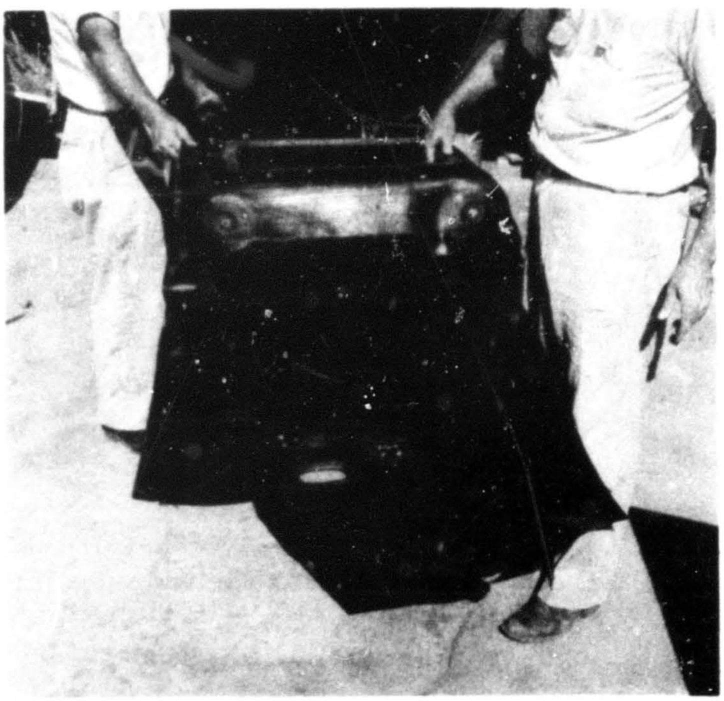


Figure 28. Left Side of Ruptured Fuel Cell.

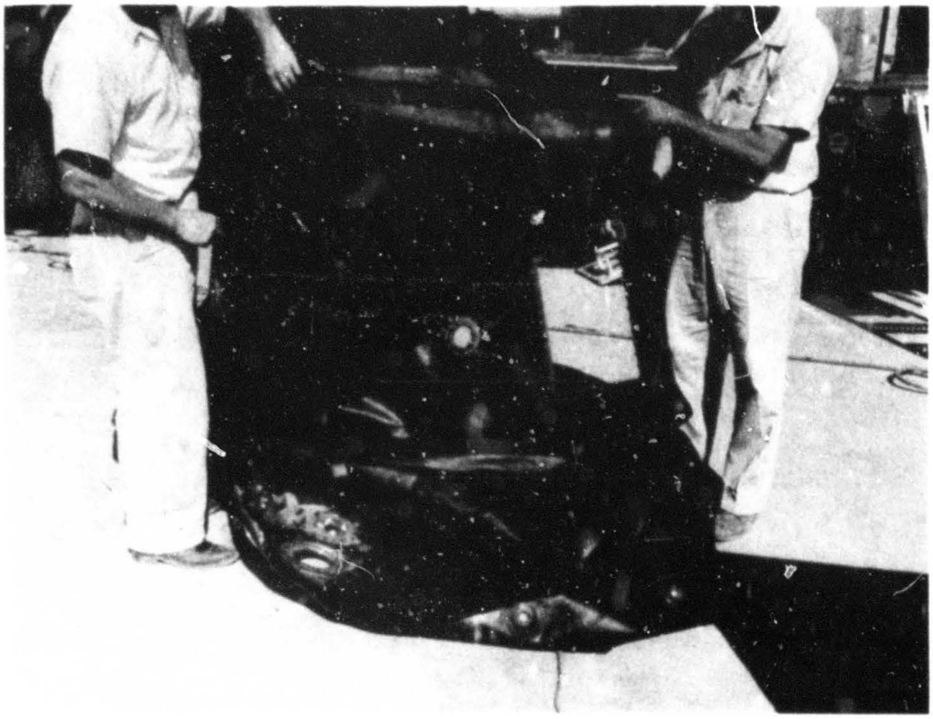


Figure 29. Size of Opening Demonstrated.

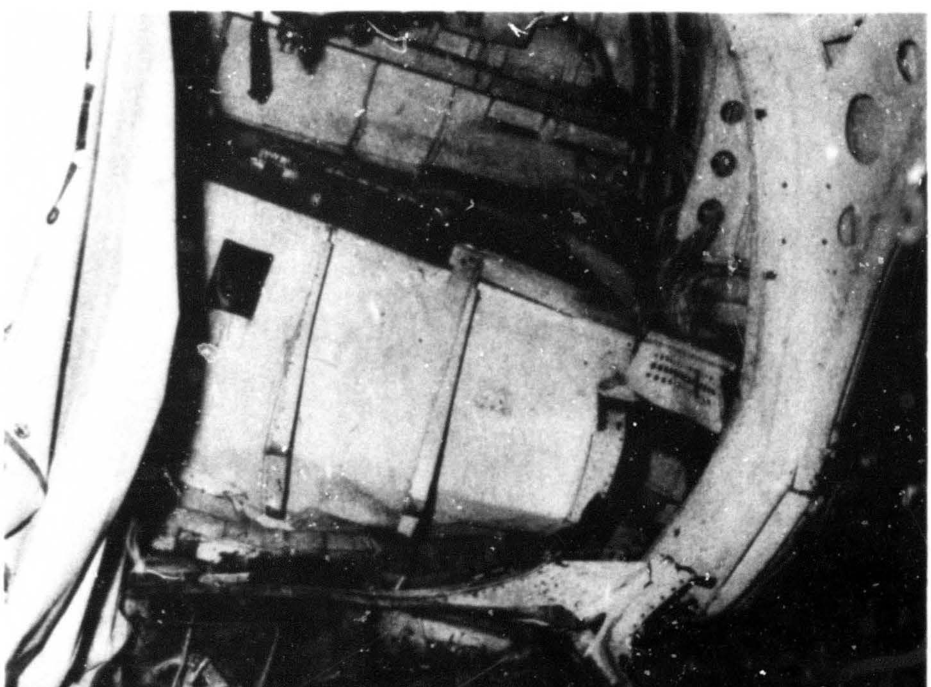


Figure 30. Forward View of Fuel Chamber Damage.

Figure 31. View Showing Forward Deformation of Front of Fuel Chamber Structure.

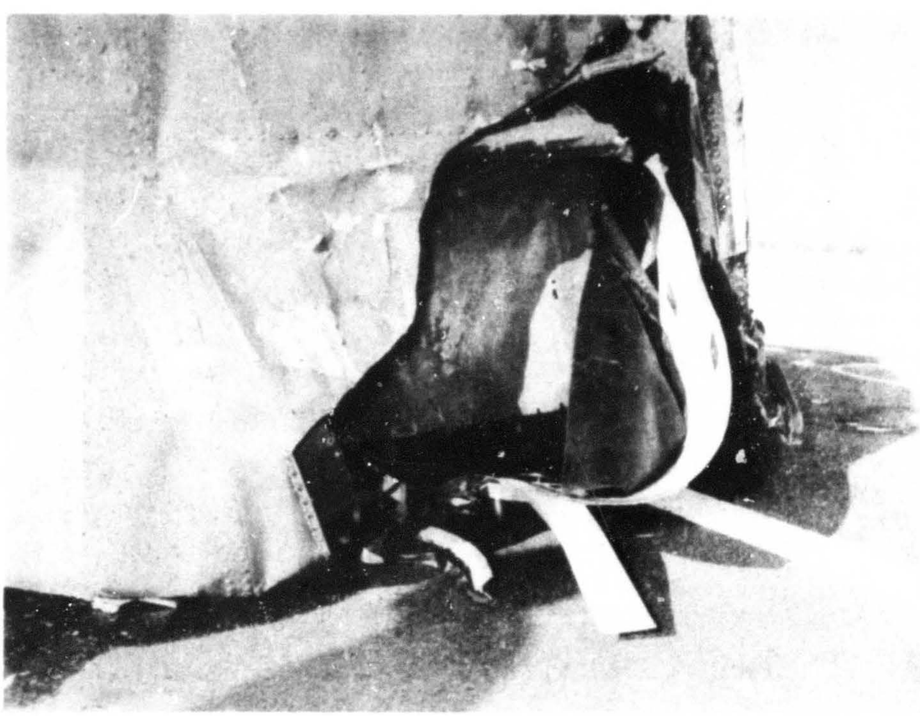


Figure 32. Opening Created in Left Side of Fuel Chamber.

The nylon liner sustained no rips or perforations. Figures 33 and 34 show the position and condition of the liner with the fuel cell removed. Upon impact and during the chamber deformation, the liner followed the metal to which it was fastened. Where separation occurred between the liner and the chamber wall, the rivets pulled through the metal and remained with the liner. The corner taping offered only minor resistance to seam separation and tore or ripped indiscriminately.

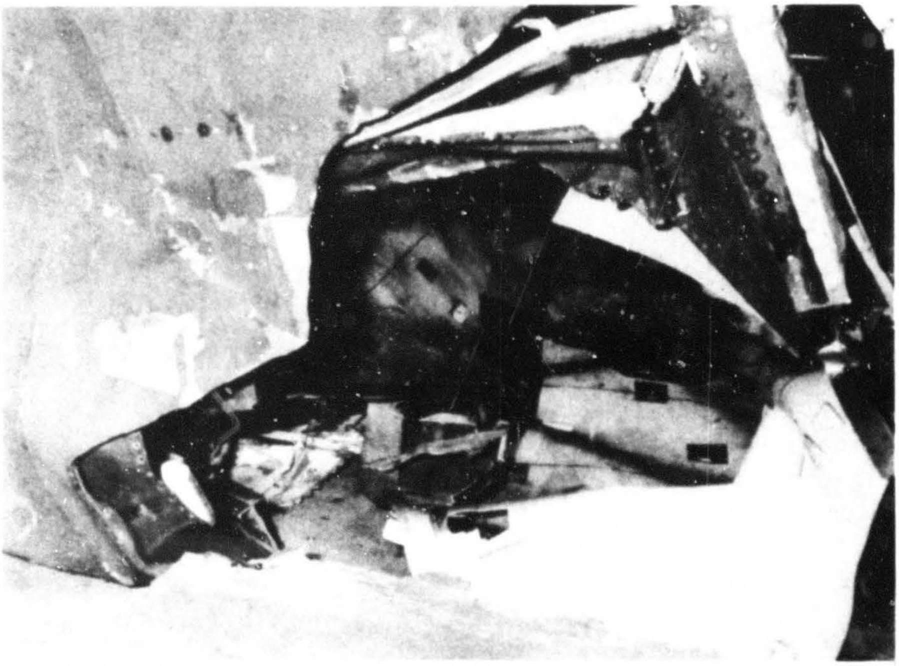


Figure 33. Liner Position After Test.

Eleven of the 31 fuel cell attachment fittings were sheared during impact. Fifteen of the fittings pulled out of the chamber wall receptacles. The attachment fittings are designed to fail below the point at which they could transmit a destructive load to the fuel cell.

DISCUSSION OF TEST RESULTS

T-12, Drone Crash

The crash forces recorded in this test were well below survivable limits as presently known. The cell puncture caused by the jagged metal shown in Figure 21 started leakage of sufficient rate for ignition by the oil fire, through abraded sparks, contact with heated metals, or any of the ignition potentials present in an aircraft crash, had actual fuel been carried in the tank. The fact that the crash forces were well within

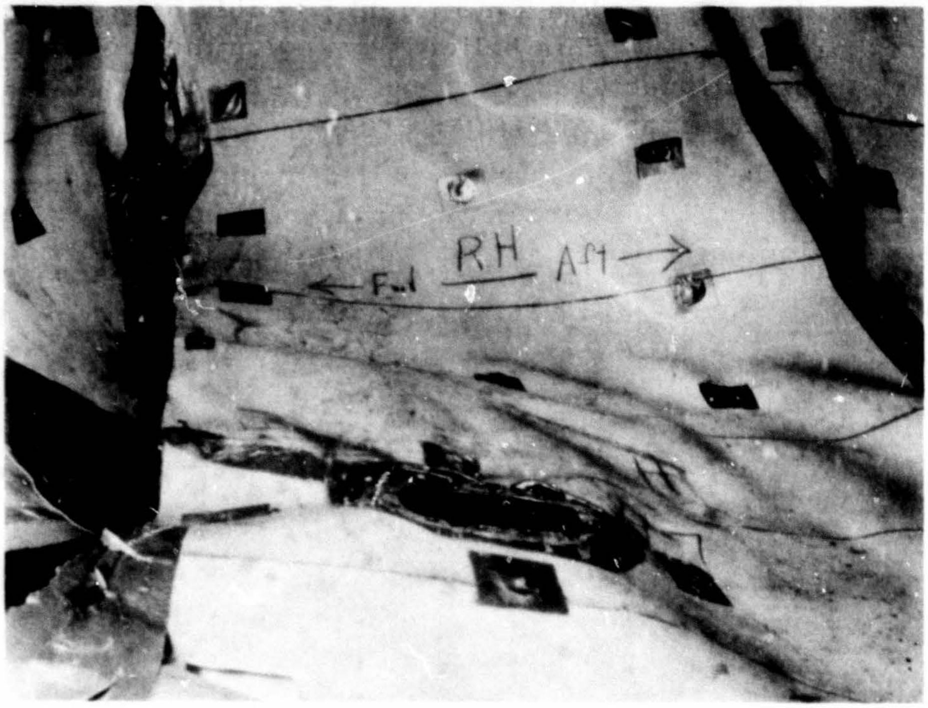


Figure 34. Postcrash Condition of Liner and Edge Taping.

tolerable limits could have been nullified by a fire due to the punctured tank.

The bladder fuel cell failure could almost be predicted, even in a crash of this low magnitude. This assumption is based on the fabric-to-metal installation of a bladder fuel cell designed for 25G loads, in a metal structure designed for 8G horizontal and vertical accelerations and 3G lateral accelerations. Accelerations recorded in the bottom of the fuel cell were in excess of the 8 and 3G limits of the chamber structure and were maintained for at least 46 milliseconds. A 1.75 safety margin is valueless since even this amount of design strength, in a typical bladder cell material subjected to a jagged metal environment, is quickly exceeded during most survivable crashes.

Perforations even smaller than those experienced in T-12 would allow some leakage and would set up a path for ignition to follow to the main fuel load. Also to be considered in this and the second test is the fact that the fuel pumps, strainers, valves, and service lines were removed from the inside and underneath the fuel cell. Their potential for damage to the fuel cell and ignition of the fuel cannot be disregarded. The engine operated at high, uncontrolled RPM for several seconds after impact and during the time that the aircraft was sliding to a stop. The engine behavior, grinding metal, and presence of electrical energy established optimum conditions for fire ignition on impact and for a considerable time thereafter.

The nylon liner that was used in T-13 might possibly have prevented the fuel cell puncture in T-12. This belief is based on the fact that the liner material was not punctured or ripped in T-13, where the severity of impact forces was almost five times greater.

T-13, Crane Drop

Objective analysis of the test results from T-13 must be tempered with the fact that the original fuel cell chamber was designed for 8G horizontal and vertical accelerations and 3G lateral accelerations. When the chamber was rebuilt for T-13, it approximated the original chamber dimensionally but the design load capability may have been redistributed in the horizontal, vertical, or lateral direction.

The crane drop method had also demonstrated, in prior tests, that impact forces would exceed the design limitations of the cell itself (25G with 1.75 safety margin). Vertical accelerations at the floor of the passenger-cargo compartment exceeded 75G in all crane drops on Vertol CH-25 and CH-21 helicopters.

The above conditions indicated that both the fuel cell chamber and the bladder cell would fail. Their manner of failure could not be predicted exactly, however, and herein lies material for possible new or modified approaches to the fuel containment problem.

Figure 35 is a kinematic sketch that depicts the fuel cell rupture resulting from the impact compression force, primarily in a forward and left direction.

The nylon liner used in this test as a protective device against jagged metal tearing the bladder cell appears to be a sound concept. Using tape to close the seams is totally ineffective, however, and soundness of the liner concept is dependent on a more effective joining process.

As a result of this test, it has been concluded that:

1. The crash resistant bladder cell is considered virtually ineffective as a crash fire deterrent in any crash wherein the supporting structure's failure is severe enough to establish a jagged metal environment.

2. The fuel cell might possibly withstand the impact forces normally encountered during a survivable-type crash if afforded the protection of a flexible seam-bonded liner, such as "wingboard", to enclose it and protect against puncture damage.

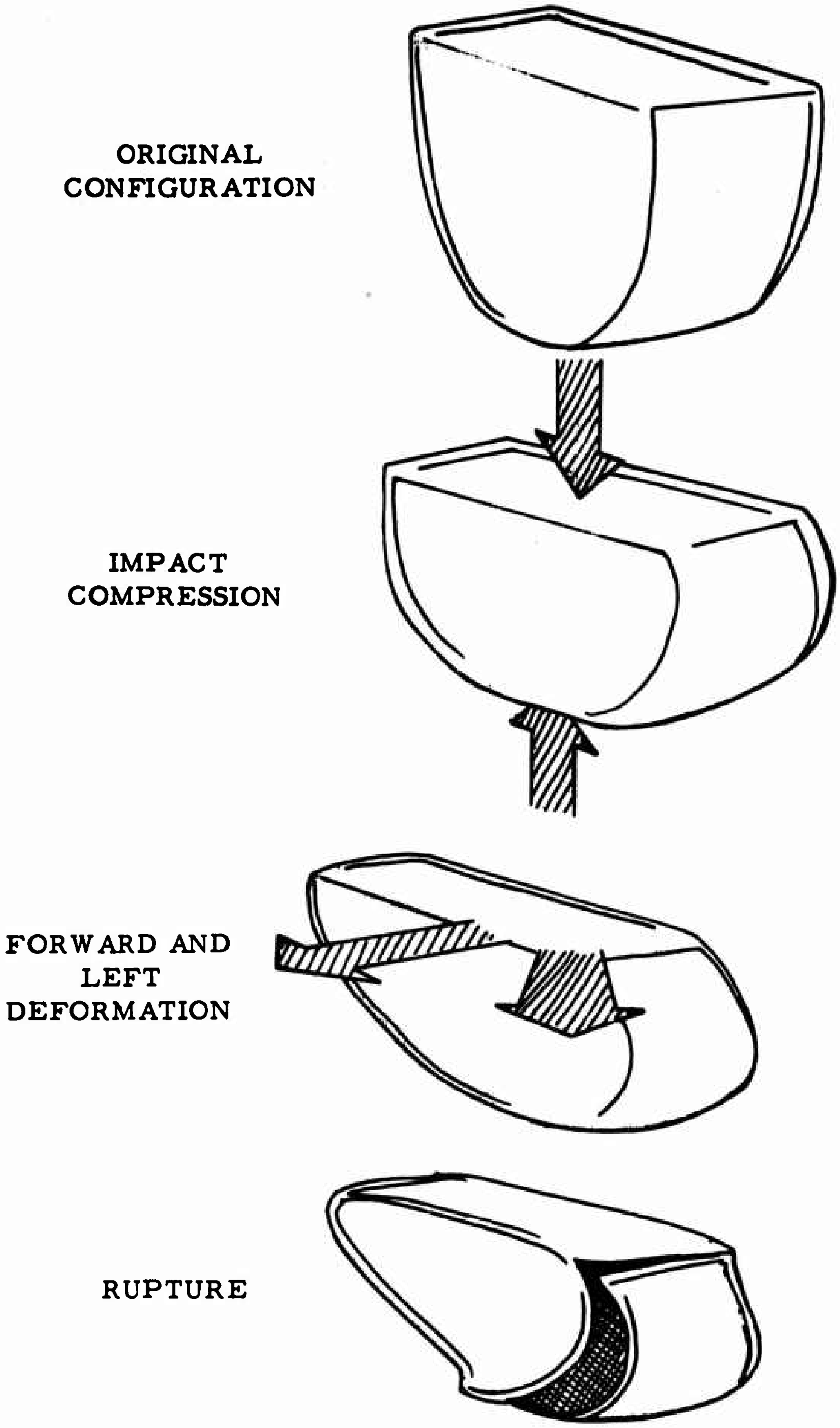


Figure 35. Fuel Cell Rupture Sequence.

3. Airframe structural strength factors surrounding the fuel cell area(s) must be upgraded to prevent:

   a. Failures of the type which increase the probability of cell puncture.

   b. Severe reduction in fuel cell chamber volume.

APPENDIX II

FULL-SCALE CRASH TESTS

The dynamic crash tests performed under this contract were accomplished by two different means: the monorail technique and the crane drop method. A brief discussion of each follows.

Three C-45 aircraft were crashed by accelerating them under their own power under remote control conditions utilizing a monorail and main gear guidance system previously developed for fixed-wing crash test programs.

The aircraft were accelerated for approximately 2,000 feet before reaching the impact site, attaining a ground speed of 80 to 100 mph during the run. At the end of the acceleration run, the landing gear of the aircraft were removed with suitable barriers, resulting in the aircraft's being momentarily airborne, after which they crashed into specially prepared barriers. Figure 36 shows the impact site layout and ground camera locations for these tests.

The wing and fuselage impact hill consisted of an earthen barrier constructed at a 35-degree angle horizontal to the aircraft flight path. The front surface of the barrier was sloped to give an effective impact angle of 30 degrees. The left wing struck the barrier first, as would occur in a wing-low accident. The right wing contacted telephone poles located in positions to impact the special fuel cell installations in the right wing, simulating an impact against trees. Following the impact with the wing barriers, the nose of the aircraft then contacted the hill, resulting in severe crash loading of the occupied area of the fuselage.

The CH-34 and CH-21 aircraft were crashed utilizing the crane drop method, as shown in Figure 37. This method involves suspending the aircraft from the boom of a crane at a height of approximately 30 feet. The crane is then accelerated to a speed of approximately 28 mph during a 4,000-foot run. An automatic release hook system dropped the aircraft at a predetermined impact point at the end of the acceleration run. This resulted in impact velocities of approximately 40 feet per second in both the vertical and horizontal directions, representing a severe but potentially survivable accident.

WING TANK TESTS

The wing tank experiments were conducted in three separate C-45 crash tests, designated as T-16, T-19 and T-24. Each of the three tests is described separately as follows, and the general results of the three tests are then summarized.

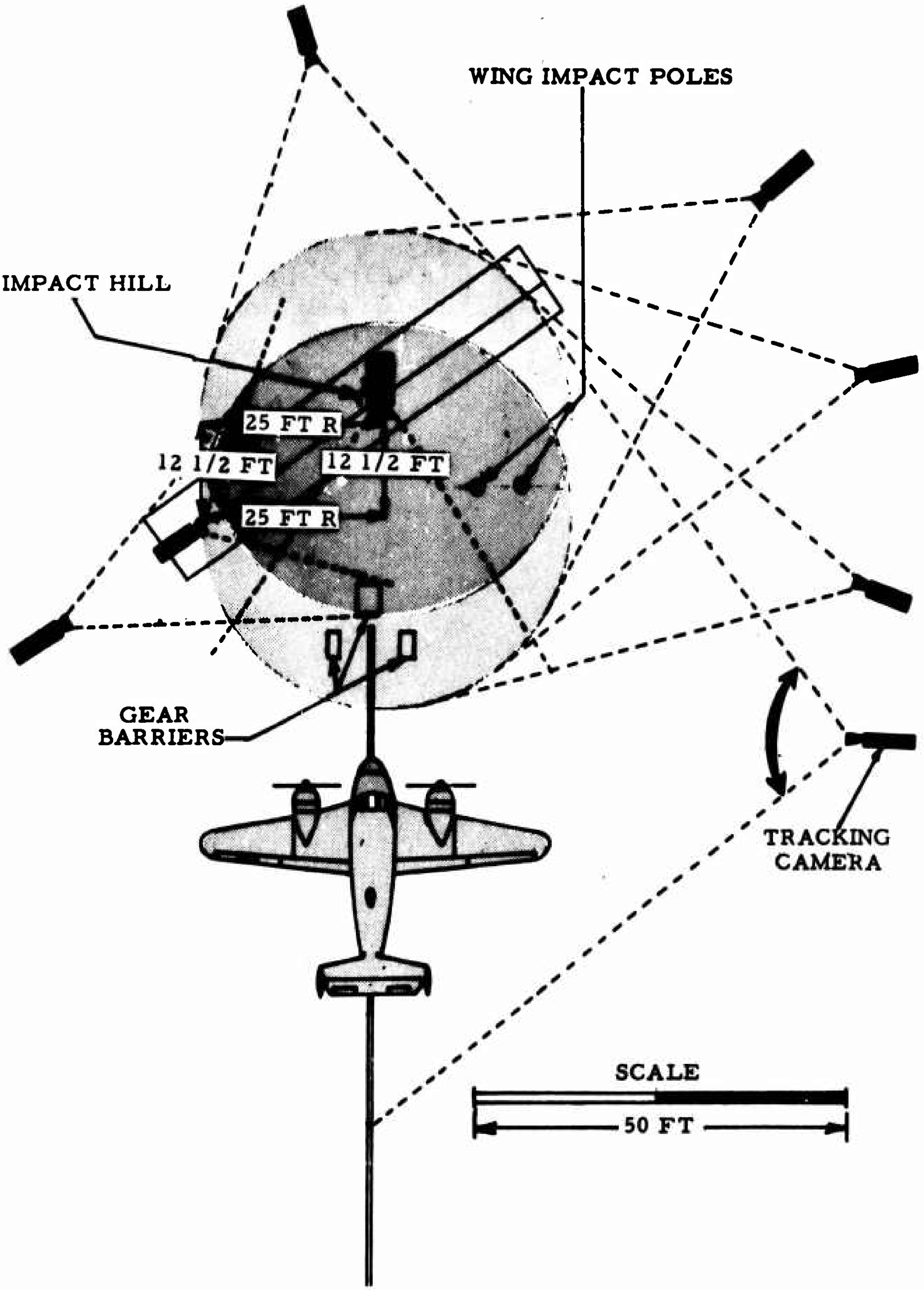


Figure 36. Test Impact Site Layout and Ground Camera Locations.

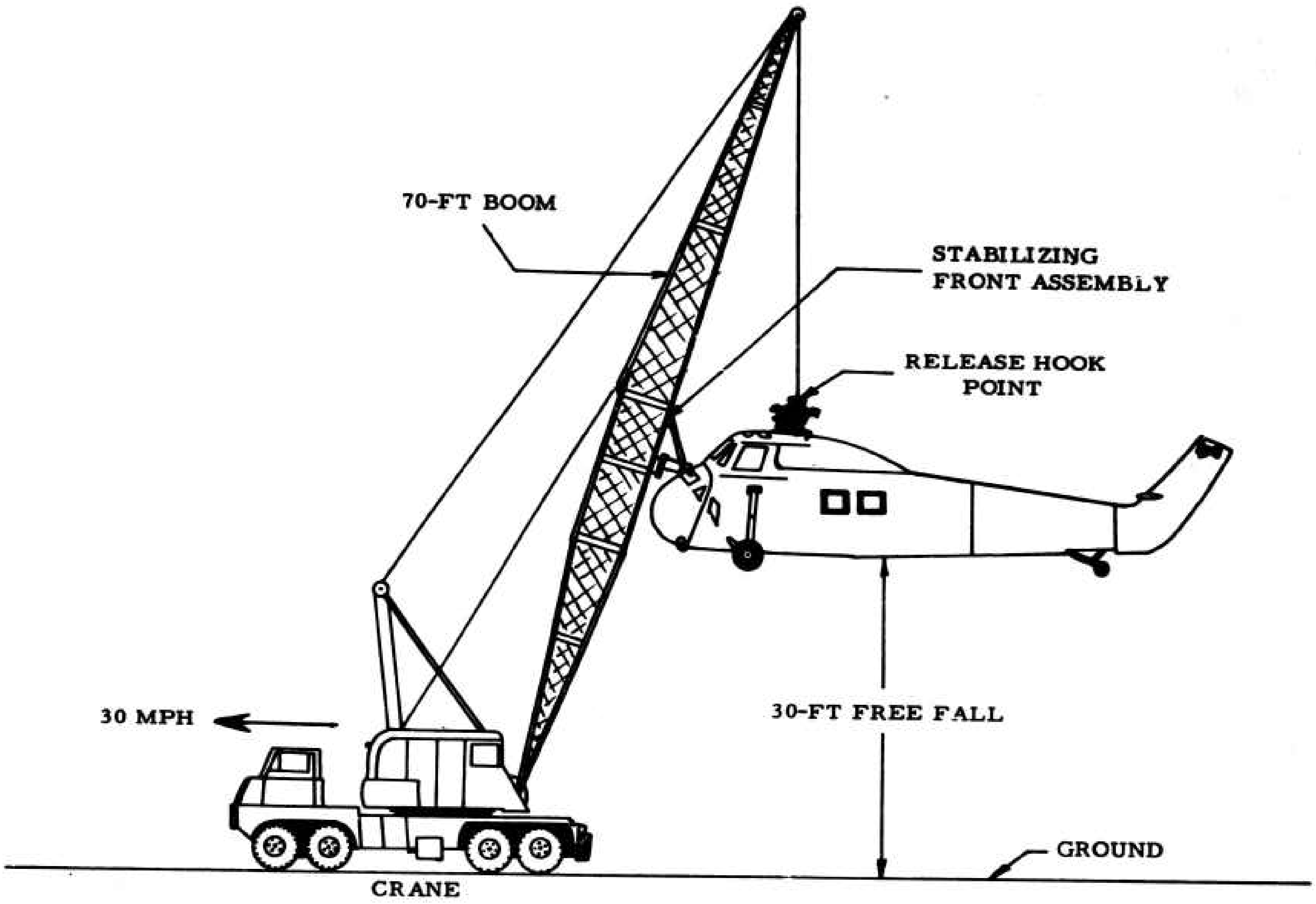


Figure 37. Crane Drop Test Method. (Test Method Using Moving Crane to Drop Helicopter on Target While Moving at 30 mph.)

C-45, T-16, Conducted 6 November 1964

This test was conducted early in the program prior to the development of new tank materials under the materials testing program. Four aluminum tanks which are typical of those installed in light aircraft were constructed. The tanks were constructed of 0.040-inch ductile aluminum and were installed in the aircraft wing, as shown in Figure 38. The purpose of these tests was to provide baseline data for comparison with other test data. The voids between the stringers on the wing skin were filled with 2-pounds-per-foot density plastic foam, in order to gain some cushioning effect and load distribution. This method was incorporated in all of the fixed-wing tank tests.

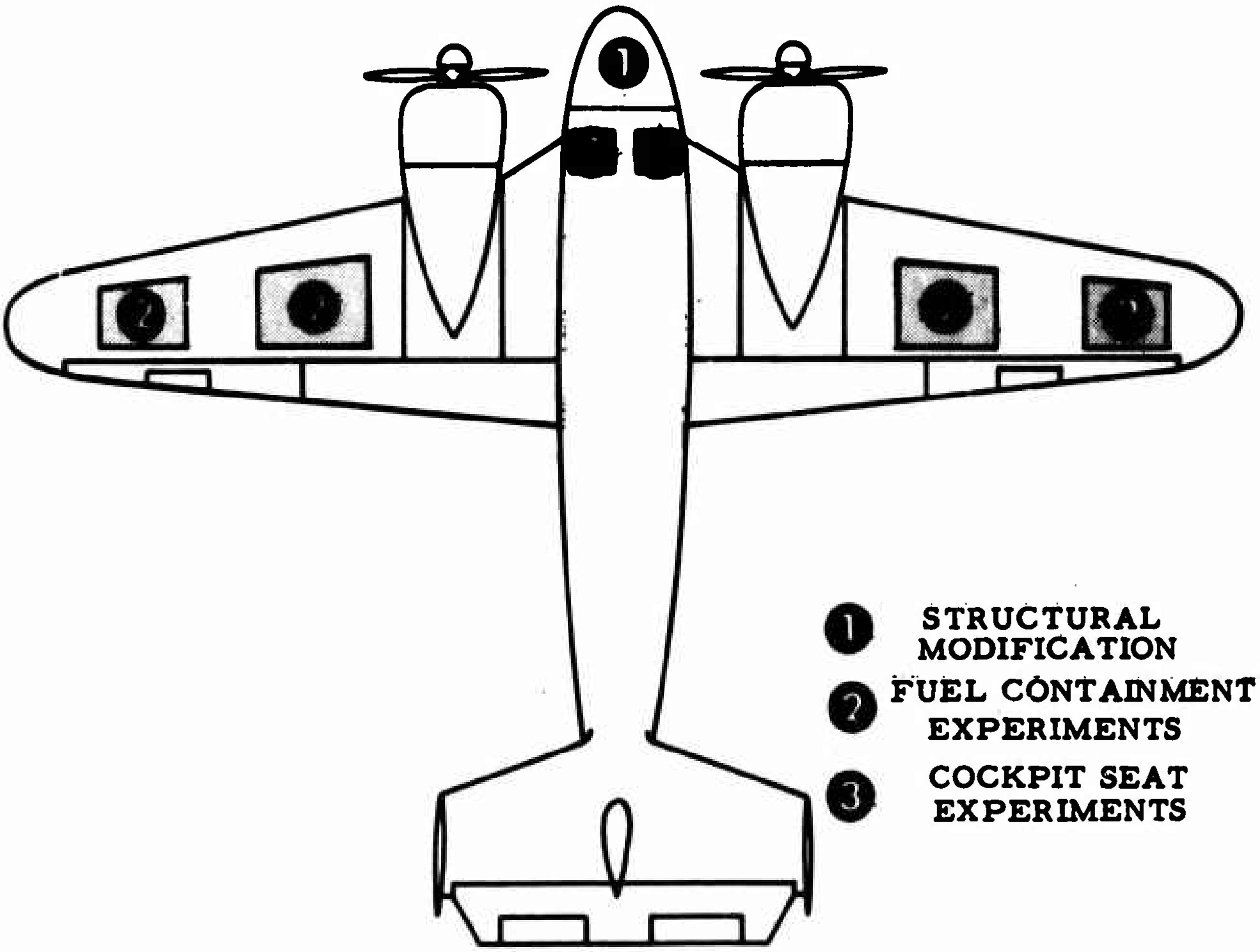


Figure 38. Location of Experiments, T-16.

The aircraft accelerated to a speed of approximately 96 mph, or slightly over 140 feet per second, at the end of the 2,000-foot run. Both of the tanks impacted by the telephone poles in the right wing and the inboard tank in the left wing failed in this test. The damage to the right and left wings of the aircraft is shown in Figures 39 and 40. Typical damage to these tanks is shown in Figures 41 and 42.

Figure 39. Damage to Aircraft Right Side, T-16.

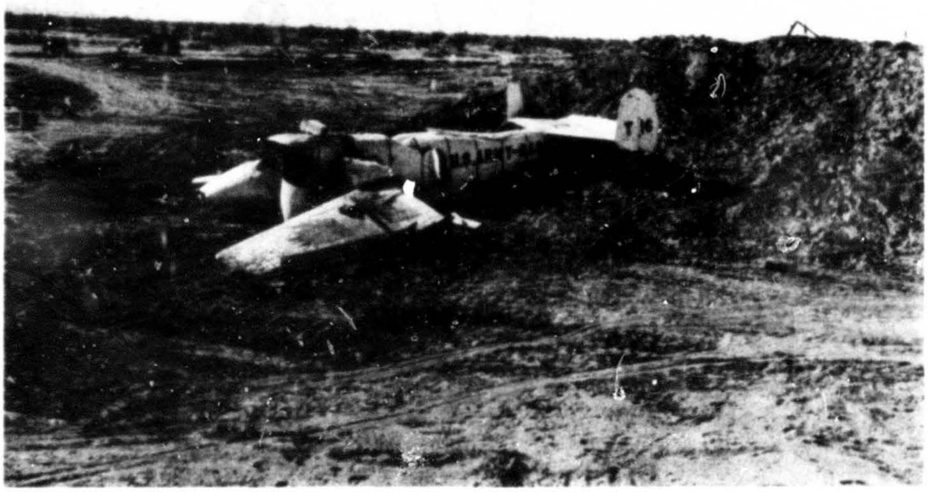


Figure 40. Damage to Aircraft Left Side, T-16. (Note That the Left Wing Nearly Severed By Hill Impact Continued Forward, Coming to Final Rest in a Swept-Forward Position.)

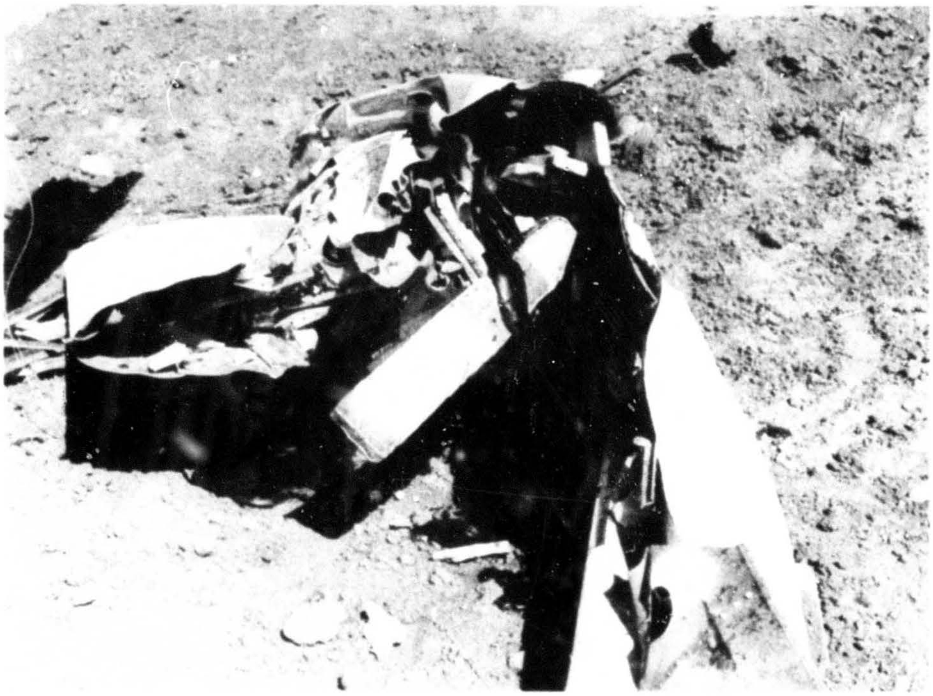


Figure 41. Right Wing Tank, T-16. (At Impact With the Pole, These Tanks Were "Accordioned" Rearward into the Structure.)

Figure 42. Left Wing Root Tank, T-16. (At Hill Impact, These Tanks Expanded in the Forward Half and Collapsed in the Aft Half.)

An analysis of the damage to the tanks and the fuel spillage which occurred during the crash revealed the following:

Right Wing Outboard Tank:	Massive spillage at time of impact
Right Wing Inboard Tank:	Massive spillage at time of impact
Left Wing Outboard Tank:	No leakage
Left Wing Inboard Tank:	Less than 1-gallon-per-minute leakage

C-45, T-19, Conducted 22 April 1965

This test was the second of the C-45 tests conducted with full-scale experimental fuel tanks onboard. A photograph of the test aircraft just prior to release is shown in Figure 43.

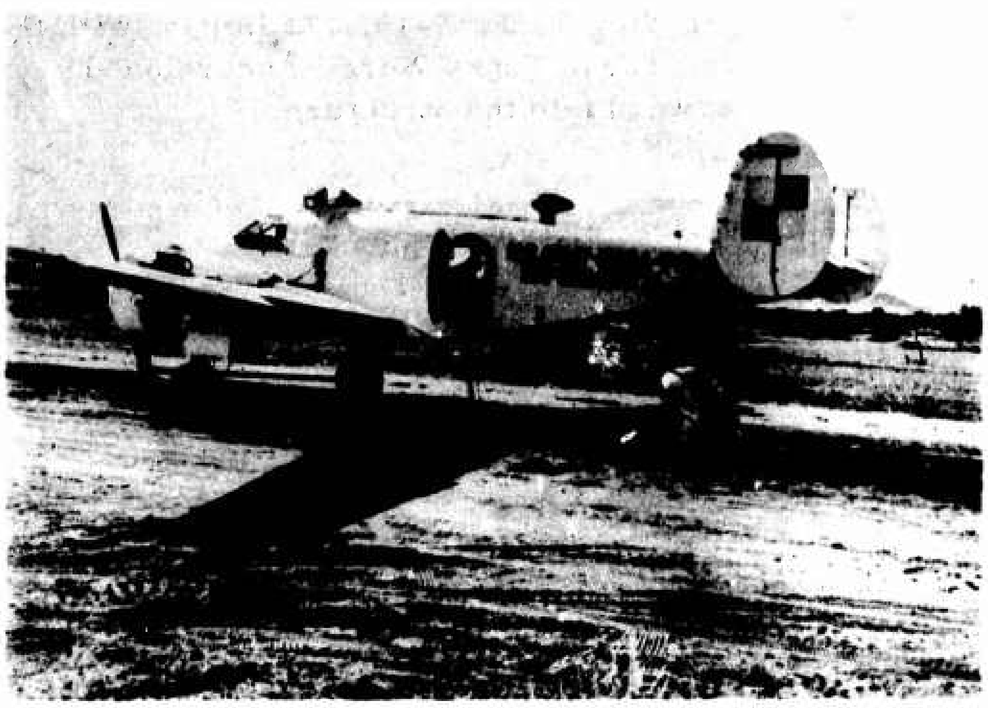


Figure 43. Aircraft on Monorail Track, T-19. (Vehicle Shown in Position for Test Run.)

A major objective of this test was to obtain data for comparison of the environment encountered in the crash of two previous, unmodified C-45 aircraft (T-15 and T-16) and the environment encountered in this test in which the aircraft was structurally modified to reduce the forces transmitted to the occupants during the crash. Another major objective was to investigate the effectiveness of the new experimental fuel tanks fabricated from the "Tough Wall" materials (Specimen F, nylon cloth with polyurethane resin laminate), as set forth in Table I.

Four experimental "Tough Wall" tanks were installed in the same wing locations as in the previous test (T-16). The inboard tanks in each wing contained a honeycomb-core material with a "Tough Wall" covering. The outboard tanks were also fabricated from the "Tough Wall" materials but were hollow. All tanks were filled with dyed water to simulate liquid fuel. Figure 44 is a photograph of the four fuel tanks. Figure 45 is a view of one honeycomb tank installed in the wing.

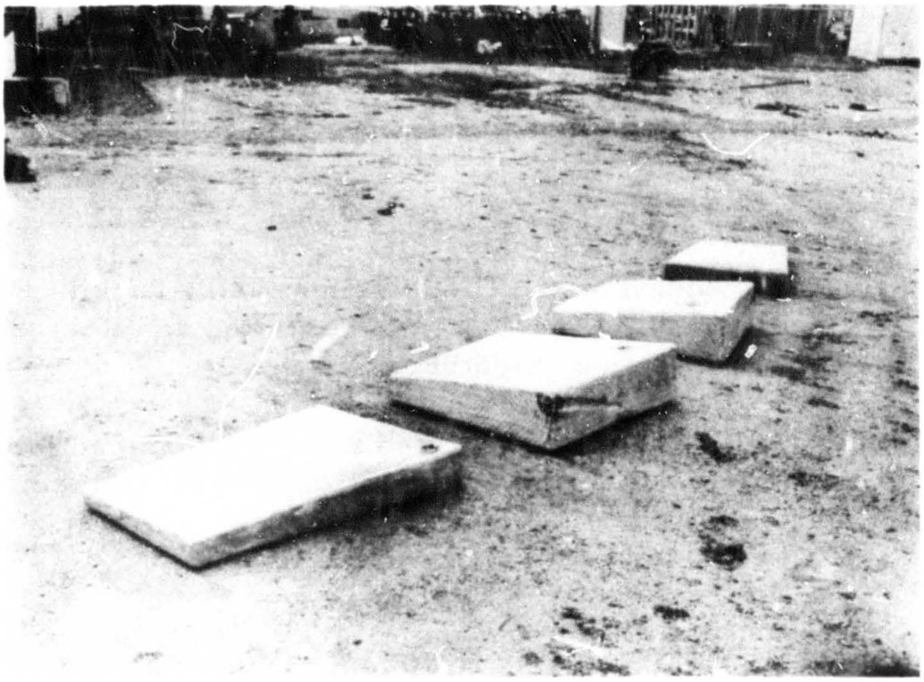


Figure 44. The Four Experimental "Tough Wall" Fuel Tanks, T-19. (The Small Tanks at Each End are Hollow; the Two Inboard Tanks are Honeycomb Filled.)

The aircraft achieved a speed of 96 mph at the point of impact. Both left and right wings outboard of the engine nacelle were torn free during initial impact with the earthen barrier and the telephone poles. When the nose of the aircraft impacted the 30-degree slope, the fuselage broke just ahead of the horizontal stabilizer, as the aircraft pitched upward. The fuselage then passed over the hill, rolled 90 degrees to the left, and impacted nose low behind the hill. Figures 46 and 47 show the aircraft in its final position.

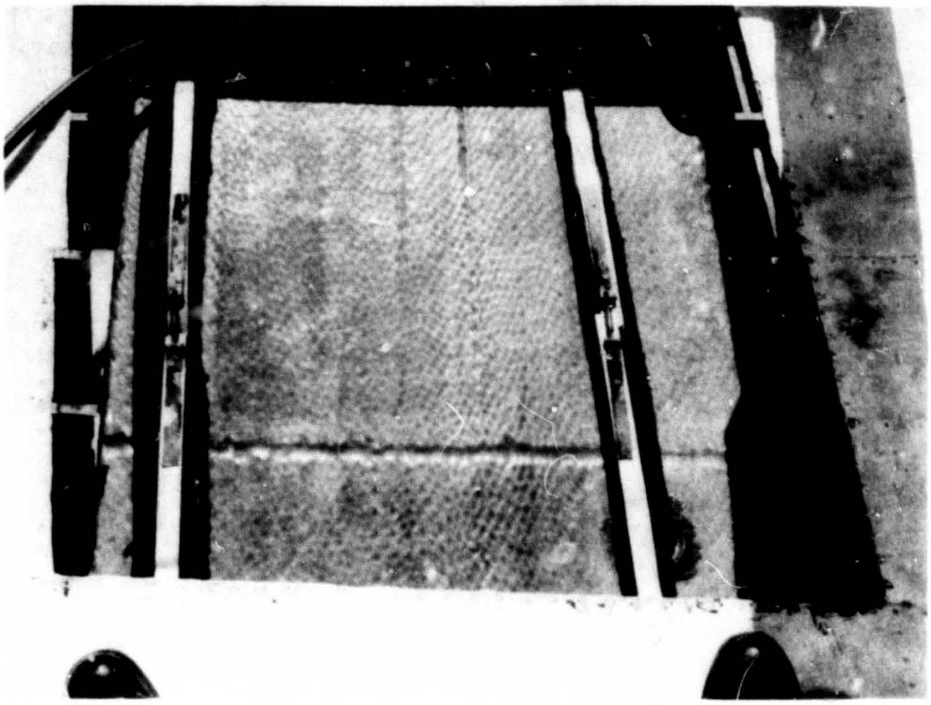


Figure 45. Honeycomb-Filled "Tough Wall" Tank in Place, T-19. (The Tank Was Installed and Restrained in Typical Lightplane Manner.)

At initial impact, the left wing separated from the fuselage just outboard of the engine nacelle. This wing section proceeded over the hill and can be seen in Figure 46. No damage or leakage was experienced with either of the two tanks installed in this section of the wing.

The right wing was separated from the aircraft just outboard of the engine nacelle as it impacted the telephone poles. The inboard honeycomb-core tank was located at the point where the wing separated from the rest of the aircraft and received a direct blow from the telephone pole. Upon separation of the wing, the tank broke through the opening in the wing structure and traveled a distance of approximately 20 feet from the pole, coming to rest on the side of the hill. The only tank damage experienced was a cut of approximately 3/4 inch in length in the forward face of the tank. Figure 48 shows this tank in its final resting place.

The right inboard fuel tank was thrown free at impact when the pole severed the wing through the inboard tank area. A 3/4-inch cut was inflicted on the front of the tank and slow leakage resulted.

The separated portion of the wing is shown in Figure 49. This portion of the wing contacting the pole was displaced rearward approximately

Figure 46. Postcrash View of Aircraft, T-19. (The Left Wing Was Torn Free at Hill Impact and Came to Rest Ahead of the Main Wreckage.)

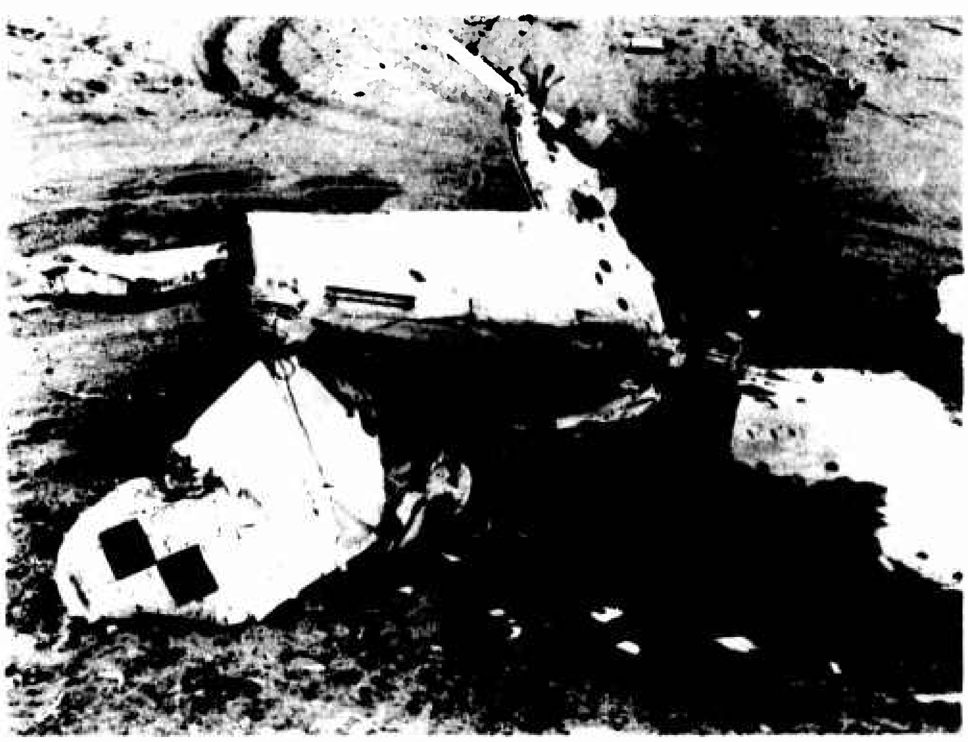


Figure 47. Fuselage Wreckage, T-19. (As the Aircraft Crossed over the Top of the Hill, It Rolled 90 Degrees to the Left and Impacted on its Side.

Figure 48. The Right Inboard Fuel Tank, T-19. (Photograph Taken 1 Hour After Impact.)

Figure 49. Pole Impact - Right Wing, T-19.

one-half of the wing chord. The telephone pole struck the center of the experimental tank, which deformed within the wing and finally bulged both the top and bottom of the wing structure outward. The tank experienced one minor pinhole-type penetration, resulting in a very slow seepage after the crash. The tank and deformed structure are shown in Figure 50.

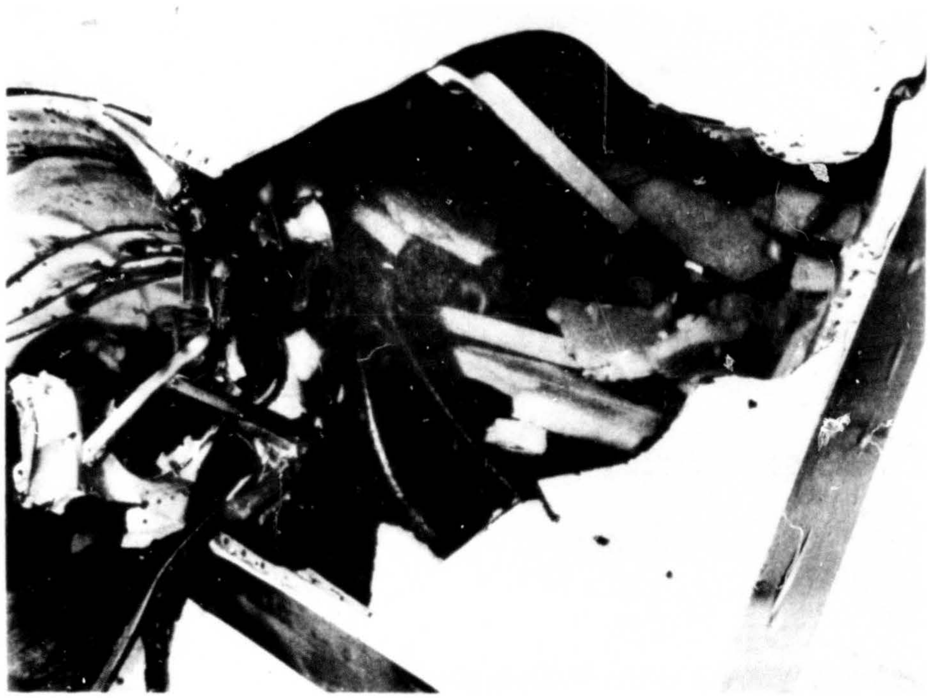


Figure 50. Right Wing Outboard Tank - In Place, T-19. (The Tank Was Displaced Rearward by the Caved-in Leading Edge of the Wing.)

An analysis of the damage to the tanks and the fuel spillage which occurred during the crash revealed the following:

Right Wing Outboard Tank:	Seepage (less than 1 quart per hour)
Right Wing Inboard Tank:	Less than 1 gallon-per-minute leakage
Left Wing Outboard Tank:	No leakage
Left Wing Inboard Tank:	No leakage

C-45, T-24, Conducted 12 August 1965

This was the third of a series of C-45 full-scale crash tests in which new experimental fuel tanks were installed. This test was conducted in the same manner as T-16 and T-19.

Four experimental tanks were again installed in the same locations in the wings as in T-16 and T-19. Following is a description of the experimental tanks tested in this aircraft:

Right Wing Outboard Tank:	"Tough Wall" (Specimen F, nylon cloth with polyurethane resin laminate)
Right Wing Inboard Tank:	"Fuzzy Wall" (Specimen I, nylon felt pad with "Crinkl-Core"* liner, Figure 51)
Left Wing Outboard Tank:	"Tough Wall" (Specimen F, nylon cloth with polyurethane resin laminate)
Left Wing Inboard Tank:	Firestone Type A (sponge-filled synthetic cloth, rubber-like resin laminate - actual composition unknown to AvSER, Figure 52)

The velocity at the point of impact was approximately 80 mph. At impact with the wing barriers, the right wing was again separated just outboard of the engine nacelle, as shown in Figure 53. The left wing was partially separated just outboard of the engine nacelle and can be seen still attached in Figure 54.

The "Fuzzy Wall" tank was installed at the point where the right wing separated just outboard of the engine nacelle. At the time of separation, the "Fuzzy Wall" tank fell out of its installation and can be seen on the ground just below the wing stub in Figure 55. An analysis of the damage to the tanks and the fuel spillage which occurred during the crash revealed the following:

*Reg. T.M., Goodyear Aerospace Company, Litchfield Park, Arizona.

Right Wing Outboard Tank:	Less than 1-quart-per-minute leakage
Right Wing Inboard Tank:	No leakage
Left Wing Outboard Tank:	No leakage
Left Wing Inboard Tank:	No leakage

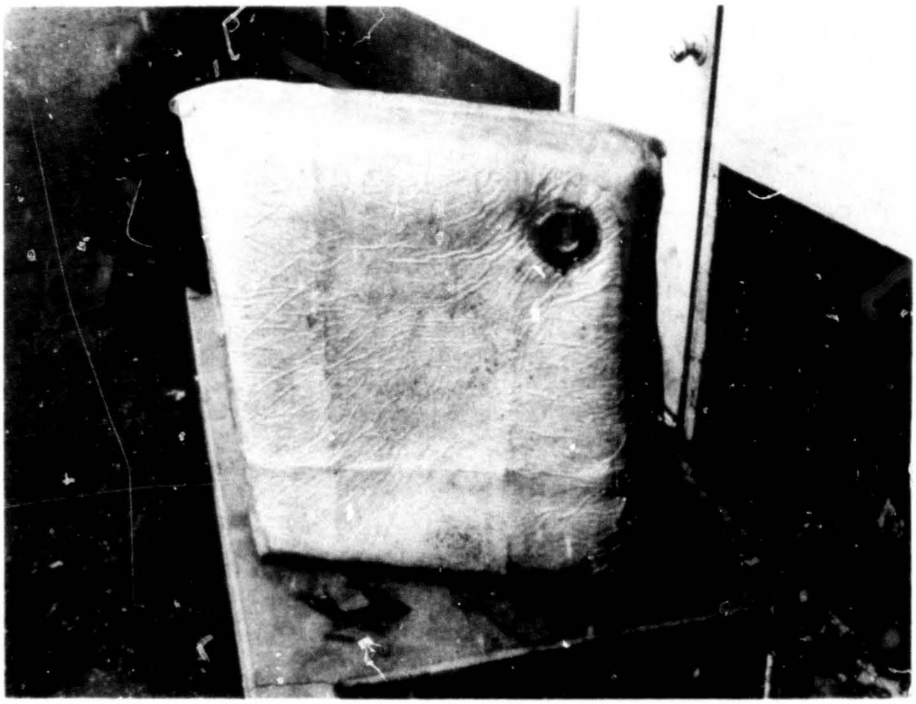


Figure 51. Experimental "Fuzzy Wall", T-24. (The Nylon Felt Tank with the "Crinkl-Core" Interliner Was Covered with a Thin Thermoplastic Film To Prevent the Felt from Functioning as a Wick Should It Become Soaked with Fuel.)

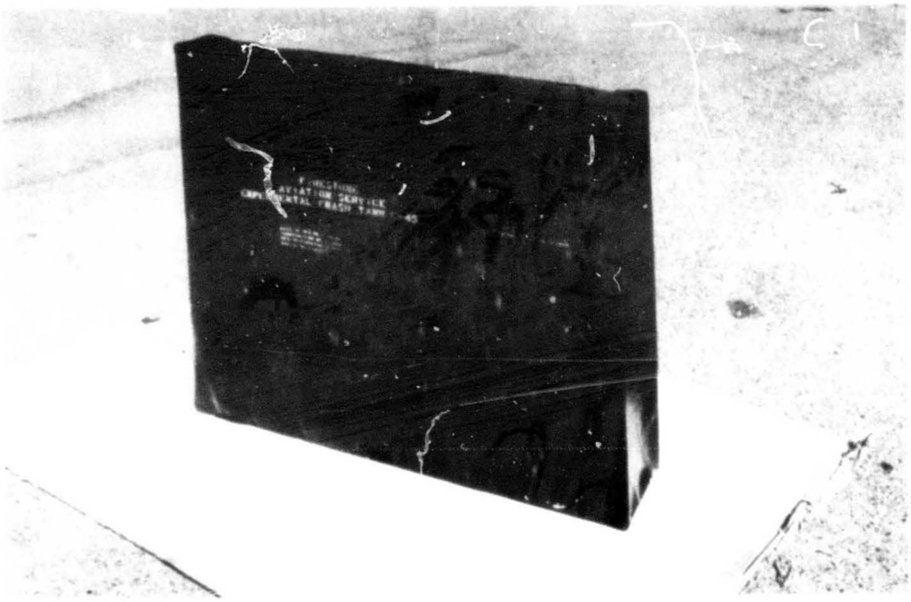


Figure 52. Experimental Sponge-Filled Tank, T-24. (This Laminated Synthetic Cloth Tank Was Filled with Open-Pore Sponges To Help Dampen Fluid Sloshing and To Retard Fluid Spillage Through a Tank Failure.)

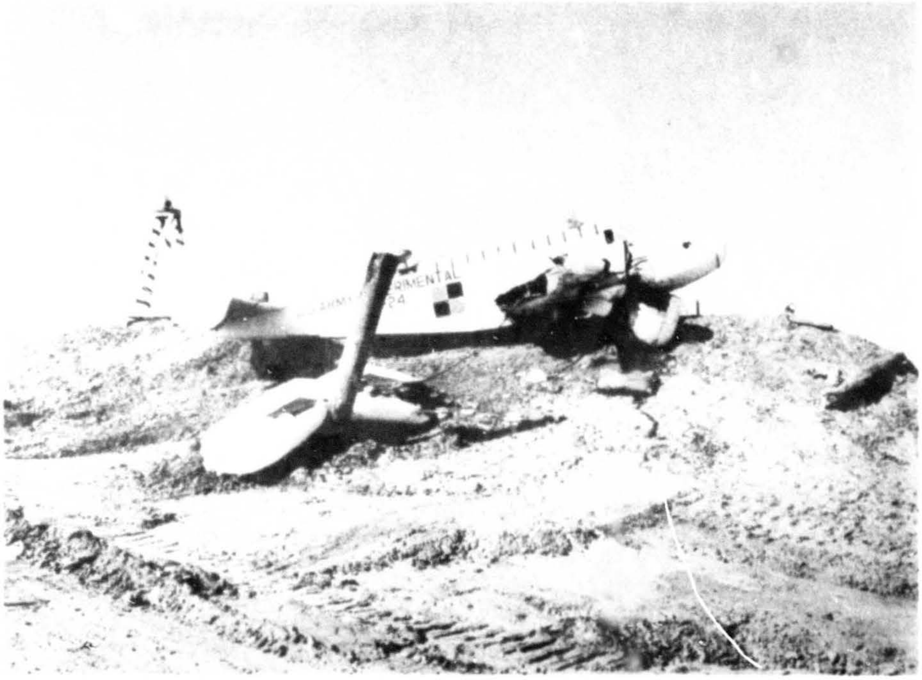


Figure 53. Postcrash View, T-24. (The Right Wing Was Torn Free at Pole Impact, and Remained Wrapped Around the Outboard Pole.)

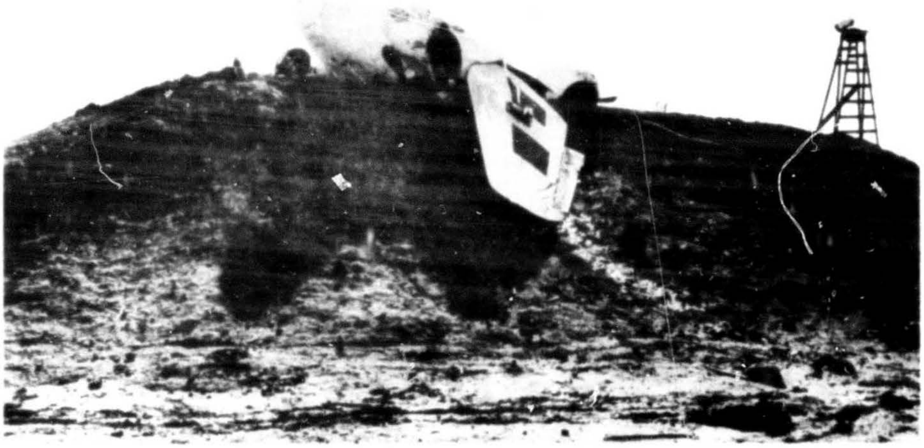


Figure 54. Postcrash View, Left-Hand Side, T-24. (The Left Wing Nearly Separated from the Aircraft at Hill Impact.)

Figure 55. Right-Hand Inboard Tank, T-24. (After the Pole Impact Severed the Wing Through the Fuel Tank Location, the Experimental "Fuzzy Wall" Tank Dropped to the Ground. The Leakage Evident in Figure 55 Is Oil from the Engine, Not Simulated Fuel.)

Summary of Wing Tank Experiments

Table V presents a summary of the fuel tank failures and leakage experienced by the various experimental tanks which were tested during the C-45 crash tests described previously.

UNDERFLOOR TANK TESTS

The underfloor tank experiments were conducted in two CH-34 crash tests designated as T-17 and T-23. The two tests are described separately, and the general results of these tests are then summarized.

CH-34, T-17, Conducted 10 March 1965

The general objectives of this test were to obtain basic crash test data for aircraft of this configuration in addition to the testing of the experimental tanks. Specific areas to be investigated were fuel tank rupture and spillage, aircraft structural behavior, and other factors related to occupant survival in severe but survivable crash conditions. The crash was conducted utilizing the crane drop method, as described previously.

TABLE V
FUEL TANK FAILURE - C-45

	Gal	No Leakage	Less Than 1 Gal/Min Leakage	Less Than 5 Gal/Min Leakage	Rapid Total Loss
Right Wing Inboard - Direct Pole Impact					
Aluminum	30	———	———	——→	
"Tough Wall"/Honeycomb	30	———	——→		
"Fuzzy Wall"	30	——→			
Right Wing Outboard - Direct Pole Impact					
Aluminum	15	———	———	———	——→
"Tough Wall"/Hollow	15	———	——→		
"Tough Wall"/Hollow	15	——→			
Left Wing - 30° Slope Impact					
Aluminum	15	——→			
Aluminum	30	———	———	———	——→
"Tough Wall"/Hollow	15	——→			
"Tough Wall"/Honeycomb	30	——→			
Firestone Type A	30	——→			

3 Separate Impact Tests; Average Impact Velocity - 129 ft/sec

The CH-34 underfloor fuel system consists of 11 interconnected flexible bag type cells. Five of these cells are of the "self-sealing" type and the remaining six are of the pliocell type. Three of the standard pliocell bags were removed from the aircraft. In their location were placed an aluminum honeycomb-core "Tough Wall" tank, a "Tough Wall" tank without the honeycomb core, and an aluminum tank. All "Tough Wall" tanks in this test were made of materials similar to Specimen D, three-ply nylon cloth with a polyurethane resin bond.

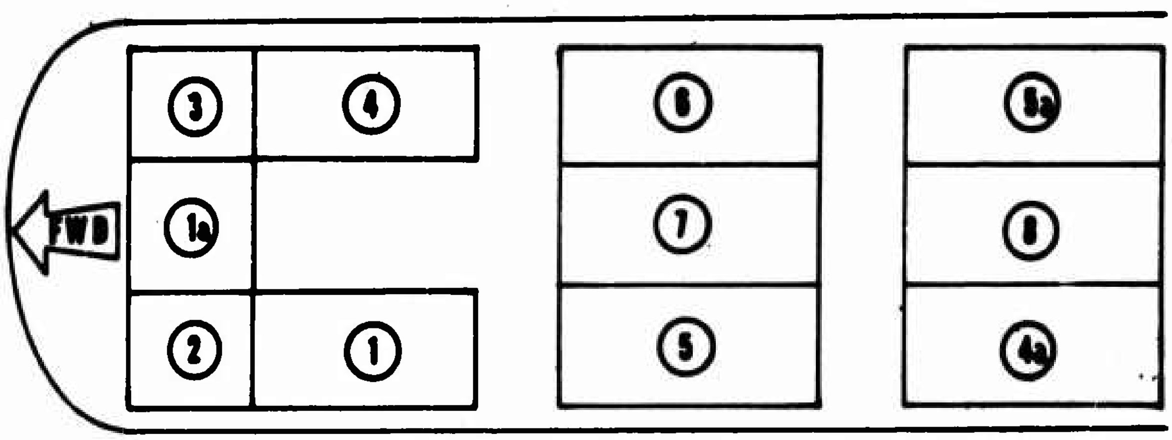
Of the three pliocell tanks retained in the aircraft, one was filled with hard, gelled gasoline and the other two were used for comparison purposes. With respect to the five self-sealing tanks, one was replaced with an aluminum honeycomb-core "Tough Wall" tank, one was filled with a hard, gelled gasoline, and one was cored with aluminum honeycomb blocks. The remaining two self-sealing tanks were used as control tanks. The location of the tanks and a code describing the type tanks installed in each location are shown in Figure 56. Figures 57 and 58 show some of the experimental tanks installed in the aircraft; Figure 59 is a pretest view of the interior of the aircraft, showing the manner in which the tanks were identified for photographic purposes.

To assure a severe test condition, a rough terrain was simulated by attaching rocks (10 to 14 inches in diameter) to the underside of the fuselage directly beneath each fuel tank. The attachment of these rocks to the bottom of the fuselage is shown in Figure 60, which also shows the locations of the various tanks by number. The impact itself was on a smooth airport taxiway, inasmuch as it was necessary for the crane to move over the impact area prior to release of the aircraft.

The test aircraft was suspended from the crane at a height of 30 feet from the ground. The crane accelerated for a distance of 4,000 feet on the taxiway, reaching a speed of approximately 28 mph at the point of release. High-speed cameras were mounted inside the helicopter to photograph the behavior of the floor structure and the tank spillage. A battery of ten high-speed cameras was installed externally.

The velocity at impact was 59 feet per second. At impact, the rocks attached to the underside of the fuselage were driven through the aircraft understructure into the tanks, and the underbelly of the aircraft was crushed some 12 to 18 inches, as shown in Figure 61. All except the three "Tough Wall" experimental tanks experienced extensive failure at impact.

The hollow "Tough Wall" tank experienced no damage or leakage. One of the honeycomb-filled "Tough Wall" tanks experienced a cut of



CODE	TANK	CORE	CONTENTS	TANK COMPOSITION
1 and 1a	Self-Sealing	Hollow	Water	Standard
2	Self-Sealing	Hollow	Rigid Gel Gasoline	Standard
3	Self-Sealing	Honeycomb	Water	Standard
4 and 4a	"Tough Wall"	Honeycomb	Water	Specimen D, Nylon Cloth/Polyurethane Resin
5 and 5a	Pliocell	Hollow	Water	Standard
6	Pliocell	Hollow	Rigid Gel Gasoline	Standard
7	"Tough Wall"	Hollow	Water	Specimen D, Nylon Cloth/ Polyurethane Resin
8	Aluminum	Hollow	Water	6061-T4

Figure 56. Fuel Cell Type and Location, T-17.

approximately 1/8 inch in length, resulting in some slight seepage of fuel. The second honeycomb-filled "Tough Wall" tank had no leakage. Figure 62 is a photograph of the fuel spillage which occurred as a result of the tank failures. Figures 63, 64, and 65 are views of three of the experimental tanks removed from the wreckage.

A summary of the leakage occurring in each tank tested in this crash is presented in Table VI.

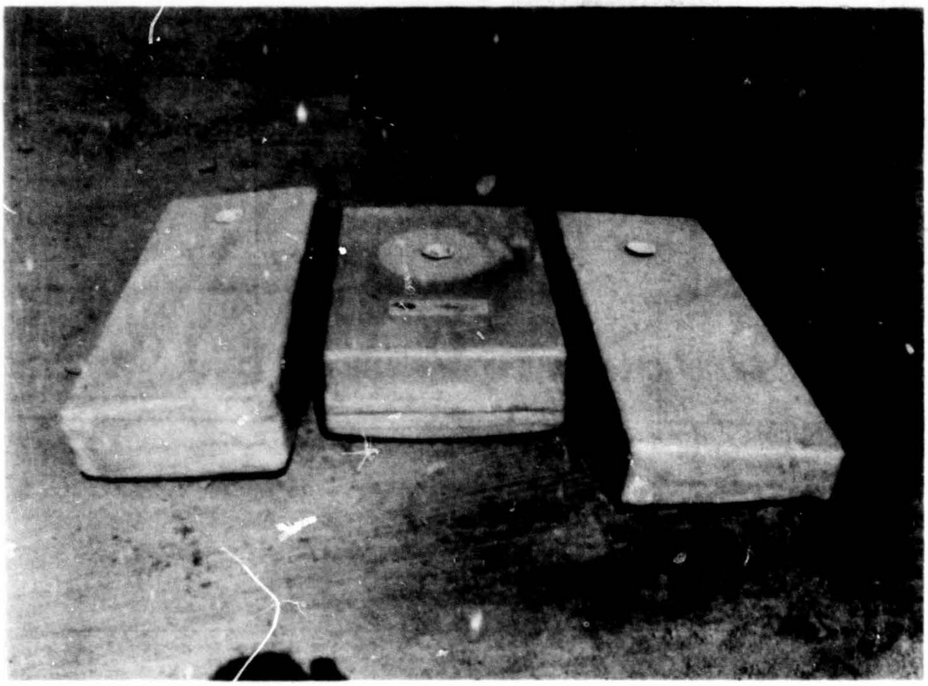


Figure 57. Experimental "Tough Wall" Tanks, T-17. (The Middle Tank Is Hollow, While the Other Two Are Honeycomb-Filled.)

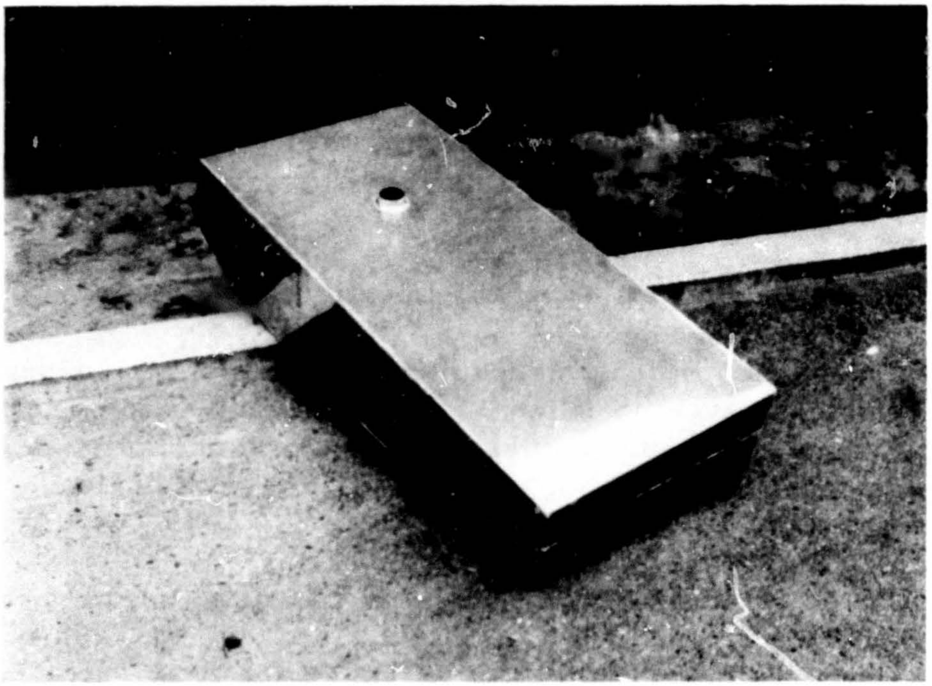


Figure 58. Experimental Aluminum Tank, T-17, Mate[illegible] 0.040-Inch 6061-T4.

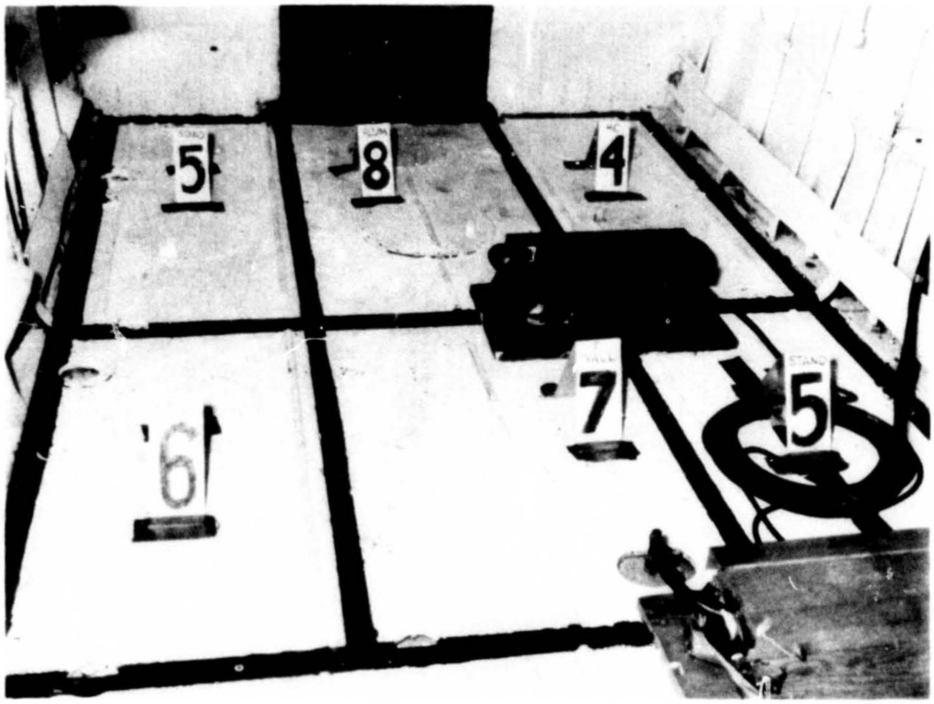


Figure 59. Fuel Tank Area, T-17. (After the Floor Was Reinstalled, Each Tank Was Identified for Photographic Purposes.)

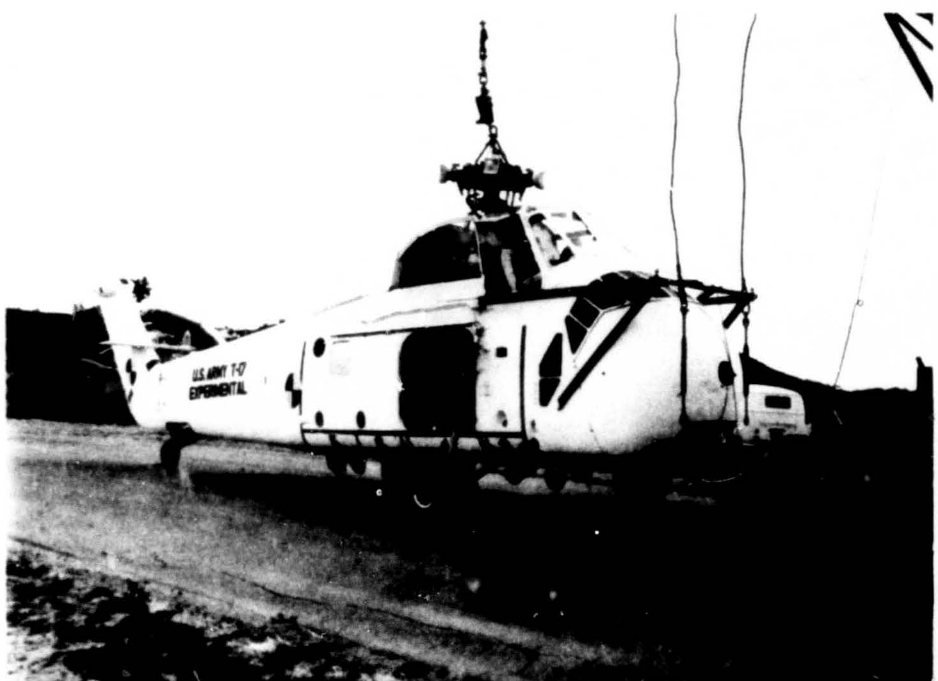


Figure 60. CH-34 Aircraft Prior to Test, T-17.

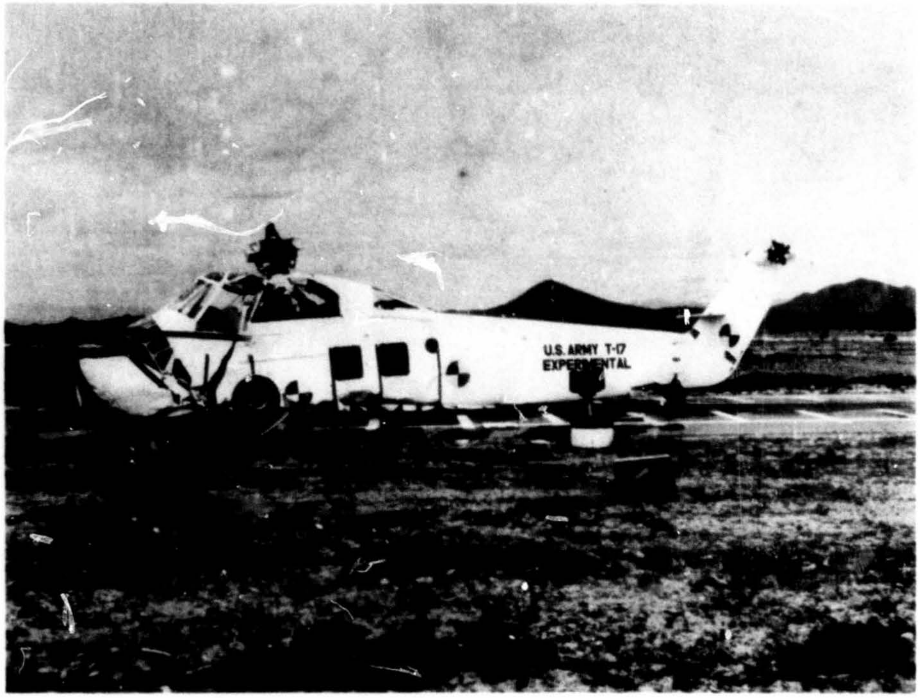


Figure 61. Postcrash View, T-17. (During the Impact, the Floor Was Crushed Upward a Distance of 12 to 18 Inches.)

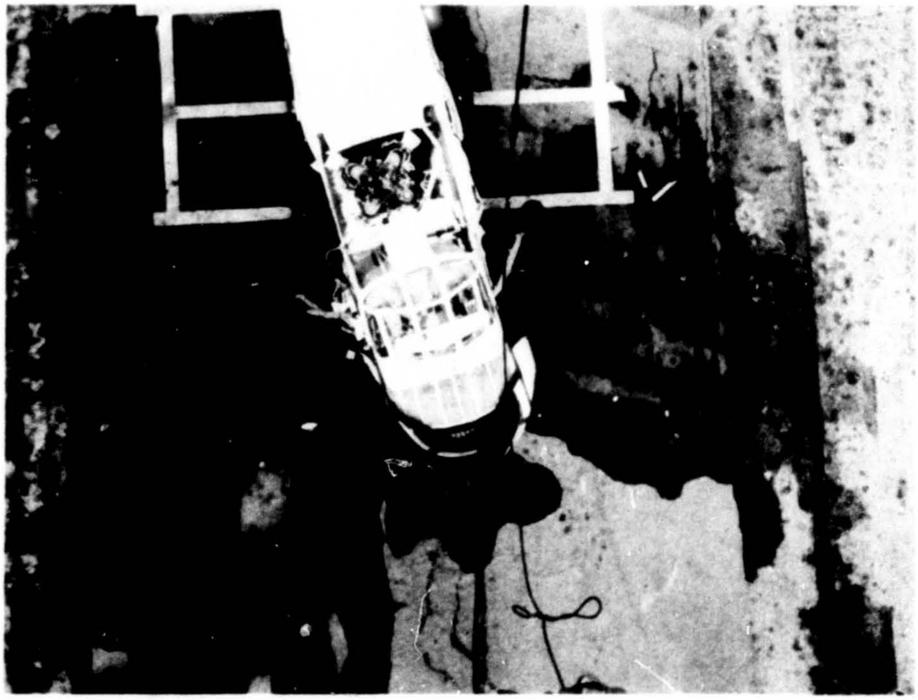


Figure 62. Fluid Spillage, T-17. (Extensive Fluid Spillage Resulted from Failure of Standard Fuel Tanks.)

Figure 63. The Ruptured Experimental Aluminum Tank, T-17.

Figure 64. Honeycomb-Cored "Tough Wall" Tank, T-17. (The Only Leakage Occurring in Either Honeycomb-Filled "Tough Wall" Tank Was the Pinhole Seepage Apparent at the Tank Midsection.)

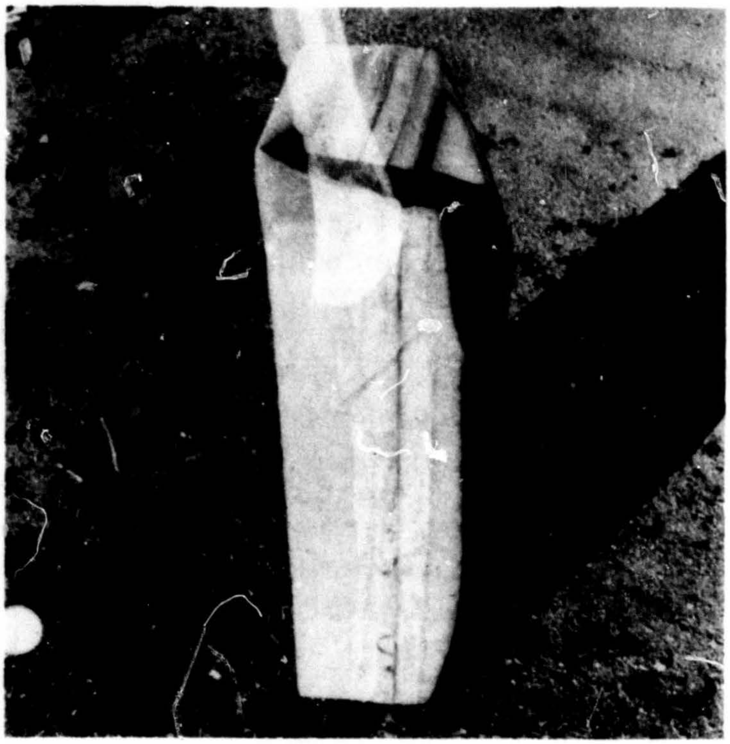


Figure 65. The Hollow "Tough Wall" Tank. (This Tank, Filled to Capacity with Water, Received a Direct Rock Impact and Did Not Fail.)

TABLE VI
FUEL TANK FAILURES - CH-34, NO CARGO

Tank*	Type	Contents	Leakage
1 and 1a	Self-Sealing	Water	Rapid Total Loss
2	Self-Sealing	Gel Gasoline	More Than 2 Gal/Min
3	Self-Sealing/ Honeycomb	Water	Less Than 1 Gal/Min
4	"Tough Wall"/ Honeycomb	Water	Minute Seepage
4a	"Tough Wall"/ Honeycomb	Water	None
5 and 5a	Pliocell	Water	Rapid Total Leakage
6	Pliocell	Gel Gasoline	Rapid Total Leakage
7	"Tough Wall"	Water	None
8	Aluminum	Water	Rapid Total

*For fuel tank layout refer to Figure 56.

CH-34, T-23, Conducted 9 September 1965

This was the second of the two CH-34 underfloor fuel tank experimental crash tests conducted. This test was conducted in exactly the same manner as T-17. Figure 66 is a photograph of the aircraft suspended behind the crane boom just prior to release. The aircraft was again suspended approximately 30 feet above the ground from the crane, which accelerated to a speed of approximately 30 mph and dropped the aircraft on a predetermined impact site at an impact velocity of approximately 59 feet per second at impact. Rocks were again attached to the bottom of the fuselage to simulate rough terrain. In this test, two 500-pound wheeled cargo carts were installed inside the cargo compartment of the aircraft to simulate wheeled vehicles. This installation is shown in Figure 67. This test arrangement created forces in the experimental tanks from both the top and the bottom, resulting in the most severe environment to which underfloor-mounted experimental tanks had been subjected in this test series.

Seven experimental tanks were installed in the manner presented in Figure 68.

Some damage was experienced with all but one of the tanks installed in the aircraft. Figure 69 shows the aircraft in its final position after the crash. The spillage pattern resulting from the failed tanks is shown in Figure 70. The "Fuzzy Wall" tank was the only tank which did not fail.

The net tank and the "Tough Wall" honeycomb tank sustained slight damage; however, the leakage was less than 1 gallon per minute. All other tanks sustained massive damage. Figures 71 through 82 show the various tanks before and after the test.

A summary of the leakage occurring in each tank tested in this crash is presented in Table VII.

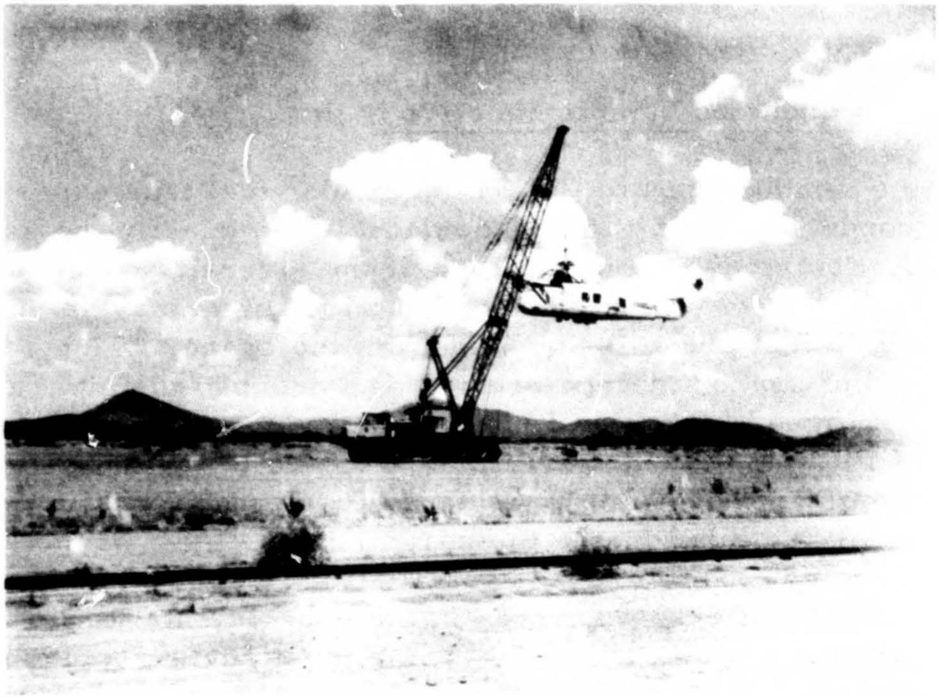


Figure 66. CH-34 Just Prior to Release, T-23. (The Landing Gear Was Removed for this Test, Allowing the Full Impact To Be Transmitted to the Fuel Tanks by the Rocks.)

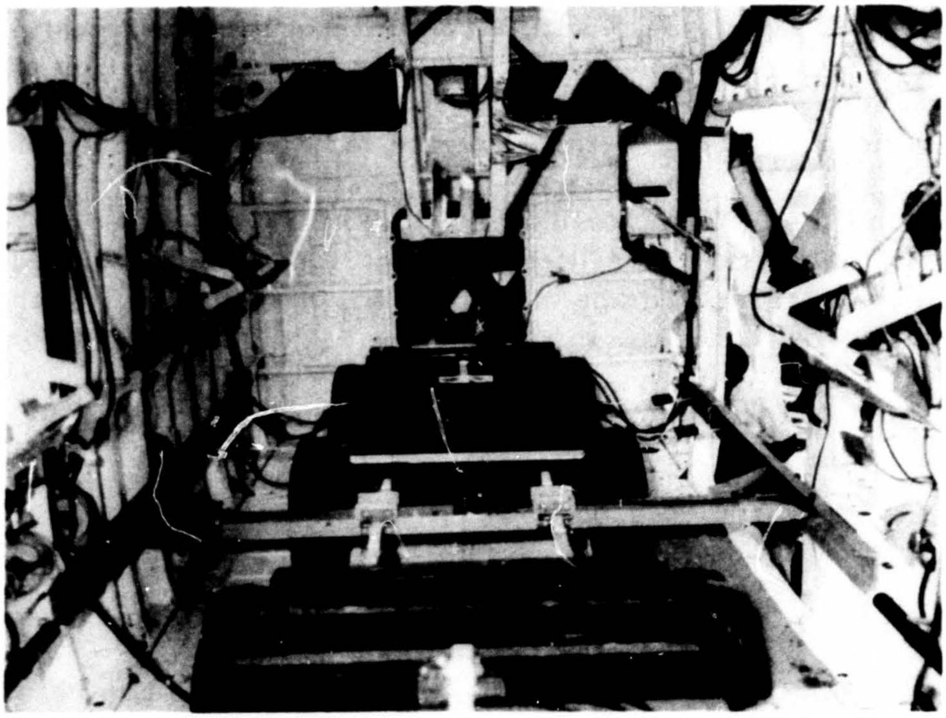
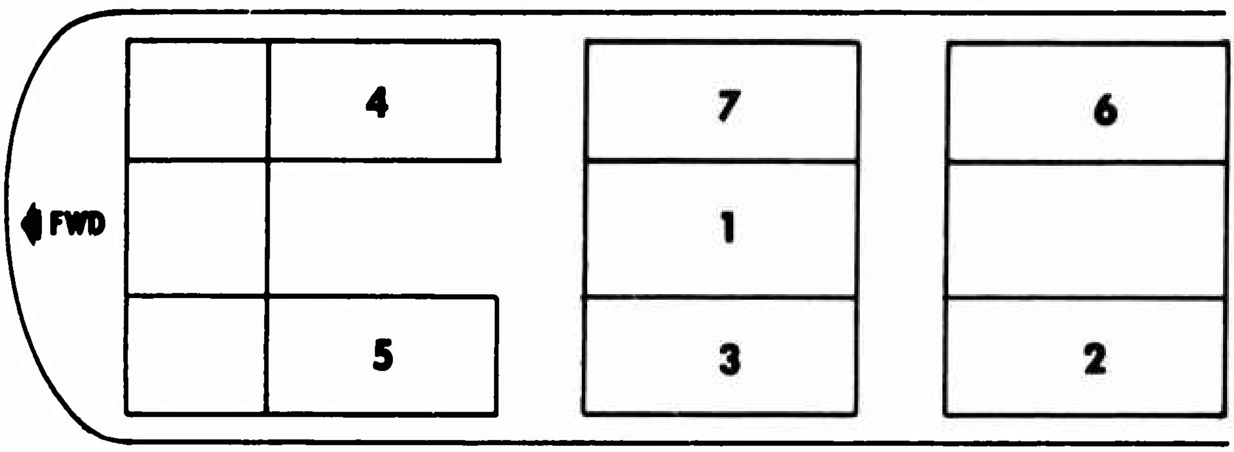


Figure 67. Cargo Experiments, T-23. (These Two 500-Pound Cargo Carts Were Installed Directly Above the Under-Floor Fuel Tanks.)



Code	Tank	Core	Contents	Tank Construction
1	"Tough Wall"	Hollow	Water	Specimen D, Nylon Cloth/ Polyurethane Resin
2	"Tough Wall"	Honeycomb	Water	Specimen D, Nylon Cloth/ Polyurethane Resin
3	"Fuzzy Wall"	Hollow	Water	Specimen I, Nylon Felt Pad/Crinkl-Core Liner
4	Net	Hollow	Water	1/8-in. Nylon Cord, Nylon Cloth, Crinkl-Core Liner*
5	Firestone A	Open Pore Sponge	Water	Synthetic Cloth/Rubber Like Resin
6	Firestone B	Hollow	Water	Synthetic Cloth/Rubber Like Resin
7	Firestone C	Hollow	Water	Synthetic Cloth/Rubber Like Resin/Polyurethane Coating

* This tank was composed of "Crinkl-Core" liner, forming a liquid-tight inner bag, surrounded with one layer of unimpregnated nylon cloth. The tank was then covered with a 1/8-inch-diameter nylon cord net, built to a 1-inch grid.

Figure 68. Fuel Cell Type and Location.

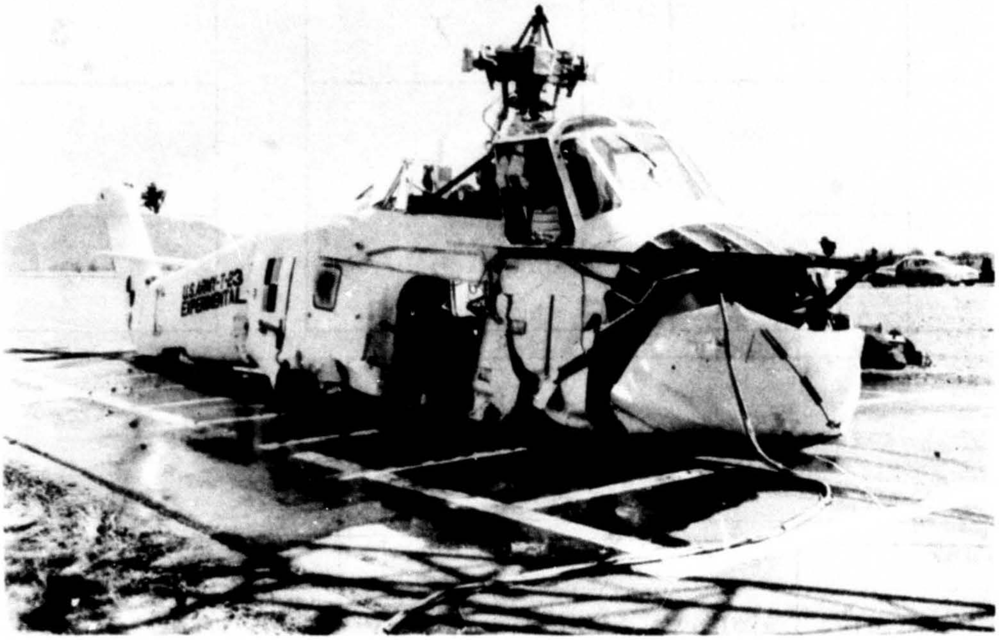


Figure 69. Postcrash View, T-23.

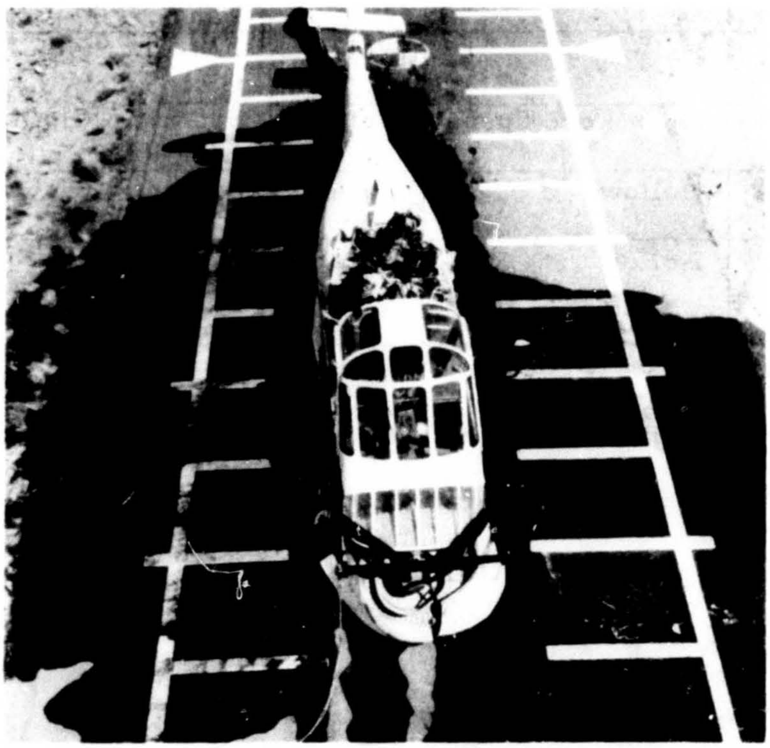


Figure 70. Fluid Spillage, T-23. (Extensive Liquid Dispersion Resulting from Ruptured Fuel Tanks.)

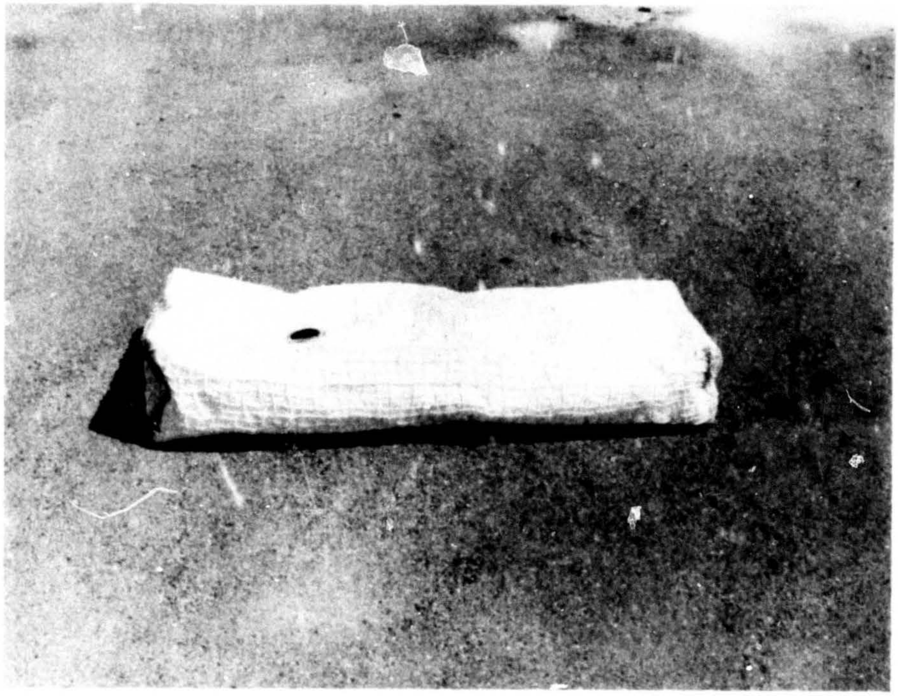


Figure 71. Net Tank - Precrash, T-23.

Figure 72. Net Tank - Postcrash, T-23. (View of the Net Tank After the Floor Was Removed.)

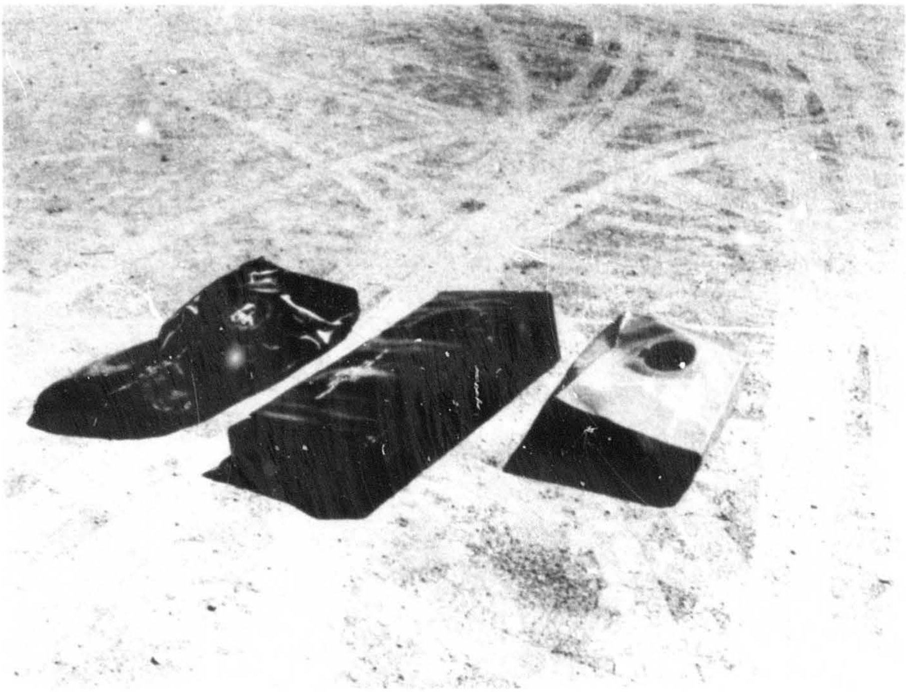


Figure 73. Firestone Experimental Tanks, T-23. (The Three Firestone Experimental Tanks Were as Follows: Hollow Rubberized Cloth, Left; Sponge-Filled Rubberized Cloth, Center; and Hollow Abrasive-Resistant Tank, Right.)

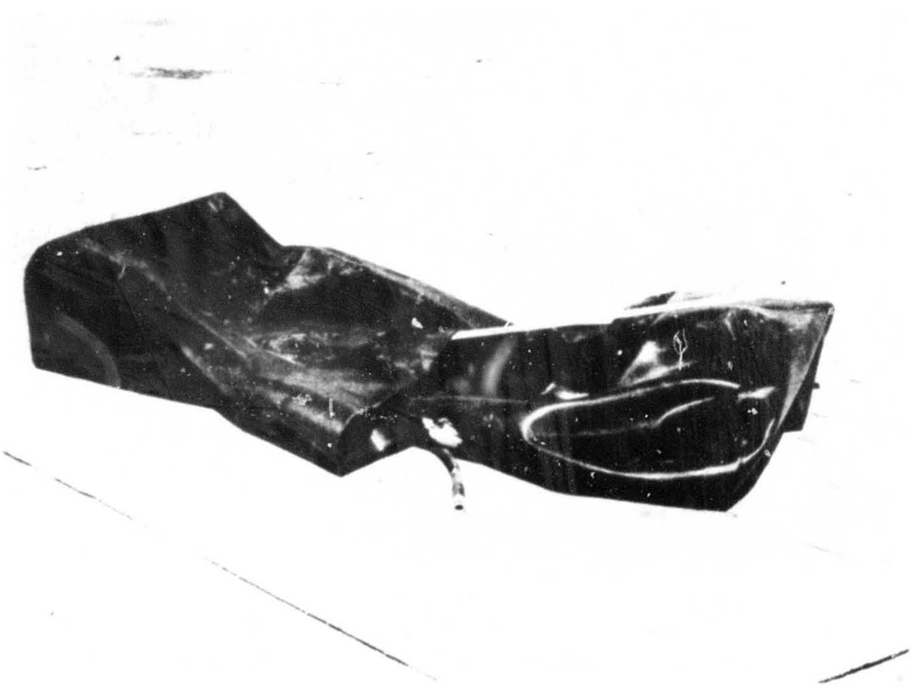


Figure 74. Firestone Tank Type B, T-23.

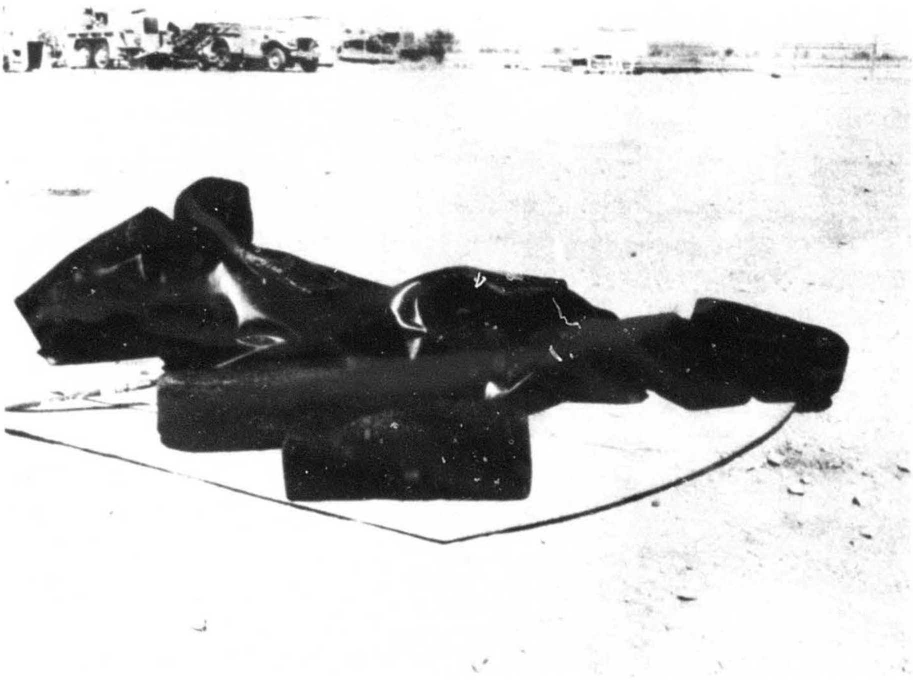


Figure 75. Firestone Tank Type A (Sponge-Cored), T-23.

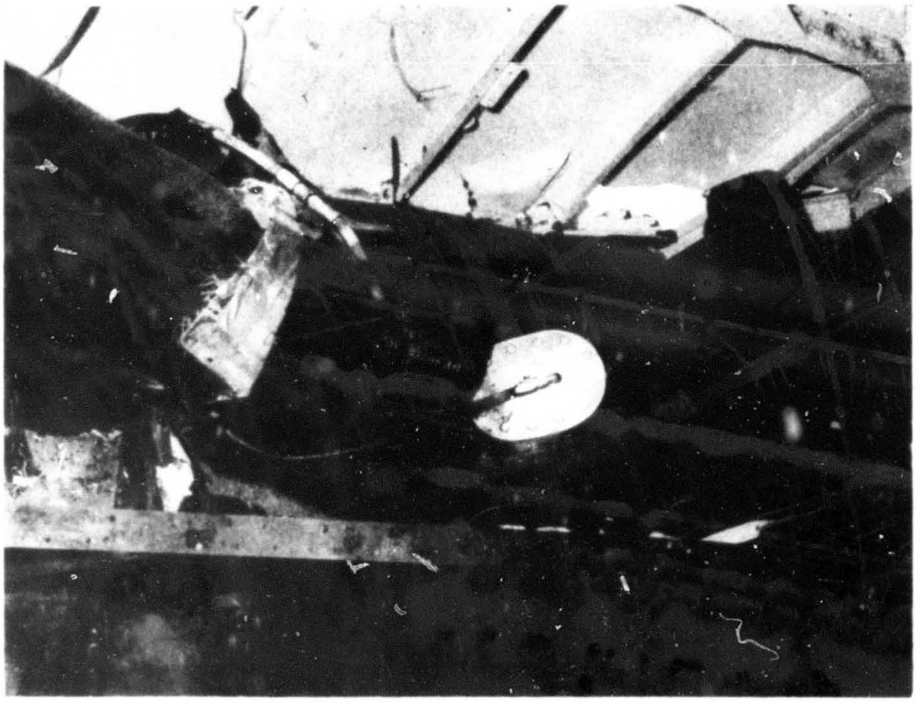


Figure 76. Type A Tank, T-23. (The Sponge-Cored Tank in Location After Floor Removal.)

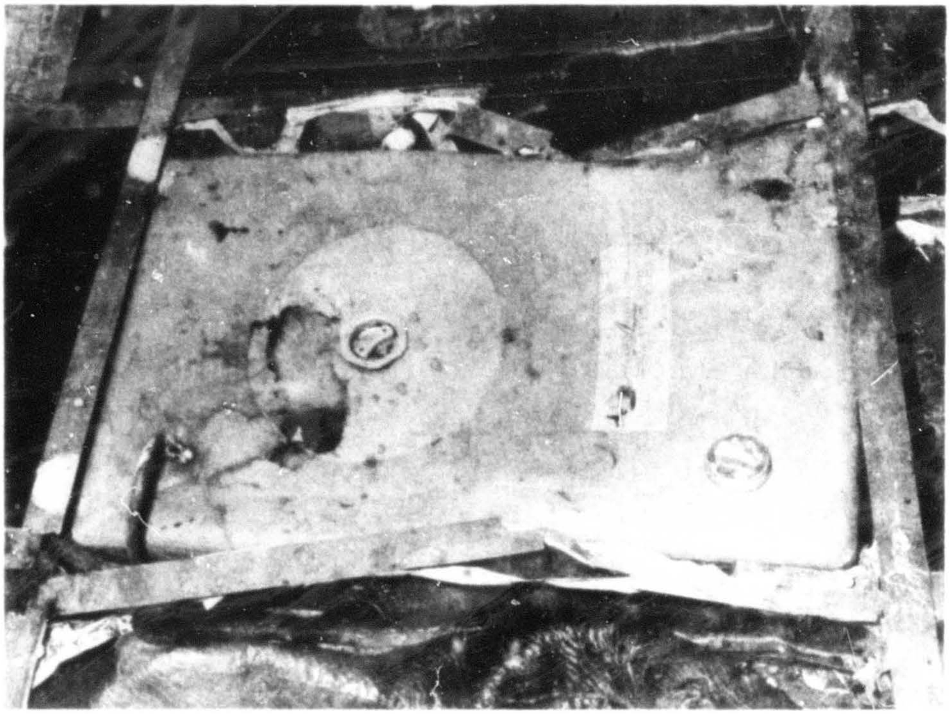


Figure 77. The Hollow "Tough Wall" Tank, T-23. (The Ruptured Tank in Location After Floor Removal.)

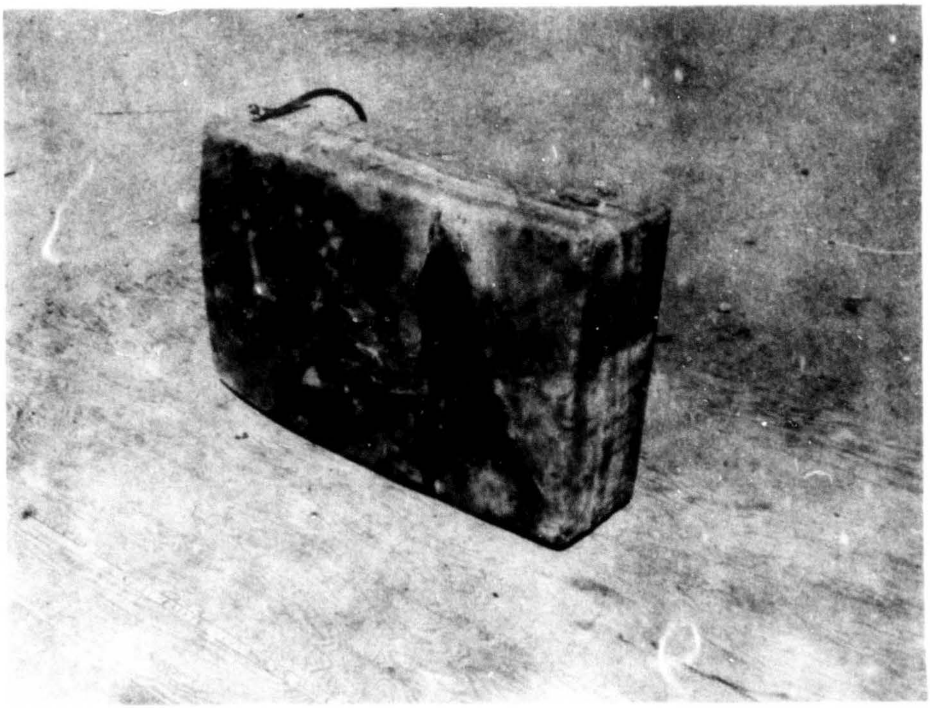


Figure 78. "Tough Wall" Tank Failure, T-23. (The Failure in the Bottom of the Hollow "Tough Wall" Tank Was Due to Rock Impact. The Tank Was Unable To Expand Upward Because of the Modification Made to the Floor To Restrain the Cargo Vertically.)

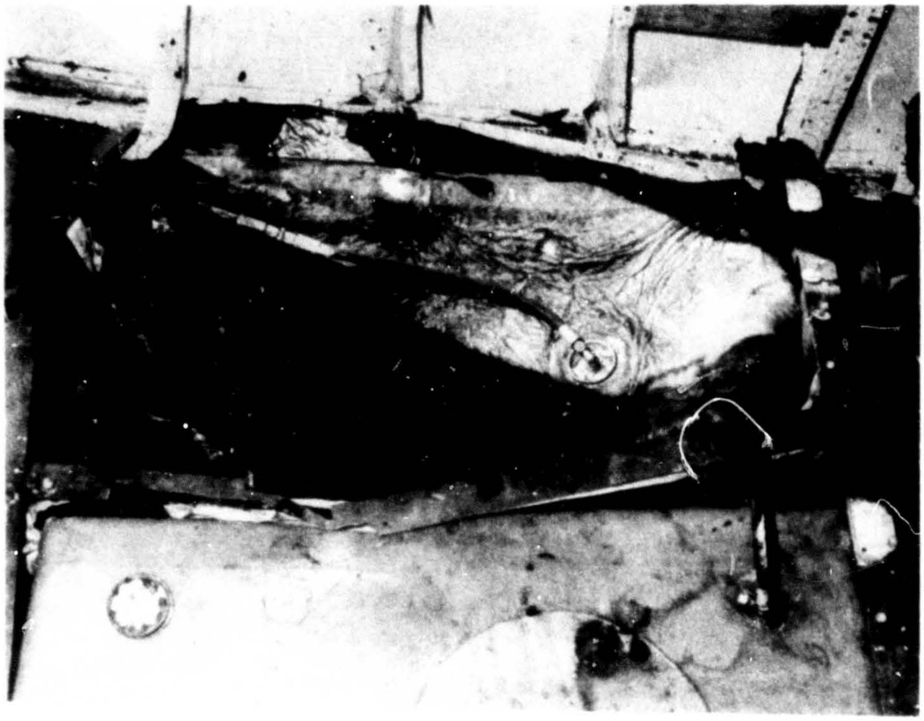


Figure 79. The "Fuzzy Wall" Tank, T-23. (The Nonleaking "Fuzzy Wall" Tank in Location with the Floor Removed.)

Figure 80. Tank Environment Damage, T-23. (With the "Fuzzy Wall" Tank Removed, the Degree of Structural Failure and Extensive Jagged Metal Surrounding the Tank Installation Are Apparent.)

Figure 81. "Fuzzy Wall" Tank, T-23. (The Bulges Apparent on the "Fuzzy Wall" Tank Bottom Are Evidence of the Tank's Ability To Contour and Deform to its Surrounding Environment.)

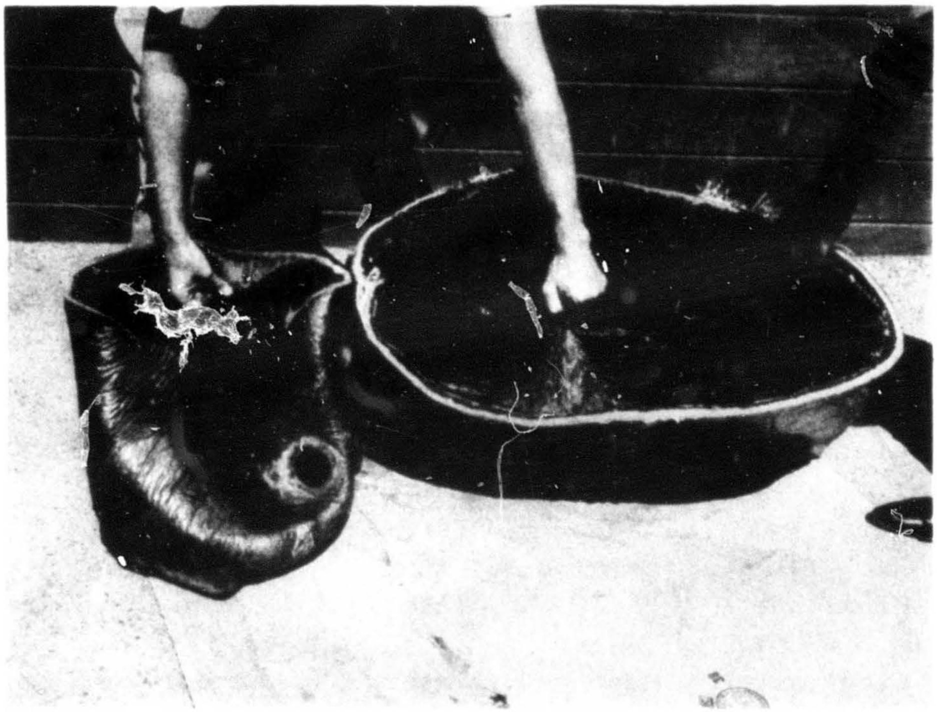


Figure 82. Cross Section of "Fuzzy Wall" Fuel Tank. (Analysis Revealed that the "Crinkl-Core" Has Unfolded in the Lower Regions, Thus Providing an Effective Barrier While the Nylon Pad Elongated. It Was Estimated that this Severe Crash Environment Utilized Less than 20 Percent of the Crashworthy Potential of the Tank.)

TABLE VII
FUEL TANK FAILURES - CH-34, 1000-LB CARGO

Tank*	Type	Contents	Leakage
1	"Tough Wall"	Water	Rapid Total Loss
2	"Tough Wall"/ Honeycomb	Water	Less Than 1 Gal/Min
3	"Fuzzy Wall"	Water	None
4	Net	Water	Less Than 1 Gal/Min
5	Firestone A	Water	Rapid Total Loss
6	Firestone B	Water	Rapid Total Loss
7	Firestone C	Water	Rapid Total Loss

*For fuel tank layout, refer to Figure 68.

Summary of Underfloor Fuel Tank Experiments

Tables VIII and IX summarize the fuel tank failures in terms of leakage experienced by the various experimental tanks which were tested during the CH-34 crash tests.

FUSELAGE TANK TEST

The fuselage tank experiment was conducted in a CH-21 crash test. This test is described below. Earlier fuel tank tests with this helicopter are discussed in Appendix I.

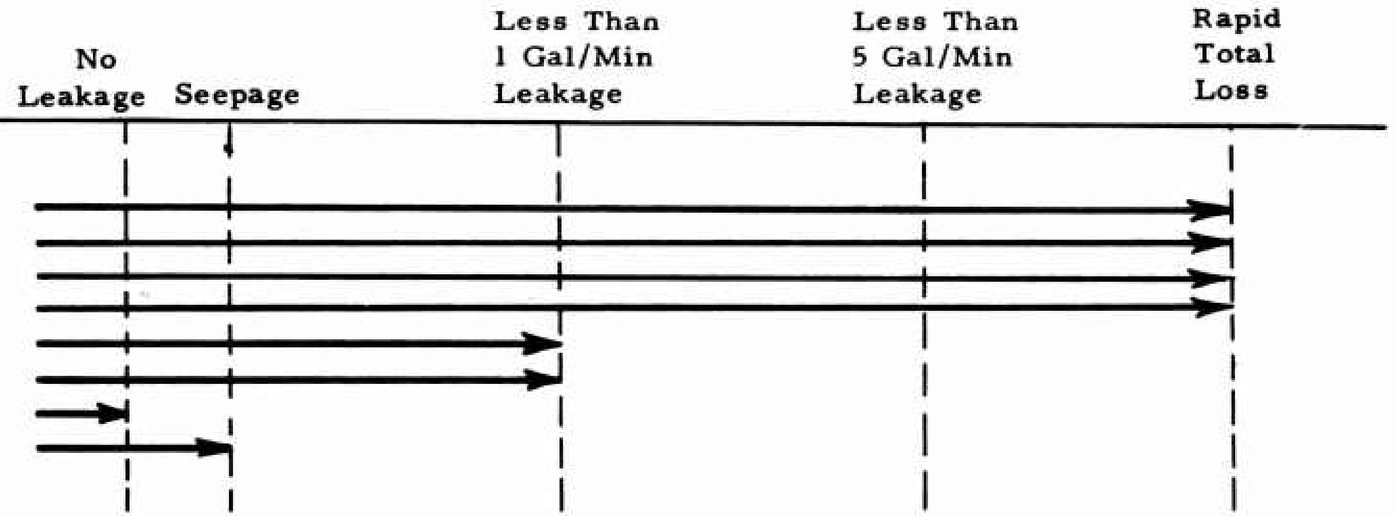
CH-21, T-18, Conducted 17 February 1965

This aircraft was crashed utilizing the crane drop method, as described herein. The test conditions were similar to those conducted with the CH-34 aircraft, whereby the aircraft was suspended approximately 30 feet above the ground. The crane accelerated to a speed of approximately 30 mph, automatically dropping the aircraft on a predetermined impact site.

TABLE VIII

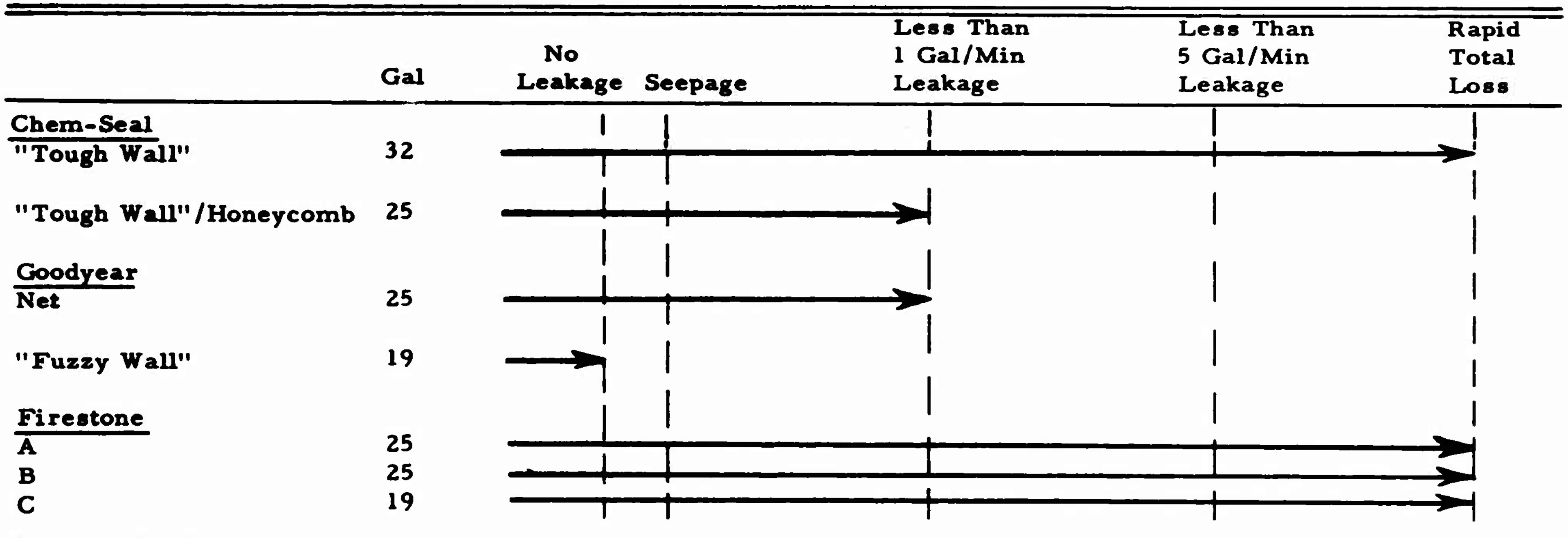
SUMMARY OF FUEL TANK LEAKAGE - CH-34, NO CARGO

	Gal
Aluminum	42
Pliocell Water	25
Pliocell Gel Gas	19
Self-Seal Water	25
Self-Seal Gel Gas	13
Self-Seal/Honeycomb	13
"Tough Wall"/Hollow	32
"Tough Wall"/Honeycomb	25



12 in. - 14 in. Rock - Direct Impact Per Tank Impact Conditions V_H = 41 ft/sec V_V = 42 ft/sec V_R = 59 ft/sec

TABLE IX
SUMMARY OF FUEL TANK LEAKAGE - CH-34, 1000-POUND CARGO



12 in. - 14 in. Rock - Direct Impact Per Tank   Impact Conditions V_H = 41 ft/sec V_V = 42 ft/sec V_R = 59 ft/sec

One of the purposes of this test was to define the behavior of the experimental fuel tank constructed of the "Tough Wall" materials (similar to that listed as Specimen B, Table I.

The standard CH-21 fuel tank consists of a large, rectangular pliocell bag containing no anti-slosh baffles. Its capacity is 286 gallons. The bag is suspended inside a fuel tank chamber just to the rear of the fuselage cabin. In this test, the fuel bag was removed and replaced with an experimental three-ply "Tough Wall" tank. For the test, the tank was filled with 212 gallons of dye-colored water to simulate a load of 286 gallons of fuel by weight. Approximate weight of the liquid was 1,750 pounds. Figure 83 shows this tank just prior to its installation in the aircraft.

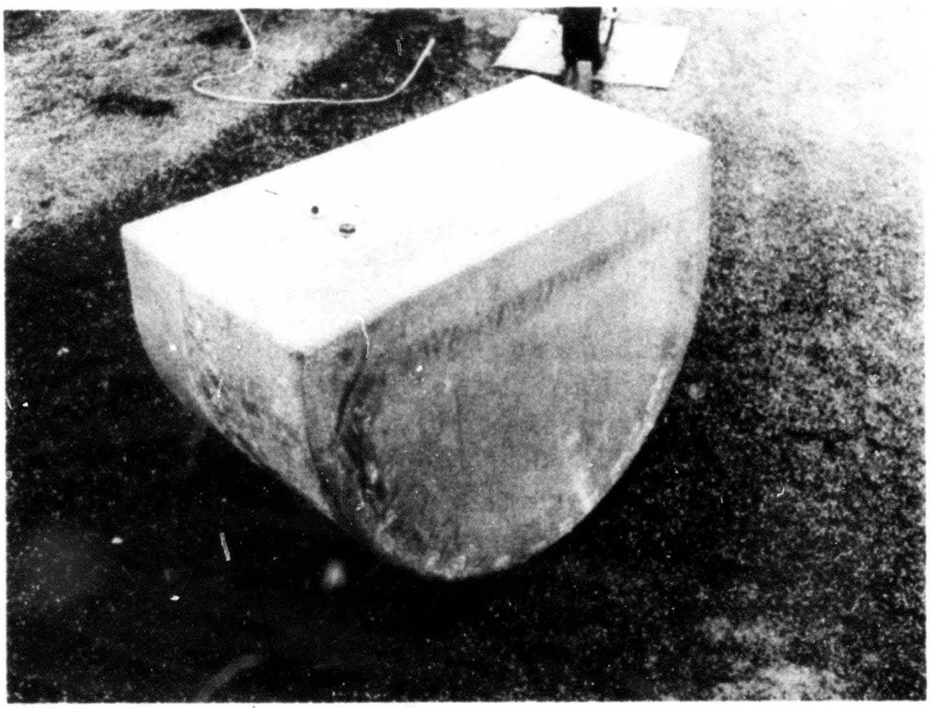


Figure 83. CH-21 Experimental Fuel Tank, T-18. (This Experimental Hollow "Tough Wall" Fuel Tank Replaced the Standard CH-21 Fuel Tank and the Crash Resistant Fuel Tank Described in Appendix I.)

In order to maintain a satisfactory helicopter center of gravity when suspended from the crane boom, it was necessary to remove the aft portion of the fuselage. Figure 84 shows the aircraft just prior to being hoisted into position on the crane boom for the test.

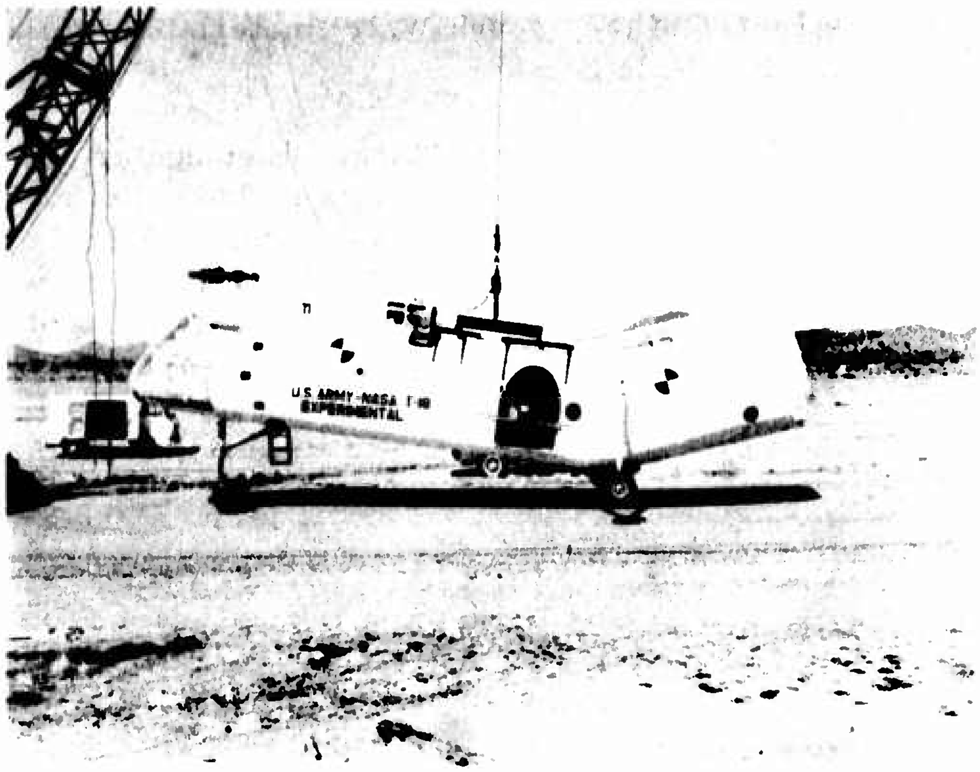


Figure 84. Test Vehicle Prior to Being Hoisted into Position, T-18.

As in the CH-34 tests described previously, rocks were attached under the fuselage directly beneath the fuel tank to simulate a rough terrain surface. These rocks were approximately 12 inches in diameter and are shown in Figure 85. Figure 86 shows the helicopter in its final resting position following impact. At impact, the underside of the fuselage was crushed, and the rocks suspended beneath the fuel tank were driven into the experimental fuel tank. Figure 87 is a view of the underside of the aircraft at the point where the rocks entered the structure. An indication of the structural breakup and torn metal environment to which the tank was exposed is presented in Figure 88.

During impact, the tank sustained five small penetrations; three of the penetrations were approximately 1 inch in length, one was approximately 2 inches in length (upper left front corner), and one was approximately 1/8 inch (bottom). The tank is shown in Figure 89 after removal from the aircraft.

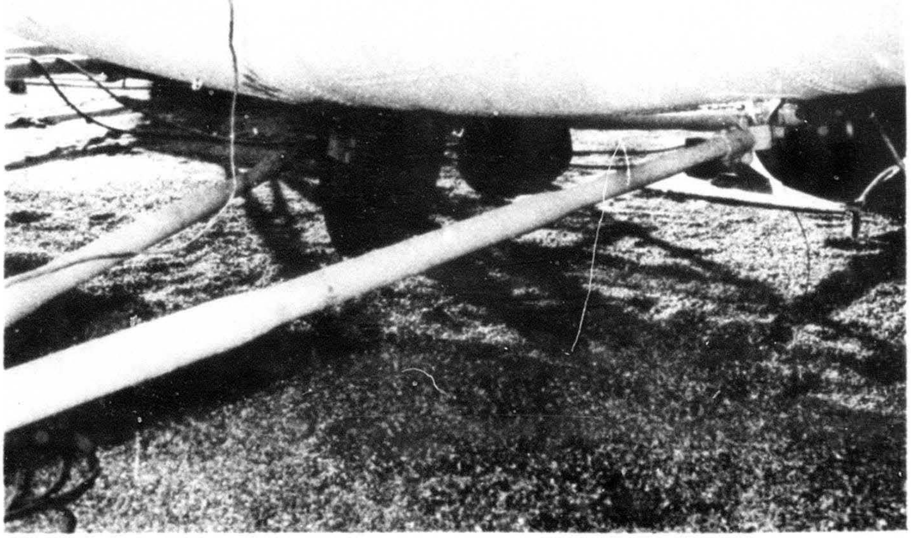


Figure 85. Rough Terrain Environment, T-18. (Rocks Attached to the Underbelly of the Fuselage Simulated a Rough Terrain Type Impact.)

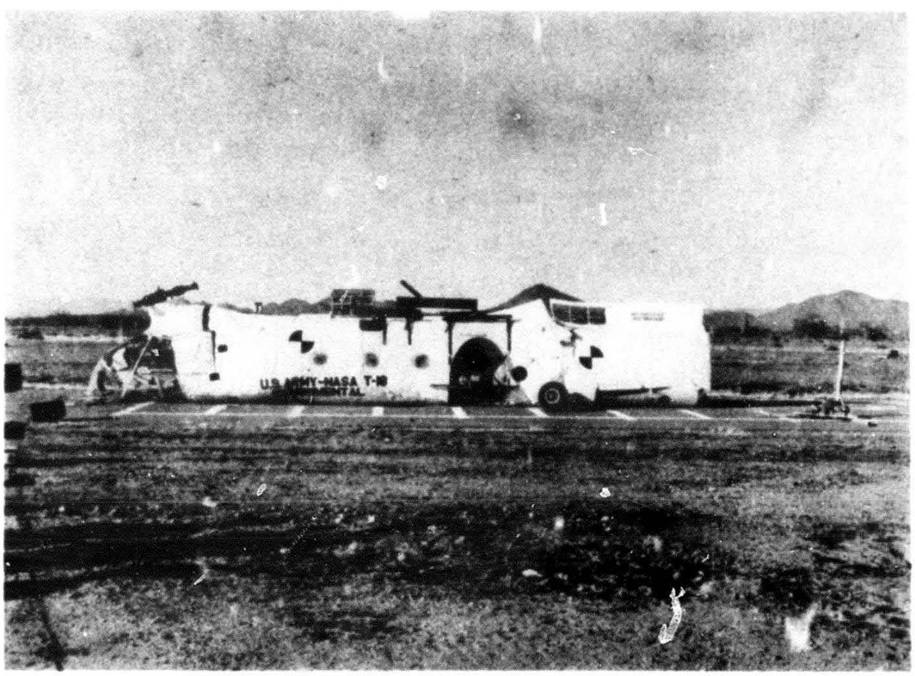


Figure 86. Postcrash View of T-18. (Helicopter Final Resting Position After the 30-Foot Free Fall.)

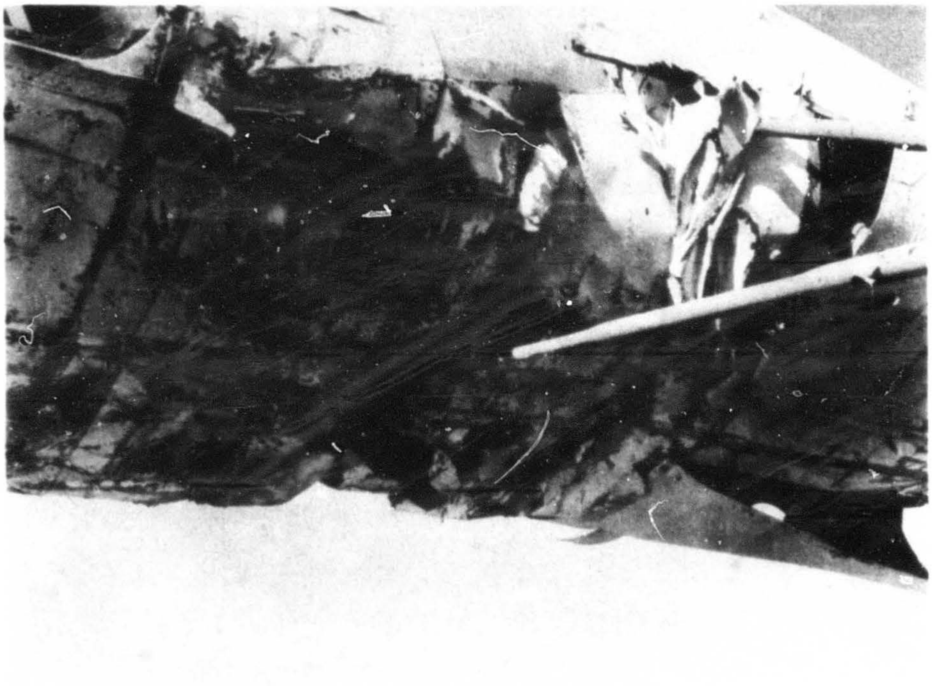


Figure 87. Rock Entry Point, External, T-18.

Figure 88. Rock Entry Point, Internal, T-18. (Rock Penetration and Structural Collapse as Viewed From Within the Fuel Tank Cavity.)

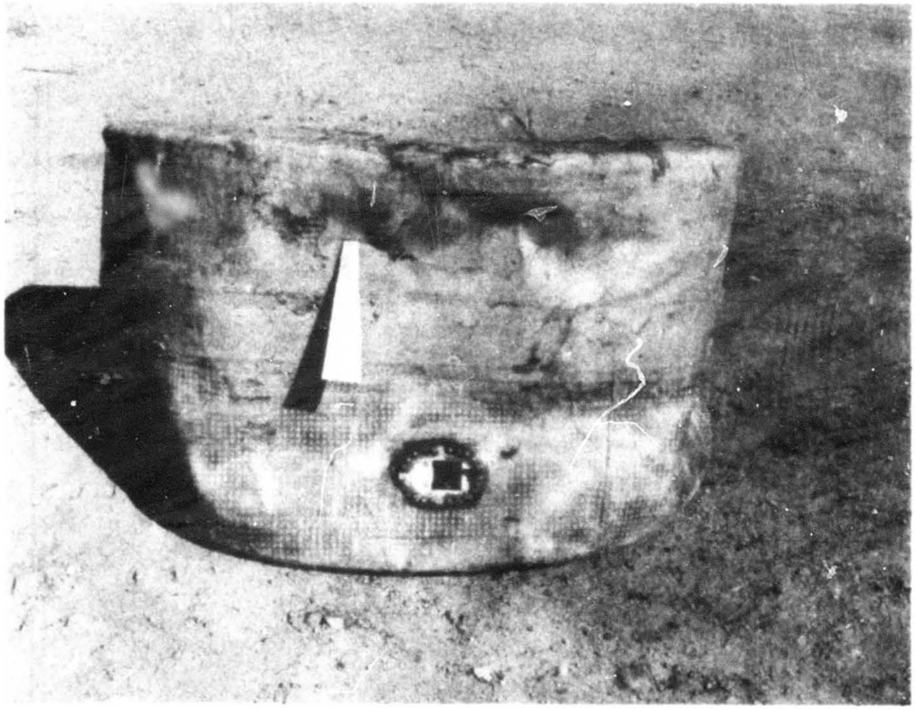


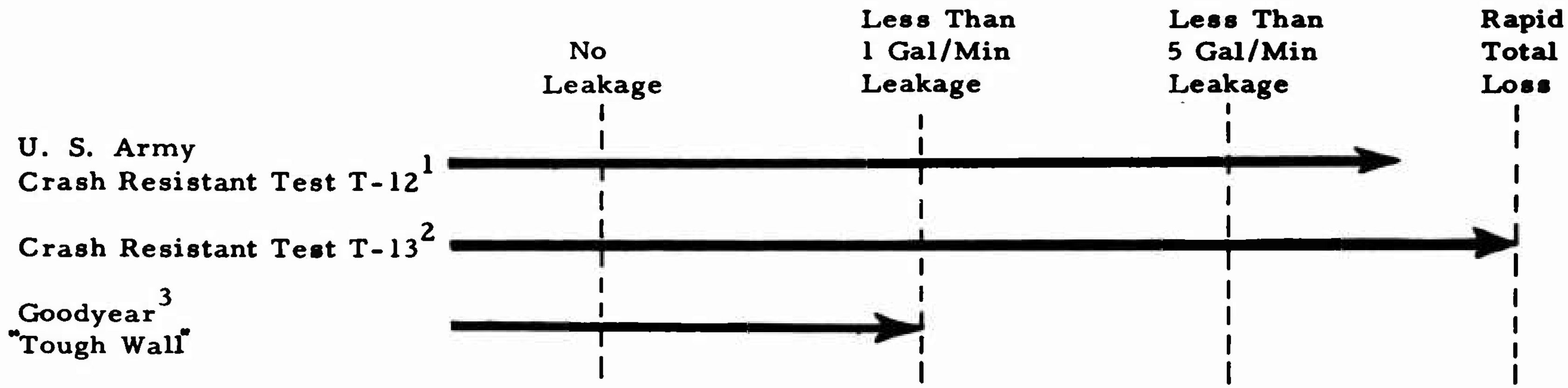
Figure 89. CH-21 Tank Cuts. (Pointer Is Inserted into Largest Cut on the Fuel Tank Bottom.)

Summary of Fuselage Tank Experiment

In Table X the leakage of this hollow "Tough Wall" tank is compared with the leakage of a standard CH-21 crash resistant fuel tank when subjected to two different crash environments.

The general fuel tank reference chart, Table XI, presents a list of all pertinent data on all tanks subjected to full-scale crash testing.

TABLE X
FUEL TANK FAILURE
CH-21
286-Gallon Tank



1. V_h - 38.5 ft/sec, V_v - 11 ft/sec, V_r - 41 ft/sec.

2. V_h - 40 ft/sec, V_v - 40 ft/sec, V_r - 56.5 ft/sec.

3. V_h - 40 ft/sec, V_v - 40 ft/sec, V_r - 56.5 ft/sec. This tank was exposed to same structural environment as crash resistant tanks except that two 12-inch rocks were attached to the aircraft underbelly directly below the fuel tank. Both rocks entered the aircraft fuel chamber area; however, the "Tough Wall" tank deflected upward, sustaining only minor cuts.

TABLE XI
GENERAL FUEL TANK REFERENCE CHART

	Tank[2] Test Results	Tank Empty Weight (lb)	Liquid Capacity (gal)	Total Weight Impact (lb)
C-45				
"Tough Wall" Hollow (F)[1]	2, 1, 1	8.25	15	132.8
"Tough Wall" Honeycomb (F)	3, 1, 1	16.3	30	265.3
Aluminum	1, 5	6.5	15	97.5
Aluminum	5, 4	8.0	30	257.0
"Fuzzy Wall"(I)	1	12.1	30	261.1
Firestone Exp. Cloth-Sponge A	1	14.5	30	263.5
H-21				
"Tough Wall" Hollow (B)	3	35.0	212	1794.6
Crash Resistant	5	64.8	212	1824.4
H-34				
"Tough Wall" Hollow (D)	1, 5	8.5	32	274.1
"Tough Wall" Honeycomb (D)	1, 1, 2, 3	18.0	25	225.5
Aluminum	5	10.0	42	358.6
Net	3	8.0	25	215.5
"Fuzzy Wall"	1	9.0	19	166.7
Firestone B Hollow	5	8.0	25	215.5
Firestone A Sponge Fill	5	13.2	25	220.7
Firestone C Abrasive Resistant	5	6.3	19	164.0
Pliocell Control Water	5	4.4	25	211.9
Pliocell Control Gel Gas	5	3.9	19	127.4[3]
Self-Seal Control Water	5	24.0	25	231.5
Self-Seal Control Gel Gas GF	4	28.0	13	112.5[3]
Self-Seal Honeycomb Water	3	20.0	13	127.9

1 The letters denote specimen curves on the damage chart, Figures 4 and 6.

2 Code 1 - no leakage; 2 - seepage; 3 - less than 1 gallon/minute; 4 - less than 5 gallons/minute; 5 - rapid total loss; spillage codes prefixed with GF (gelled fuel) refer to total escaped fuel without regard for time.

3 Gasoline weight of 6.5 pounds was used for these calculations. All others used water, weight 8.3 pounds.

4 Tank capacity was 286 gallons; 212 gallons of water = the same weight as 286 gallons of fuel

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13. ABSTRACT

Accident statistics indicate that postcrash fire is the most serious threat to human life in aircraft crashes. Several methods are available to reduce this hazard; however, the simplest and most effective immediate method is through control of the fuel spillage. Accident investigation reveals that fuel tanks developed to current crash resistant fuel tank specifications fail even under relatively moderate crash conditions. A discussion of the factors which must be considered when establishing specifications that will result in a crashworthy fuel tank is presented. Experiments were conducted with fuel tank material specimens and with experimental fuel tanks subjected to actual aircraft crashes. Results indicate that practical fuel tanks can be built today that are capable of preventing fluid spillage during accidents involving decelerative loading above the human survival range. Evaluation of the test data indicates that additional analysis is needed in order to fully understand why certain materials function as excellent tank materials and others do not.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

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