FAA ADS - 19

FAA ADS - 19

TECHNICAL REPORT

ADS - 19

STRUCTURAL DESIGN FOR FUEL CONTAINMENT UNDER SURVIVABLE CRASH CONDITIONS

by
P. M. Nissley and T. L. Heid
General Dynamics | Convair, San Diego, Calif.
Under Contract No. FA-WA-4607

for

138 p

FEDERAL AVIATION AGENCY

Washington, D.C.

August 1964

ACCESSION # AD 609615

STRUCTURAL DESIGN FOR FUEL CONTAINMENT UNDER SURVIVABLE CRASH CONDITIONS

Contract FA-WA-4607

Technical Report ADS-19

by
P. M. Nissley and T. L. Heid
General Dynamics/Convair
San Diego, California

August 1964

This report has been prepared by General Dynamics/Convair for the Federal Aviation Agency under Contract FA-WA-4607. The contents of this report reflect the views of the contractor who is responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policy of the FAA.

CONTENTS

CONTENTS (Continued)

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATION (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

BLANK PAGE

SUMMARY

This study was made to develop design principles for improving fuel containment in aircraft fuel tanks during survivable crash conditions. Efforts were confined to integral fuel tanks for multi-eng'ned transport aircraft.

The first section of the report defines crash loading as related to wing structure. The loading conditions considered are concentrated impact, distributed impact and internal pressure due to fuel inertia. The probable mode of failure is described and fuel containment design priciples are listed for each condition. The study indicates that the most critical loading is concentrated impact along the front spar and lower surface as the aircraft strikes obstacles such as trees or poles. The design objective for this loading is to break the tree or pole. Probably the most likely crash loading condition is a distributed impact which might result from a wheels-up landing. However, any wing which can break trees can also sustain severe ground contact loads. Most transports have the inherent strength to sustain the third type of loading, the internal fuel pressures that build up during a survivable crash.

Recommended design details for fuel containment are described and illustrated for conventional and advanced structures. The recommended manner of reinforcing wings for breaking poles is to strengthen the front spar rails and the skin panels aft of the rails. If the reinforcing material is added primarily to the lower rail and lower surface, fuel containment can be efficiently improved for both the most critical and the most likely crash conditions. The material added in these areas of the wing box can be included as primary bending material and therefore is not a significant penalty to the structural weight of the wing.

Analytical results were substantiated by a test program conducted with full scale fuel tank specimens. The specimens were representative of contemporary design and construction practices.

Results of the study indicate that a substantial improvement in fuel containment capability can be designed into wings similar to those in use today. Probable weight increase would be 1% of the total wing weight; probable increase in total program cost would be less than 0.5%.

INTRODUCTION

This study is part of a comprehensive program seeking to increase the probability of aircraft passengers surviving a moderate to severe crash. Many lives have been lost when passengers who had survived the crash impact with only minor injuries were fatally burned before they could escape from the aircraft. Containment of aircraft engine fuel is one of the means by which these fires can be minimized or prevented.

A major problem in fuel containment today results from the fact that the high-speed aircraft now in general use require greater fuel supplies than their predecessors and therefore are forced to use all available space for fuel storage, including the wing center section in the fuselage. Under more severe crash conditions, where the wing is torn from the aircraft, fuel containment efforts are directed primarily toward minimizing the amount of released fuel.

Although complete containment for all crash conditions is not feasible, maximum containment must be assured for the following types of loading:

a. Local impact against trees, poles, large rocks, etc.

b. Distributed impact against earth mounds or during wing low ground contact.

c. Puncturing from rocks, stumps, dislodged aircraft parts, etc.

This report, prepared under the direction of the Federal Aviation Agency, is a study of methods of designing and constructing aircraft integral fuel tanks to increase their capability for containing fuel under crash loading. The report is divided into five sections. The first, a summary of design criterion, is called the "Crash Environment." The second and third sections are concerned with design principles and design configurations. The fourth summarized the test program and test results. The final section deals with feasibility of advanced design concepts.

1 CRASH ENVIRONMENT

1.1 CONCENTRATED IMPACT LOADS

1.1.1 TREE OR POLE IMPACT — When an aircraft wing hits a tree or pole, either the pole is broken or the forward part of the wing is crushed and the wing is sheared or broken. The desired result is that the wing not be damaged to the extent that fuel is spilled. Therefore, some knowledge of tree and pole strength under relatively high speed impact conditions is needed to obtain optimum fuel containment.

A study has been made to clarify the failure pattern of trees and poles when hit by the wing of an airplane. Assumptions for, and results of, this study are shown in Appendix A. The study shows that the loads required to break 10 to 14-in.-diameter trees and poles are usually within the shear and bending strength envelope of contemporary wings but not within the local crushing strength capacity of these wings. The study also showed that airplanes weighing from 45,000 to 150,000 lb. and traveling at speeds of 120 to 150 mph would lose less tan 1% of their kinetic energy while breaking through trees of this size.

The test program (Appendix B) included pole breaking tests which indicate that the results of the study are conservative. During the late stages of the test program, a fuel tank specimen repeatedly broke sections of the largest available telephone poles and pilings. Maximum impact load on the tank was approximately 100,000 lb.

1.1.2 LOCAL RUPTURE OF TANKS — A wing sliding along the ground will be dented or punctured when obstacles such as rocks, tree stumps or pieces of broken aircraft are encountered. Likelihood of puncture may be lowered by choosing ductile lower wing surface materials which will bend and stretch rather than rupture.

1.2 DISTRIBUTED IMPACT LOADING

1.2.1 WING TIP GROUND CONTACT — A study was made to determine the limits of roll angle and descent rate within which an airplane can impact the ground without spilling fuel. The analysis assumes a gear-up airplane. Pitch attitude is level or slightly nose up. Aircraft studied were a twin-engine, 44,500-lb. straight-wing transport and a four-engine, 148,000-lb., swept wing jet transport.

Results of the study (Appendix A) indicate that wing flexibility is the most important single parameter in determining roll and descent limits. Wing flexibility is important for two reasons, the first and most obvious is that the wing will not break and spill fuel if it can bend away from the obstruction. The second reason is that bending the wing takes time; if a wing is to deflect several feet at the tip, the airplane must descend a similar distance and this descent takes time during which the ground reaction will roll the airplane as a function of time squared.

The study also indicates the importance of moving the fuel tanks inboard. This furnishes additional structure that can be crushed and worn away as the airplane is descending. As the structure is crushing, the increased available time allows more leveling of the airplane.

A third indication of the study is that strengthening the outer wing has relatively little effect on the roll angle and descent rate limits. A stronger wing will not necessarily bend more, nor will it appreciably affect the time available for leveling the aircraft.

1.2.2 SLIDING AND PLOWING LOADS — The forces involved are entirely dependent upon the type of terrain over (or through) which the structure is moving.

The critical structure is that in the vicinity of the wing lower front spar. The design objective here is similar to that for tree impact; that is, the structure must be designed for maximum practical impact strength, the upper limit being that load which will break off the wing in shear or bending.

It has been assumed that sliding and plowing loads act over several feet of span. Plowing loads are a direct function of frontal contact area and soil composition. Sliding loads are dependent upon normal force and coefficient of friction. Reference 5 provides an indication of both sliding friction and plowing coefficients for one type of soil (friction coefficient = 0.3 and plowing coefficient 7,200 to 9,000 psf of contact area). Different types of soil and/or plowing shapes will change both the friction and plowing coefficients.

1.3 INTERNAL PRESSURES DUE TO INERTIAL LOADING

1.3.1 CRITERION — This is simply a bursting pressure inside the fuel tank. The steady-state condition can be calculated easily when the airplane inertial loadings are known or assumed. For a given deceleration, the internal fuel pressure at any point is a function of the fuel head behind the point. All degrees of freedom should be considered, as well as vertical longitudinal loads.

It is important to design the wing to withstand these pressures without failing internal structure which could seriously reduce the ability of the structure to withstand local impact loads.

1.3.2 CONFIGURATION EFFECTS — Wing planform and structural configuration affect the fuel head. Low aspect ratio and high sweep increase the head as does spreading the front and rear spars to increase the fuel capacity of the wing. Configuration of intermediate spars and ribs can affect the internal pressures. For example, strategic placement of fuel tight spars and ribs can lower the available fuel head; web-type spars and ribs with minimum size fuel transfer holes, although not affecting the fuel head, can arrest fuel slosh. Structural stiffness can affect the internal fuel pressure in at least two ways:

a. Dynamic response in over-all wing bending may locally magnify the deceleration rate.

b. Large local deflections (ballooning) will tend to reduce the fuel head.

1.3.3 FUEL SLOSH EFFECTS — Analytical treatment of this problem is quite involved if such important parameters as tank shape, tank wall flexibilities, complex baffling (truss ribs, web ribs with holes, immersed stringers and intercostals, etc.) and deceleration time history are considered. However, it is felt that slosh is not a major design criterion for the following reasons:

a. Tank structure will be designed to withstand high inertial loading with full tanks.

b. Pulse time of high-g loadings will be short. These short pulse times, although well within the range of structural response, are too short to form high momentum-type fluid waves (vs. pressure pulses which travel approximately at the fluid speed of sound).

c. Rapid fuel movement over and through internal tank structure will entrap air in the fuel. As the fuel-air mixture "bottoms out" against the restraining tank walls, the entrapped air must be squeezed out before the fluid can be considered incompressable. This action dampens the shock of fuel impact against the tank walls."

d. Baffling will be more effective during conditions of slosh than in the full tank design condition.

2 FUEL TANK DESIGN PRINCIPLES

Using the crash environment load criteria of the preceding section, analyses (Appendix A) and tests (Appendix B) indicate that fuel containment can be improved without significant increases in weight or cost. The crash loadings affecting fuel containment are: (1) concentrated impact, (2) distributed impact, and (3) internal fuel pressure. The effects of these loadings, and the recommended design principles, are discussed in the following paragraphs. Paragraph 2.4, includes a summary of the design principles recommended to improve fuel containment for each loading.

2.1 DESIGN FOR CONCENTRATED IMPACT

2.1.1 FAILURE MODES – The usual mode of failure is local crushing of the structure at the point of impact. Most contemporary leading-edge structures will crush back to the front spar under low local loading and with negligible energy absorption. With the use of leading edge high-lift devices, heavier structural elements are required. The danger with such leading edge devices is that some mechanism or mechanism support structure may be forced through the front spar web and into the tank, allowing fuel spillage.

After the secondary structure has crushed, the most forward primary structure (usually the front spar caps) must bear against the obstacle and distribute the impact loads to the wing structural box. The load in the spar caps must be transmitted to the wing skin panels to prevent the spar caps from rupturing in bending. This produces local chordwise compression loads in the skins. Accordingly, for most existing aircraft, the skin panels adjacent to the front spar caps are the critical part of the structure. As the skin panels in the vicinity of the impact buckle, the spar caps bend and cause further buckling until either the caps or panels rupture. An additional factor in determining impact resistance is the effect of internal pressures produced by the deceleration. Restraint against "ballooning" of the spar web and skin panels increases impact resistance. An internal support structure that does not prevent ballooning permits earlier skin buckling and reduces the allowable impact force.

2.1.2 RECOMMENDED DESIGN PRINCIPLES – Analytical studies and tests indicate that efficient methods to increase resistance to local impact loading are:

a. Increase the skin panel chordwise stiffness between the front spar and first (or second) stringer. The recommended method is by increasing the local skin gage and adding local, chordwise stiffners.

b. Maintain the structural box shape for the internal pressures accompanying impact loads. The internal structure – ribs, stringers, intercostals – used to maintain the shape should not fail in a manner that will puncture the tank walls. Tests (Appendix B) indicate that webbed ribs are superior to truss ribs for tanks subjected to very high internal pressures.

c. Strengthen the front spar caps, primarily by increasing the skin-leading edge leg width and/or thickness.

d. Use ductile materials for spar caps, spar webs and skin panels. Ductility of the lower spar cap and skin panel are of particular importance to resist penetration by sharp objects during sliding crash conditions. Table I indicates the ductility and tear resistance for various materials. In addition to ductility, resistance to ignition of the fuel-air mixture due to friction sparking should be considered when choosing materials that can be in sliding contact with the ground. Figure 1 compares friction sparking characteristics of various materials.

Table I. Tear Resistance and Ductility of Aluminum Alloys (Ref. 23)

Material		Longitudinal				Transverse			
		F_{tu} (psi)	F_{ty} (psi)	Elong. (%)	Tear Res.* (in.-lb./in.^{2})	F_{tu} (psi)	F_{ty} (psi)	Elong. (%)	Tear Res.* (in.-lb./in.^{2})
2014	T6	71,600	65,700	10.4	250	71,000	63,600	10.0	180
2020	T4	50,000	34,200	16.5	1,110	49,400	31,600	16.5	1,060
2020	T6	82,000	77,500	7.4	30	81,800	75,400	7.0	15
2024	T4	69,700	48,200	20.3	705	67,500	45,200	19.8	610
2024	T3	69,600	52,400	19.5	710	67,400	46,400	19.7	600
2024	T36	75,100	63,600	15.1	425	73,400	56,400	15.0	385
2024	T6	67,200	53,200	9.5	275	66,300	51,800	8.8	245
2024	T81	74,200	69,800	6.6	170	73,600	69,000	6.1	150
2024	T86	77,100	72,400	6.4	125	76,100	71,200	6.1	115
2219	T4	55,400	37,000	21.0	1,460	55,700	33,600	19.5	1,300
2219	T87	69,700	57,700	9.5	235	70,000	57,600	9.4	295
2618	T6	61,300	56,200	6.2	270	60,600	54,200	6.0	235
7075	T6	82,300	74,900	11.2	290	82,300	72,500	10.8	220
7075	T73	71,600	60,300	10.6	510	72,900	61,000	10.3	400
7079	T6	76,000	68,600	10.9	510	75,900	66,600	10.8	370
7178	T6	88,800	80,900	12.2	140	88,000	77,000	11.9	130

*Unit Tear Propagation Energy

Note: The values presented are for thin gage (0.063) sheet material. Recent tests indicate that tear resistance decreases markedly as thickness increases. The relationship between alloys, however, is apparently unchanged

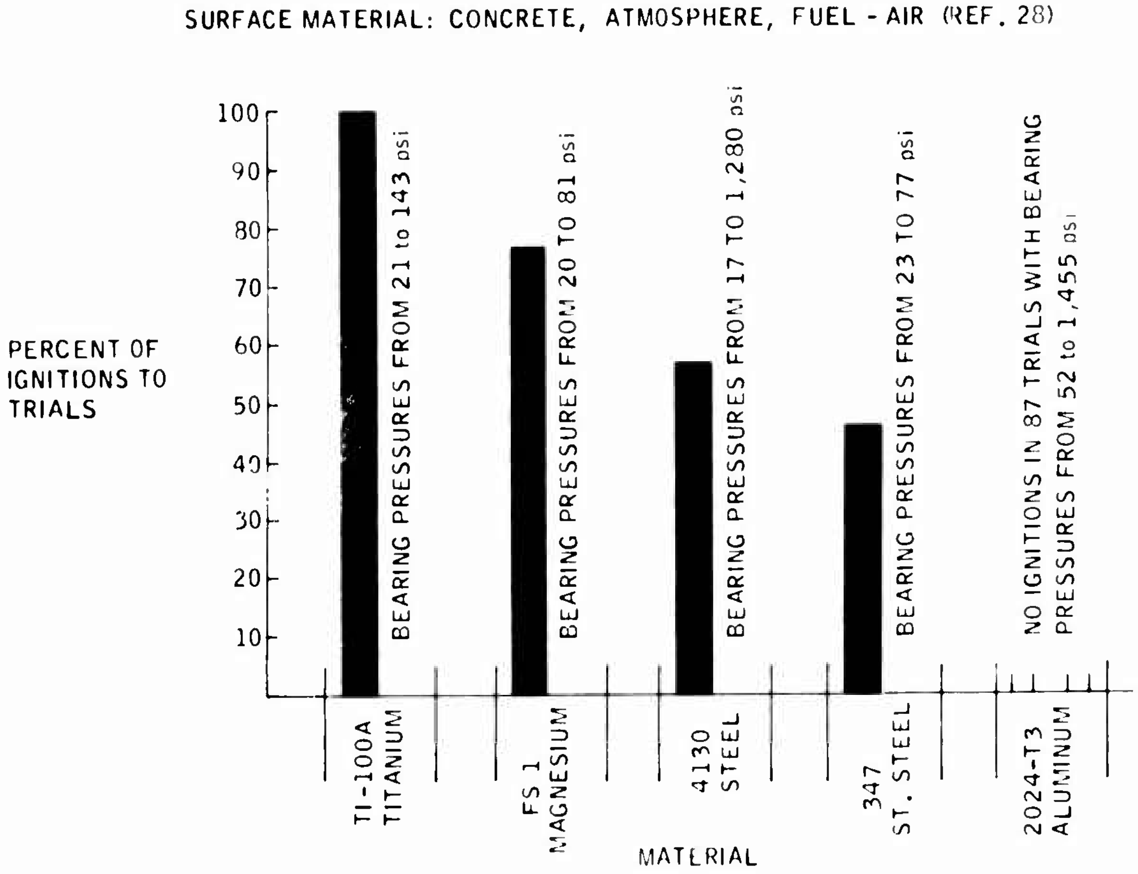


Figure 1. Comparison of Friction-Spark Characteristics of Various Metals

2.2 DESIGN FOR DISTRIBUTED IMPACT

This is the most probable type of crash loading.

2.2.1 FAILURE MODES — The failure mode for this loading is similar to that for concentrated impact. The load, however, will be distributed over a greater length of span. The primary contact surfaces will be the lower front spar and lower wing skin.

2.2.2 RECOMMENDED DESIGN PRINCIPLES — With the failure modes similar for both concentrated and distributed impact loading, the principles recommended to improve fuel containment (Paragraph 2.1.2) are similar. Items a, c and d are of greater importance on the lower portion of the wing for this loading. Item b is of greater importance for distributed impact since the decelerations, and corresponding fuel pressures may be higher and of longer duration.

2.3 DESIGN FOR INTERNAL FUEL PRESSURES

This is usually the least critical of the three listed types of loading.

2.3.1 FAILURE MODES – Note that there is no single internal fuel pressure for which all transport fuel tanks should be designed. The design pressure(s) will vary with airplane size, wing configuration, tank and wing stiffness, fuel type, etc., and will vary with location in the wing. Crash deceleration criteria will vary and will be limited by the longitudinal loading that a particular airframe can sustain without completely demolishing the passenger compartment. Pressure is a dynamic function of local deceleration and effective chordwise fuel head.

Large swept wing aircraft of the present generation with thick skinned wings designed for large flight loads, are usually not critical for internal inertial fuel pressures. Many other designs may be made adequate with minor design refinements. Most transport aircraft can be designed to sustain the fuel pressures normally encountered during survivable crash conditions with little weight penalty.

The failure mode of integral fuel tanks under crash inertial pressures varies with structural configuration and stiffness. A light, ductile tank with marginal skin support will "balloon" out under comparatively low pressures but will maintain high pressures as a membrane type container – providing eccentricities are kept to a minimum and attachments hold. A tank with stiff skin panels (sandwich construction as an extreme) holds its shape until failure pressures are approached by beaming the load into ribs, stringers and spars. Tank rupture may originate from substructure failure, attachment failure or panel failure in bending.

2.3.2 RECOMMENDED DESIGN PRINCIPLES – Prevention of the two failure modes described above (membrane and plate) require somewhat different design approaches. It should be noted that many of the design details which are important for good impact strength (Sections 2.1.2 and 2.2.2) also are important for containing high inertial pressures for the stiffer type structures. Good design practices for the membrane-type failure mode include: (see Appendix B).

a. Front spar web on the forward side of the spar cap vertical leg.

b. Tapered spar cap legs.

c. Large root radius on spar cap.

d. Symmetry of gages in the front spar region, i.e., equal thickness of spar cap legs and $t_{skin} = t_{web}$.

e. Good tension allowables on spar web and skin fasteners to the spar caps. High-strength steel attachments must be used with caution, however, since local stress concentrations may develop around the bolt heads. Attachments with wide collars or washers are preferable.

Some good design practices for the stiffer plate type structure are:

a. Substructure must hold the cover plates in position. This means special consideration for loads on ribs, stringers, intercostals and spars, especially in the regions of large fuel heads (front spar region). A web-type rib with full intercostaling is obviously better for this condition that a truss-type rib with either full or partial intercostaling. Intercostals must be analyzed as tension fittings as well as shear transfer medium. Existing stringer clips are often adequate, usually having been designed by fatigue considerations; their attachments, however, may be inadequate.

b. Eventual breakup of the substructure must not puncture, tear or place high secondary stresses on the tank walls. Avoiding "extra strong" spots as well as "weak links" will alleviate this problem.

c. If the cover plates are not heavy enough to withstand the maximum crash pressures but will contain most anticipated pressures, then the substructure could be designed to give way (uniformly) before the skins fail in local bending. The skins then could go into a combined plate-membrane failure mode.

Note however, that a good substructure also is a prerequisite for local impact resistance; therefore, the above is not recommended except for those cases where design for local impact is impractical.

d. Eccentricities which induce prying on attachments should be minimized.

2.4 SUMMARY OF FUEL TANK DESIGN PRINCIPLES FOR FUEL CONTAINMENT

2.4.1 IMPACT LOADING

a. Increase the chordwise stiffness of the skin panels between the front spar cap and first (or second) stringer.

b. Provide internal support structure to maintain structural shape (ribs, stringers, intercostals).

c. Use ductile material for lower surface skin.

d. Strengthen front spar caps in chordwise direction.

e. Minimize hard points.*

2.4.2 FUEL INERTIAL LOADING

a. Design internal structure to resist inertial fuel pressure.

b. Provide adequate tension fasteners at the front spar rail, web and wing skin joints.

c. Minimize hard points.*

---

* Hard points are caused by elements of the structure that deflect relatively less than the adjacent structure under crash loads. Such deflection discontinuities add local secondary stresses.

BLANK PAGE

3 | FUEL TANK DESIGN CONFIGURATIONS

3.1 REVIEW OF PRESENT-DAY TANKS

3.1.1 MATERIALS — Upper skins and stringers, traditionally critical in compression, are predominately high strength alloys. The highest strength alloys (e.g., 7178-T6) are avoided for lower surface skins and stringers which are usually critical in tension and fatigue where ductility and tear resistance are important. The medium-strength, ductile alloys are used on the lower surfaces of most aircraft wings. The selection of material used for other structural elements also appears to be based upon whether the element is critical for static strength or fatigue life. Within this general pattern the detail design of a structure is probably more important than the material used.

3.1.2 DESIGN DETAILS — Contemporary transport aircraft design details vary, but over-all configurations are similar. Spars are of built-up construction featuring extruded tee or angle spar rails. Skin-stringer combinations include both conventional stringers, specially shaped stringers and integrally stiffened skins. Ribs of both truss and web type are used, with truss ribs predominating. Reinforcement of these structures to improve fuel containment on existing airplanes would be costly in both weight and money.

3.2 DESIGN OF FUTURE CONVENTIONAL STRUCTURES

3.2.1 FUEL CONTAINMENT DESIGN DETAILS — Considering multi-engine transports ranging in size from a DC-3 replacement to an intercontinental jet transport, the first step is to decide what crash conditions the aircraft under consideration might be expected to survive with reasonable design refinement for fuel containment. For example, it is not reasonable to expect a DC-3 replacement to cut down 14 to 16-in.-diameter telephone poles. However, the same airplane with very little weight penalty could be designed to withstand fuel inertial pressures equivalent to 25 g, could also be designed to withstand substantial plowing loads, and could have good resistance to rupture incurred by sliding over rocks, broken pieces of aircraft, or other obstacles.

A larger 150,000-lb. swept-wing airplane might be designed to cut down 12- to 18-in.-diameter poles at a cost of 1 to 2% increase in wing structural weight. The resulting structure would inherently have the strength to contain inertial fuel pressures within the deceleration capability of the airframe (approximately 10 g).

Deceleration capabilities vary with airplane size, with the trend being a decrease in longitudinal deceleration as gross weight increases. The deceleration produced by fuselage crushing is one indication of airplane capability. Reference 36 indicates that although actual crushing-force magnitudes increase with airplane size, the resulting decelerations decrease. For the airplanes studied, the large transport sustained a deceleration of 5 g, with wings intact. The comparable deceleration for the smaller transport was 8 g. Crash landings during which the deceleration forces are applied to the entire airplane, such as ditching or landing in a swampy area, are probably the only conditions that will produce high decelerations and still allow the occupied portions of the fuselage to remain intact.

Crash criteria for concentrated impact loading, distributed impact loading and fuel inertial loading are detailed in Section 1 of this report and the recommended design principles for fuel containment are detailed in Section 2. Appendix A includes applications of the design principles which were developed by analytical methods. The analytical predictions were substantiated by the test program (Appendix B).

Survivable transport crashes usually occur at or near airports in reasonably clear areas. Distributed impact loading and concentrated piercing loads therefore are more frequently the cause of fuel spillage than are concentrated impact loads. The emphasis for incorporation of fuel containment design principles should be placed on the lower, forward surface of the wing.

3.2.2 INCORPORATION OF FUEL CONTAINMENT PRINCIPLES — Design modifications for fuel containment that are "tacked on" to a wing design already well along in its development cycle will add unnecessary weight and cost. Weights and costs can be minimized if fuel containment design criteria are considered during the layout stage of a new design. Since good fuel containment practices involve only sound structural design practices and since fuel tanks are primarily structural beams, it is logical that fuel containment design features can compliment the primary strength of the wing beam.

3.2.2.1 Weight — The more important fuel containment design features and their estimated weight costs, based upon per cent of total wing structural weight, are listed below.

a. Stronger fasteners in specific areas — negligible weight increase.
b. Good substructure - 0.5%.
c. Small eccentricities - negligible.
d. No "hard points" - negligible.
e. Stiffened forward skin panels - 0.1 to 0.5%.
f. Ductile lower skin - 0.0 to 1.0%.
g. Good wing tip design - negligible.
h. Heavy front spar caps - 0.0 to 0.5%.

3.2.2.2 Costs — On a typical production program involving 100 or more aircraft, nonrecurring costs such as design, drafting and tooling are a relatively small part, perhaps 10 to 15%, of the over-all 100 airplane program costs. Recurring costs (materials and manufacturing) generally are in proportion to the airframe weight involved.

Based upon the above and assuming: 1) a 2% increase in airplane nonrecurring costs, 2) that the wing empty weight is one fourth of the total airframe weight, 3) a 1% to 2% wing weight increase, the total program cost increase is 0.425% to 0.725%.

3.3 CONTAINMENT IN FUEL LINES

Fuel containment depends upon the integrity of the fuel lines as well as of the tank itself. Even though the fuel tanks are not damaged, containment is not realized if fuel lines outside the tank are ruptured or opened to allow fuel flow. Shutoff valves are required (CAR 4b.482) in the tank-to-engine lines so that flow can be stopped in case of an engine fire or failure. However, shutoff valve actuation is not necessarily accomplished in cases of engine detachment or displacement.

Consider the engine-tank arrangement in a pod-mounted configuration. Figure 2 (a) is an example of an undesirable wing-mounted pod-pylon installation with the fuel line shutoff located above the firewall in the pod. Often, during a crash, failure of the engine to wing attachment occurs at the wing rather than at the pod. Predetermined failure points, located at the pylon-wing attachment, are provided to allow separation without damage to the tank structure. Loss of the pod and pylon in a wheels-up condition then carries the shutoff valve away with the engine. Fuel line rupture can allow an uncontrolled flow. Figure 2(b) illustrates an improvement in shutoff valve location. Since the valve is mounted on the tank lower surface, separation of the pod and pylon from the wing can allow continued operation of the shutoff. Figure 2(c) illustrates the ideal location for

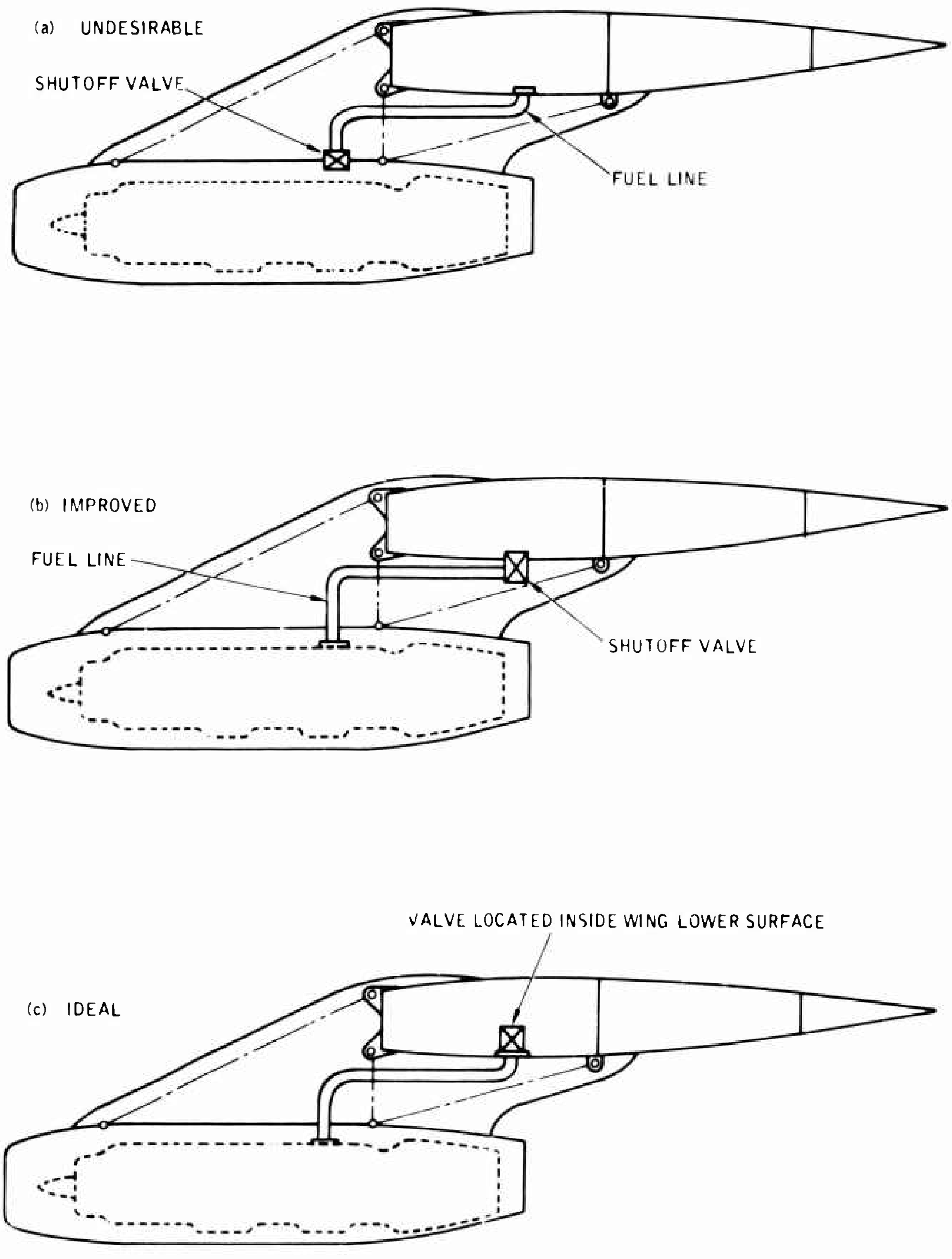


Figure 2. Tank-to-Engine Fuel Shutoff Locations

fuel containment. The location shown in Figure 2(b) can allow valve and wing lower surface damage after the pod-pylon has separated and the wing contacts the ground. Locating the valve inside the wing will reduce the probability of valve damage until the lower surface is punctured or ruptured.

In addition to the need for proper shutoff location, a means of automatic operation should be included. Present installations are usually manual systems operated from the cockpit and are satisfactory when sufficient time is available. In crash emergency conditions, however, an automatic system would be a great advantage. Reference 35 provides a basis for a system actuated by engine displacement. Not only is the system automatic, but it provides a means for detecting the need for operation. Excessive displacement in any direction must actuate the shutoff. Another method of actuating the shutoff is to combine a quick disconnect-shutoff feature. If the engine and pylon are separated from the wing, this predetermined failure point in the fuel line will cause shutoff actuation.

Engine-fuselage fuel line leakage can be reduced in a similar manner in aft fuselage-mounted engine configurations. The pod-pylon design should allow failure without significantly affecting the fuselage structure. The shutoff valve should be located inside the fuselage cell. Fuel lines in the fuselage between the wing and engines, however, present more of a problem. The fuel lines are subject to damage as the fuselage is collapsed or ruptured at impact or during subsequent ground slide. Rupture of these lines, even without fuel flow, allows fire under the passenger section. Positive shielding for all fuselage damage possibilities is doubtful; however, shielding for the case of lower fuselage collapse is possible.

3.4 LOCATION OF FUEL TANKS

For long-range airplanes, designers usually are forced to use all available space for fuel storage. However, for short range aircraft the designer may have some freedom of choice in locating the fuel tanks. From a fuel containment point of view, the optimum location on a conventional airplane would be approximately midway between the fuselage and the wing tip.

This location places the fuel outboard of the landing gear and probably outboard of the engine. Consequently, there is a good possibility of avoiding fuel spillage when the wing is broken from the fuselage. Keeping the fuel tank some distance inboard of the wing tip minimizes the danger of fuel spillage in an accident when the initial ground contact is at a wing tip.

A review of accident records shows that airplanes with fuel tanks in this mid-span location have a considerably better than average record in regard to fuel containment under crash conditions.

BLANK PAGE

4 FUEL CONTAINMENT TEST PROGRAM

The test program presented in Appendix B was used in addition to the analytical studies to determine the recommended structural reinforcements for fuel containment. The test program included: (1) spar rail bending tests to determine the effects of spar rail and attachment details that will increase the ability to withstand internal pressures, and (2) simulated tank drop tests to determine the effects of arrested stop and impact loadings on wing structures of conventional and reinforced designs.

4.1 SPAR RAIL BENDING TESTS

The assumption for this series of tests was that internal pressure will produce tank deflections sufficiently large to cause failure of the front spar-wing skin joint. Subsequent tests of tank specimens indicated that this membrane-type pressure loading is seldom the most critical design condition.

The test specimens consisted of 3-ft.-long strips of sheet aluminum attached to a section of extruded angle, simulating a short span of spar web, spar rail and wing skin. Various materials and gages were tested. The specimens were loaded in tension, as shown in Figure B-1 of Appendix B.

4.2 DROP TESTS

The test specimens used in the drop-test program consisted of 6-ft. span tanks suspended on a 50-ft. pendulum. The tank chords were 4-ft. with a depth of 16 in. Two ribs were equally spaced between the end plates. The basic tank construction simulated that of contemporary aircraft, using built-up spars, skin-stringer combination and truss ribs. Water simulated the fuel load.

Reinforcement was added as the tests progressed to improve the crash loading capability. The reinforcements include: (1) skin doublers adjacent to the front spar, (2) increased thickness of the front spar rails, (3) full intercostaling of the ribs to skin, and (4) changing the truss ribs to web ribs.

4.2.1 TEST PROGRAM — Three crash-loading conditions were simulated in the test program. Arrested stop tests produce high internal pressures with reasonably long deceleration distances, concentrated impact tests produce high local crushing forces at the front spar, and inclined mount tests indicate the effects of distributed impact.

4.2.1.1 Arrested Stop Tests — Arrested stops were obtained by catching the descending tank with hooks attached to stainless steel straps. Strain-gaged load links were located in the strap system to measure the arresting force. Deceleration distances of up to 20 in. were obtained as the straps stretched. Drop heights from 5 ft. to slightly over 36 ft. produced internal pressures up to 45 psi. The maximum velocity attained was 48 fps with a maximum deceleration of 46 g. (Ref. Table B-II, Appendix B.)

4.2.1.2 Concentrated Impact Tests — Concentrated impact tests were of two types. During the first series of tests, specimens struck a section of log mounted on a strain-gaged dynamometer. The deceleration distance was determined by the amount of local crushing of the log and specimen, with the impact forces recorded by the dynamometer. Sixteen drops of from 2 to 12 ft. were made. Maximum velocity attained was 27.8 fps with a maximum deceleration, determined from the dynamometer loads, of 42g. The second series of concentrated impact tests allowed the specimen to break sections of poles. Eight-foot lengths of telephone and piling, from 6.6 to 17.4 in. in diameter, were mounted to allow the tank specimen to impact at the center of the pole. Thirteen drops were made with drop heights from 5 ft. for the 6.6-in. diameter pole to 35 ft. for the 17.4-in. diameter piling. The maximum velocity attained was 47.4 fps with decelerations of over 50g recorded. The specimen used in this series included the reinforcements recommended for improved fuel containment.

4.2.1.3 Distributed Impact Tests — The inclined mound impact tests used sand and sand/rock combination mounds to decelerate the tank speciment. The surfaces were sloped at 30 degrees to the horizontal. Fourteen drops were made at heights of 5 to 25 ft. The maximum velocity attained was 40.1 fps and decelerations ranged from 5.6 to 22.9g. The tank specimen used in this series included the reinforcements recommended for improved fuel containment.

4.2.2 TEST RESULTS INTERPRETATION

4.2.2.1 Arrested Stop Tests — Containment of fuel due to internal pressure does not appear to be a critical design condition for tanks designed for impact loadings although failure of the internal structure can puncture tank walls due to large deflections. Web-type ribs resist internal pressure better than truss-type ribs. Full chord intercostaling between the ribs and skins also helps to reduce deflections.

4.2.2.2 Concentrated Impact Tests — Containment for this loading depends on the strength of the front spar rails and the wing skins immediately adjacent to the spar rails, the ability of the tank surfaces to transfer loads into the ribs, and the ability of the tank to retain its shape. To provide the strength to resist an impact force of 100,000 lb. (50,000 pound per rail), the spar rail thickness was increased to 0.25 in. Doublers and stiffeners were added to the skin panels immediately aft of the spar to beam the load to the ribs and the skin to rib attachment was improved by adding full chord intercostals to redistribute the impact load from the front to rear spar. In addition, the truss ribs were replaced by solid-web ribs. This reinforcement was included to prevent rib failure due to the high internal pressures. The test speciment requirement for web ribs to prevent ballooning due to internal pressure is probably not a requirement for all aircraft. The high g loadings, resulting from the low weight of the test specimen, produced internal pressures that would not be attained on large aircraft under the same impact load.

4.2.2.3 Distributed Impact Tests — These tests indicated that a tank designed to resist concentrated impact will be satisfactory for distributed impact. The usual impact area will be the lower spar rail and skin with less need for reinforcement of the upper rail and skin. The probability of spar web and lower skin puncture by some external obstacle is increased. Attachment of the lower skin to spar rail may be critical for peeling the lower skin away from the spar rail.

5 FEASIBILITY STUDIES OF ADVANCED CONCEPTS

5.1 ADVANCED STRUCTURES

Crash criteria detailed in Section 1 and design principles listed in Section 2 are generally applicable to all transport aircraft with integral fuel tanks. As stated in Section 3, however, the relative importance of specific crash criteria will vary with aircraft physical specifications. For example, a large airplane might never experience large inertial loading during a survivable crash. The loads required to demolish the aircraft, including the occupied areas, are not large enough to give high load factors to the large mass. The wing structure would probably be inherently strong enough to plow through reasonable obstacles such as trees, small buildings, etc., without tank rupture. However, consideration should be given to designing the tanks to resist penetration during the breakup and subsequent sliding over secondary structures, equipment and obstacles.

5.1.1 MATERIALS — With the materials presently available, those used in current practice appear to be the most satisfactory for crash loadings. More ductile materials are available, but are generally unacceptable from a strength to weight standpoint. Table 1 (page 7) indicates the ductility and strength characteristics of several aluminum alloys and tempers.

Local design detail configuration can be of greater importance than actual material choice. Brittle joints or local, relatively stiff areas should be avoided since large deflections are usually present during crash loadings. Materials exhibiting the greatest ductility consistent with strength and weight considerations should be used in all areas subject to crash loads.

A material property that must be considered during any crash effects study is resistance to spark ignition. During a crash, some elements of the structure can be expected to rub over rocks, concrete or other metal. Friction sparks from some materials (aluminum) will not ignite an explosive fuel-air mixture. Sparks from other materials (titanium) will consistently ignite such a mixture. Figure 1 (page 8) indicates the variation of friction-sparking, fuel-air ignition characteristics of several metals.

5.1.2 DESIGN FEATURES — Figures A-10 through A-24 in Appendix A are sketches of unconventional design features that might be considered during the early development stages of an airplane. Advantages and disadvantages of the particular design are included with each sketch.

5.1.3 WEIGHTS AND COSTS — Design modifications for fuel containment which are "tacked on" to a wing design that is already well along in its development cycle will add unnecessary weight and cost. Weights and costs can be kept at a minimum if fuel containment design criteria are considered during the layout stage of a new design. Good fuel containment practices involve only sound structural design practices. Since fuel tanks are primarily structural beams fitted to the aerodynamic shape of a wing, it seems logical that good fuel containment features can compliment the primary strength of the wing beam.

Table I in Appendix A lists the more important design features for fuel containment. Estimated weight cost for these features, based upon percent of total wing structural weight, is listed on page 15.

5.2 ENERGY-ABSORBING STRUCTURES

In any crash condition, the maximum kinetic energy that might be absorbed by wing energy absorbing devices is that energy required to tear the wings from the aircraft. On fixed-wing aircraft, this limiting energy is negligible when compared to the over-all kinetic energy of the airplane (Ref. 36). In fact, the major gain derived by severing the wings from an aircraft is not the energy absorbed but the kinetic energy lost as the gross weight of the structure containing the passengers is reduced. It follows then that the only practical use of wing energy absorbing devices is to promote fuel containment.

Several energy absorbing schemes for wing fuel tanks are sketched in Appendix A, Figures A-19 through A-24. Note that many of the devices do not absorb energy without some fuel spillage. Note also that the energy absorbed is small. The devices do, however, act as shock relievers. An object struck by the wing must be accelerated out of the way. The acceleration, and therefore impact load, will be lower with an energy absorbing device because of the greater available acceleration distance.

Although the idea of crash energy absorbing devices is attractive, it is felt that the idea (in the forms conceived here) would required considerable refinement considering the weight involved for the nebulous advantages.

5.3 MINIMUM-FIRE CONCEPTS

The minimum-fire concept is based upon the principle that a fire can burn only as fast as fuel is supplied. The concept follows the assumption that some fuel tanks on an airplane would probably be ruptured during a survivable crash and fuel would be spilled. One such study (Ref. 37) forms the basis for the brief evaluation presented in this report.

The form taken by a multicellular tank may be as varied as the imagination of the designer. Pesman's study (Ref. 37) proposed individual, polyhedron-shaped cells about the size of pingpong balls. The cells could be placed in the tanks loose for ready removal or could be bonded together, and to the tank walls, so as not to spill out of any rupture in the primary structure. A design approach that might be more easily removable for tank purging would be continuous tubes, sectioned and vented. A configuration that would furnish structural strength is vented honeycomb (or any similar structural core).

Logic indicates that the multicellular concept need be applied only to that part of a wing where tank puncture or rupture might occur. This leads to compartmentation of the cells. An example is a wing having ductile and comparatively thick lower skins which resist rupture resulting from sliding over objects. Such a wing would require fuel cells only in the forward part of the wing (Figures A-14, A-20 and A-21, Appendix A). Some features that would be expected of any multicellular configuration are:

a. Minimum fuel spillage through any tank wall rupture. Loose cells would fly through any sizable opening and might roll some distance from the aircraft (or along a path parallel to that of the aircraft. Fuel spillage rate would be limited to that escaping through the vent holes until a sustained fire started; then the shell of the cells would probably be consumed. Leakage in a crushed area could be restricted by efficient "wadding" of the cell walls, especially the smaller cells that are found in structural cores.

b. Minimum lost tank volume. Pesman indicated that this loss might be 5% for rounded-off polyhedron cells (2.5% if only forward half of wing has cells). The loss might be 6 to 8% using full depth structural core or could be on the order of 2% with more efficient use of structural core material (Figures A-15 and A-21, Appendix A).

c. Minimum fuel flow restriction. The engines must not be starved for fuel. Fuel pumping requirements must be reasonable and refill time must not be increased. Also the intrapped fuel must be a very small part of the total fuel load.

d. Minimum added weight. Two to five per cent of the fuel weight must be added for cell weight, depending upon the complexity of design.

e. The cellular material must be inert in contact with fuels.

f. The cell structure must not "wad" during extended usage and under repeated fuel slosh loading. This is probably the critical strength condition for cell wall thicknesses and for bonding of cells.

g. Tank cleaning operations must be simple and reliable.

h. The bacterial growth problem must not be compounded. This requirement may dictate the material used for the cells.

The above design and operational requirements are formidable. A range penalty, either in added weight or reduced fuel volume, seems inevitable. The concept itself is debatable. In general, the cost for added weight and complexity might better be turned to more direct methods for fuel containment. Exceptions might be smaller aircraft where structural reinforcement for fuel containment becomes costly. Breakaway tanks might also use this concept advantageously.

An additional minimum fire concept, "fuel gelling, " will not be discussed here since it is presently under extensive study.

5.4 FUEL DUMP DEVICES AND BREAKAWAY WINGS

Perhaps the biggest problem with fuel dump devices and breakaway tanks is accidental operation. The operation must be reliable and also must be fast acting. The goal should be to drop all fuel. A stream of fuel dumped along the route of a skidding airplane could act as a fuse to the fuel remaining in the tanks.

5.4.1 FUEL DUMP DEVICES — The objective is to dump all fuel as soon as all engine power requirements are gone. This could be immediately before or after touchdown. An important requirement is that the fuel be dumped clear of any iginition source. Any practical evacuation will be by gravity which means openings of some kind at low points in the wing. Operation, or at least arming of any automatic device, must be at the pilot's option. For example, it might be dedirable to dump fuel during a forced landing in a marshy area but it would not be desirable to open buoyant fuel tanks during an open-water ditching operation.

Figure A-25, Appendix A, plots time to empty a typical 1,000-gal. wing tank versus diameter of clear opening required and versus the horizontal distance covered by the aircraft during the emptying operation. A typical point on the graph indicates that, for a 1-ft. diameter egress, 4 sec. would be required to empty a one-half full 1,000-gal. tank. The airplane, traveling at an average speed of 100 knots, would cover a ground distance of 676 ft. Figure A-25 is based upon a round unlipped hole — the most efficient egress configuration that can be expected.

The design and operation of any presently conceived fuel dump device presents difficult problems. Splitting the tanks open with explosive charges has obvious design problems that probably are solvable but not necessarily "sellable." A similar approach is the use of large structural doors held on with explosive bolts. The above difficulties would be lessened if fuel pressurization were by an inert gas — a feature that might be realized on supersonic transports.

A more conventional approach would be quick-acting actuated doors. The weight penalty must include mechanism weight plus the extra weight involved in nonstructural doors. The design must include a positive door locking device and must be leak-free after years of service. The whole system might be dormant for the life of the airplane — yet high reliability is required.

In view of the above, the actuated door concept appears the least attractive of the three suggested systems. In fact, solving the original problem, that of fuel containment, appears less difficult than eliminating the problem by any presently conceived fuel dump method.

5.4.2 BREAKAWAY WINGS — Several accidents have occurred during which one or both wings of a commercial airplane were broken from the fuselage during the early stages of a survivable crash. All fuel either remained with the wings or gushed out when the wings separated from the airplane. The hot engines either remained with the wings and fuel or bounced off along some path of their own. The fuselage with its passengers came to rest some distance from the major fires.

In addition to the reduced fire hazard in the occupied area, a second benefit derived from breakaway wings is the resulting decrease in kinetic energy in the compartment carrying the passengers. The decrease in gross weight may be on the order of 20 to 50 per cent. Two formidable problems immediately apparent are: (1) how to design the structure to break away only during crash conditions, and (2) what to do about the fuel carried in wing carry-through structure. This center section structure usually is vital to the strength of the fuselage which must remain intact to protect the passengers. A reasonable solution is to design the structure so that the carry-through tanks will be unaffected by the separation of the wings and to build adequate fuel containment capabilities into the under-fuselage tank. Because of the great chordwise strength inherent in the root section of some wings, it might be best to locate the break at the most inboard engine. Fuel containment principles would be incorporated in the tankage that remained with the fuselage.

The design approach for breakaway wings should be based upon the configuration details of the particular airplane under study. A straight, high-aspect ratio wing may lend itself to a breakaway design which will cost little in extra weight, especially if the fuel can be kept outboard. Because of inertia relief, such a wing will have a structurally lighter root section than one with the fuel inboard. A straight high-aspect ratio wing, regardless of fuel location, will tend to break off at the root under impact loads which occur in the middle or inner span. Local overstrength should be provided on the fuselage side of the wing root.

Most swept wings are comparatively strong near the root for aeroelastic reasons. Many have root sections which are wide and thick for practical reasons, such as enveloping the retracted main gear. With conventional structure, such wings are not susceptible to failure at the root from chordwise crash loads.

CONCLUSIONS

Analytical studies and test results, as related to fuel containment in the integral tanks of modern multi-engine transport aircraft, lead to the following general conclusions:

a. Large aircraft may be designed to withstand severe impact conditions such as striking trees or poles up to 18 in. in diameter. This will result in an increase of approximately 1% in wing weight and production costs. To avoid relatively large weight penalties, smaller aircraft should be designed for impact with proportionately smaller obstacles.

b. Aircraft wings also can be designed to sustain reasonable distributed impact loads such as those resulting from contact with the ground. Provisions made for tree impact (see Item a) will usually suffice for ground impact. However, in this case, attention should be directed primarily towards supporting the lower front spar cap.

c. "The impact strength of the structural shell protecting the passengers limits the decelerations that can be considered as survivable Fuel tanks need not be designed for pressures greater than those resulting from this deceleration." Considering these limitations, fuel inertial pressures and slosh loads can be contained in integral tanks incorporating reasonable design refinement and little weight increase.

DESIGN GUIDE

GENERAL RECOMMENDATIONS

a. Fuel containment principles should be considered during the preliminary design phase of airplane development.

b. Reasonable crash loads criteria should be established for the particular airplane under consideration. Impact loading is usually of prime importance.

c. When the designer has freedom to choose a location for fuel tanks, choosing an area with low probability of being damaged may be the greatest possible single contribution to fuel containment.

STRUCTURAL RECOMMENDATIONS

a. The front spar rails and structure aft of the rails must be designed to react impact loads. Particular attention should be given to the lower surface.

b. Use a ductile lower skin material to resist penetration.

c. The internal wing structure, e.g. ribs and stringers, must react the maximum internal pressure without large deflections. Any significant "ballooning" of the structure can greatly reduce its resistance to impact loads.

d. The wing-tip area should be designed to crush progressively under ground impact loads, in contrast to breaking off in large sections.

e. If a fuel tank ruptures as a result of internal pressure, large structural deflections will probably occur before the tank fails. In such cases, it is important to eliminate "hard points" or areas of greater stiffness which could cause premature local failure.

f. Structures which may be broken from a wing during a crash (such as an engine pod or landing gear) should be designed so that the failure will not rupture the fuel tank.

REFERENCES

1. "Prevention of Injuries in 'Unpreventable' Aircraft Accidents," Dr. F. H. Quimly and A. H. Hasbrook. Reprint from Research Reviews, August 1956.

2. "Recommendations on the Design of Aircraft and Equipment with Respect to Crash Survival," Air Transport Association of America, April 1954.

3. "Crash Forces and Crash Survival," Otto E. Kirchner. Paper presented at the Flight Safety Foundation Air Safety Seminar, Santa Fe, New Mexico, November 1954.

4. "Crash Survival and Crash Fires," David L. Posner of CAA. Presented to IAS, Washington Section, 7 April 1953.

5. "Accelerations in Transport Airplane Crashes," G. M. Preston and G. J. Pesman, NACA TN 4158, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, February 1958.

6. "Fire Lessons from La Guardia Airport Electra Crash," M. G. Beard, American Airlines, 15 May 1961.

7. " 'Notes' covering the 13th Annual International Air Safety Seminar," O. E. Kirchner, Boeing Airplane Co., Chandler, Arizona, November 1960.

8. "Notes: Flight Safety Foundation's 14th Annual International Air Safety Seminar," O. E. Kirchner, Boeing Airplane Co., Naples, Italy, November 1961.

9. Air Analysis of Fire Accidents in Scheduled Air Carrier Operations. Bureau of Safety Investigation, C. A. B., 1949.

10. A Review of U. S. Air Carrier Accidents in Which Fatalities Resulted from Fire Following Impact, 1952-1961, J. J. Carroll. Bureau of Safety, C. A. B., 1962.

11. "Behavior of Metals Under Impulsive Loads," J. J. Rinehard and J. Pearson. U. S. NOTS, China Lake, Calif., published by American Society for Metals, 1954.

12. "Limited Investigation of Crushable Structures for Acceleration Protection of Occupants of Vehicles at Low Impact Speeds," T. C. O' Bryan and H. G. Hatch, Jr., NASA TN D-158, October 1959.

13. "Effects of Impact on Simple Elastic Structure," J. M. Frankland, Ph. D. Report 481, U. S. N., David W. Taylor Model Basin, April 1942.

14. "Plasticity and Man-Linear Elastic Strains," M. E. Backman. U. S. NOTS, China Lake, Calif., April 1961. NAVWEPS Report 7648, NOTS TP 2665.

15. "Discussion of the Post-Crash Fire Problem," Av-SER Report 62-30, 6 December 1962.

16. "Preliminary-Bibliography: Synthesis of Aircraft Fire, Rescue and Evacuation Technology," Av-SER, 26 July 1963.

17. "An Investigation of the Crash-Fire Problems in Transport Aircraft Fuel Tanks, R. L. Field, M. F. Miller and G. L. Pigman, C. A. A., Indianapolis, Technical Development Report No. 134, January 1951.

18. "Origin and Prevention of Crash Fires in Turbojet Aircraft," NACA TN 3973, May 1957.

19. "A Combined Water-Bromotrifluoromethane Crash-Fire Protective System for a T-56 Turbopropeller Engine," NASA TN D-28, August 1959.

20. "Practical Solution of Plastic Deformation Problems in Elastic-Plastic Range, NASA TR-R-28, 1959.

21. "Calculation of the Strength of Crash-Resistant Fuel Cells for the Wings of a Twin-Engine and a Four-Engine Transport Airplane," FAA Task No. 59-203.4, April 1961.

22. "Accelerations in Fighter-Airplane Crashes," NACA RM E57G11, 4 November 1957.

23. "Tear Resistance of Aluminum Alloy Sheet as Evaluated by Kahn-Type Tear Tests," J, G. Haufman. Alcoa Research Lab. Report 9-62-42, 28 November 1962.

24. "Principles of the Properties of Materials," J. P. Frankel. McGraw-Hill, 1957.

25. "Engineering Materials Science," C. W. Richards. Wadsworth Publishing Co., In., San Francisco, 1961.

26. "Supersonic Transport Safety Considerations," Ray D. Kelly, Director of Technical Development, United Airlines.

27. "Impact Testing of Materials," Wilhelm Spath. Gorden and Breach, Science Publishers, New York.

28. "Appraisal of the Hazards of Friction - Spark Ignition of Aircraft Crash Fires," J. A. Campbell. NACA TN 4024, May 1957.

29. "Ditching Characteristics of Convair's Model 30 (990) Jet Commercial Transport," W. B. Barkley. Convair Report ZH-30-001, March 1961.

30. "Synthesis of Impact Acceleration Technology for Aviation Crash Injury Prevention (Project SIAT)." U. S. Army, TRECOM, Technical Report 63-31A, June 1963 (AvSER).

31. "Bibliography of Impact Acceleration Literature (Annex to Project SIAT)." U. S. Army, TRECOM, Technical Report 63-31B. June 1963, AvSER.

32. "Dynamic Behavior of Liquid in Moving Container," H. Norman Abramson, Applied Mechanics Reviews, July 1963.

33. "Economic Losses Following Accidents," M. G. Beard, American Airlines, Second Annual Air Transport Conference of New York University, May 1962.

34. "Some Economic Factors in Air Transport Loss Prevention," J. Lederer, International Air Transport Seminar. 27-31 March 1961, New York University.

35. "Proposed Initiating System for Crash-Fire Prevention Systems," J. C. Moser and D. O. Black. NACA TN 3774, December 1956.

36. "Crashworthiness Design Principles," FAA Report, September 1964.

37. "Multicellular Fuel Tanks as a Means of Reducing the Aircraft Fire Hazard," G. J. Pesman, NASA, October 1963.

38. "A Study of the Flammability of Magnesum," Paul Boris, Systems Research and Development Service, FAA. FAA Technical Report ADS-14, April 1964.

BLANK PAGE

APPENDIX A | STRUCTURAL DESIGN AND DESIGN PRINCIPLES STUDY

A.1 CONVENTIONAL INTEGRAL FUEL TANKS

Studies included in this section are (1) pole or tree impact, (2) wing tip ground contact, (3) wing strength of contemporary aircraft, and (4) design features for fuel containment.

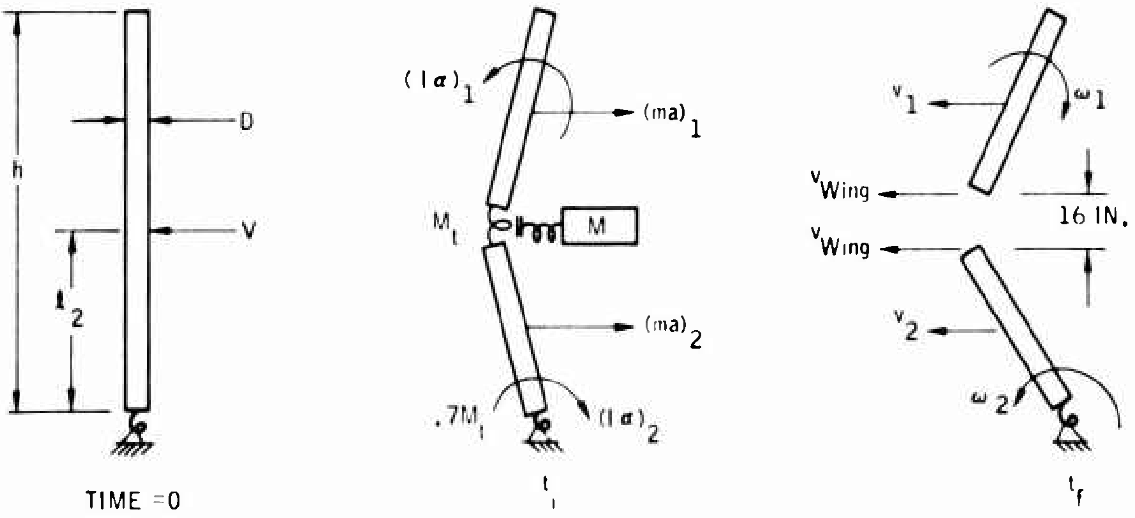
Crash loading conditions on fuel tanks are concentrated impact loading, distributed impact loading, and fuel pressure inertial loading. The above have been listed in order of design difficulty although design solutions to concentrated and distributed impact are similar. Conversely, reasonable inertial fuel pressures may be contained rather easily in contemporary wing configurations.

The weight penalties and fabrication costs involved in fuel containment design are approximately in direct relation to the degree of design difficulty. Since a weight and/or cost limitation for incorporation of fuel containment principles probably would be established for a new airplane, the designer must arrive at a compromise that will offer the least fuel spillage for the more probable crash conditions. The more likely survivable crash condition is that of distributed impact on the lower wing surface and along the lower part of the front spar such as might occur during wheels-up or one-wing low ground contact. It is therefore recommended that incorporation of fuel containment principles be emphasized in the lower-forward part of the wing fuel tanks.

A.1.1 TREE OR POLE IMPACT — Analysis and tests indicate that when an aircraft wing hits a tree or pole, one of two things happens: (1) the pole is broken, or (2) the forward part of the wing is crushed so that the wing fails locally in shear. The aircraft is not slowed a significant amount. The desired result, of course, is that the wing cut through the tree or pole. Therefore, some knowledge of tree and pole strength under relatively high speed impact conditions is needed.

A study has been made to clarify the failure patterns of trees and poles which are hit by a wing moving at speeds of 120 and 150 mph. Strength and energy dissipation studies were made for trees 20, 30 and 40 ft. high with diameters of 10, 12 and 14 in. Assumptions for the study follow. Note that secondary breaks occurred in some trees (Figure A-1). Tree inertia loads, incurred while pushing the trees clear of the wing, were large enough to cause these secondary tree trunk failures.

Wing sweepback would modify the results, additional degrees of freedom would be involved, and there might be a significant sawing action as the tree slides outboard along the wing leading edge.



A preliminary survey of the problem indicated the many complexities of a rigorous solution. The following is a simplified approach that establishes trends and gives approximate results.

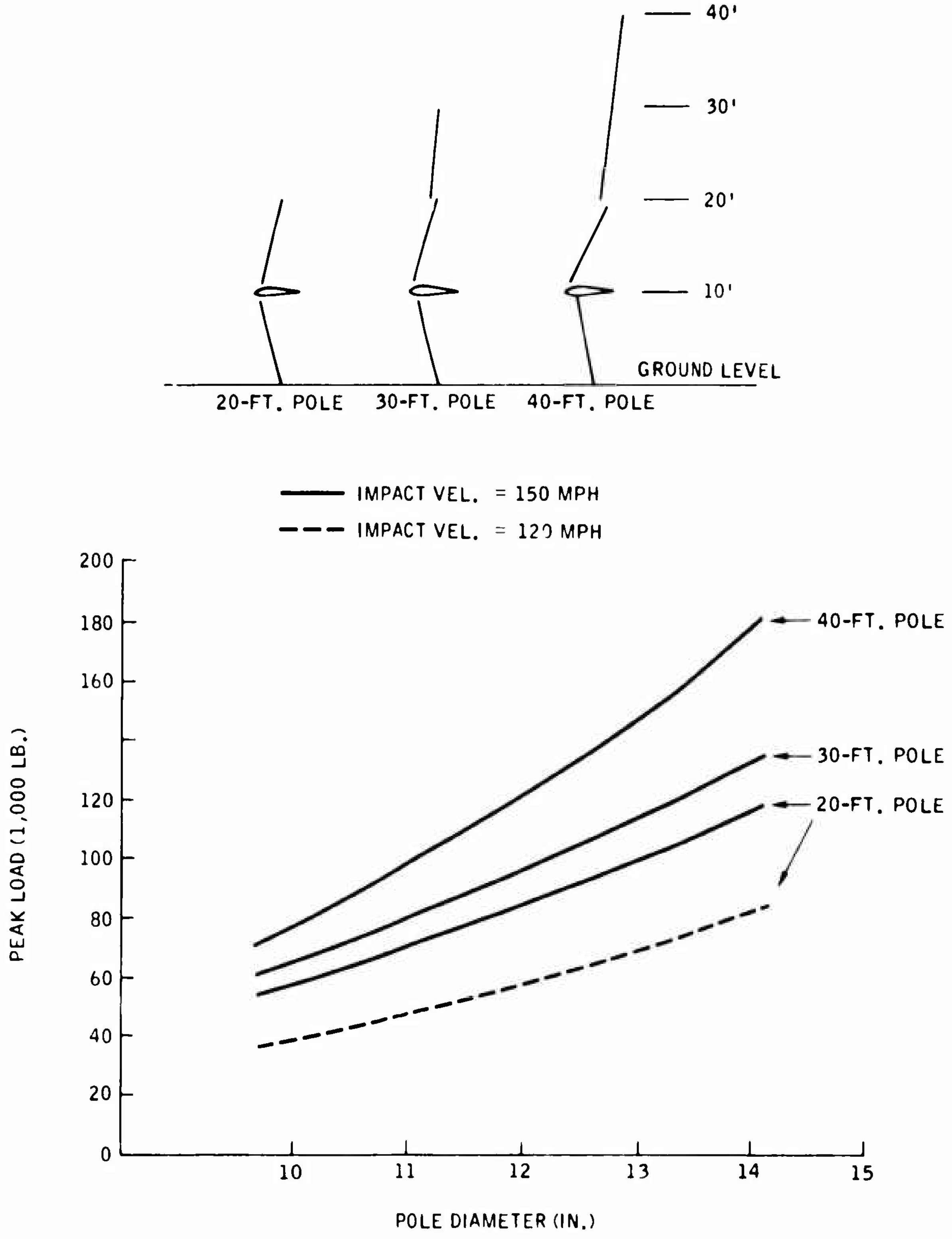


Figure A-1. Peak Loads Required to Cut Through Trees or Poles 10 Ft. Above Ground Level

Assumptions are:

a. $h = 20$ ft., 30 ft. & 40 ft., $\ell_2 = 10$ Ft., $D = 10$ in., 12 in. & 14 in.

b. $\rho = 50$ lb./ft.^{3}, $F_{BU} = 12,000$ psi, $F_{SU} = 1,000$ psi, $E = 1.3 \times 10^6$ psi

where ρ = pole density

F_{BU} = rupture stress

F_{SU} = ultimate shear stress

E = modulus of elasticity

c. $V = 120$ mph, 150 mph

d. Acceleration at the point of contact is constant from the time of impact until the wing is clear of all pole sections.

e. Aircraft wing spring rate is 75,000 lb./in.

f. Aerodynamic damping is negligible.

g. The section of pole attached to the root pivots about the root. All other sections have two degrees of freedom: (1) forward horizontally, and (2) rotation about the lateral c.g.

h. Maximum elongation of pole fibers during bending is 10%.

The energy balance is:

$$\begin{array}{c}\text{Change in Aircraft}\\ \text{Kinetic Energy}\end{array} = \begin{array}{c}\text{Wing}\\ \text{Deformation}\end{array} + \begin{array}{c}\text{Pole}\\ \text{Deformation}\end{array} + \begin{array}{c}\text{Change in Pole}\\ \text{Kinetic Energy}\end{array}$$

a. Calculations have shown that the change in aircraft kinetic energy is less than 1%. Pole linear and rotational acceleration loads are calculated in parts, the parts being; (1) acceleration of the complete pole during the primary failure at the point of impact, (2) acceleration of pole sections during secondary pole failure, and (3) acceleration of sections of pole still in contact with the aircraft after primary and secondary failure. The above when converted to energy is added to the energy expended in breaking the pole and in crushing the wing.

b. The load used in wing deformation calculations is the maximum load encountered whether that required to break the pole or that required to accelerate broken sections of pole.

c. The load required to break the pole (primary or secondary failure) is calculated from the conventional bending formula for a round cross section. This is a simplification at the point of impact where crushing and cutting of the pole occurs. The local crushing and cutting change the effective cross section of the pole and complicate the stress distribution pattern to the point where a rigorous analytical analysis is considered impractical. Pole breaking tests (Appendix B) have indicated that pole strength is reduced considerably as a result of crushing at the point of impact.

A. 1. 2 WING TIP GROUND CONTACT — The analysis assumes a gear-up airplane contacting the ground with one wing low. Pitch attitude is level or slightly nose-up. Crushing and wearing-off of the tip and outer wing will begin when contact is made with the ground and will progress along the wing until a fuel tank is opened, the wing is broken off, or the airplane is righted by the loads which are crumbling the outer wing.

The purposes of the study are to define the limits of roll attitude and descent rate beyond which the loads required to level the airplane will break off a wing or cause fuel spillage, and to evaluate means by which these limits can be increased. One means of increasing the limits is to move the fuel tanks inboard so that more structure can be crushed without spilling fuel. Righting loads will increase as the crushing progresses inboard; and additional time will be available for leveling the airplane. Another method of increasing the roll and descent limits is that of increasing the strength of the wing tip to provide larger airplane leveling loads.

The aircraft studied were a twin-engine 44,500-lb. straight-wing transport and a four-engine 148,000-lb. swept-wing jet transport. Desc nt angles up to 12° and roll angles up to 20° were considered.

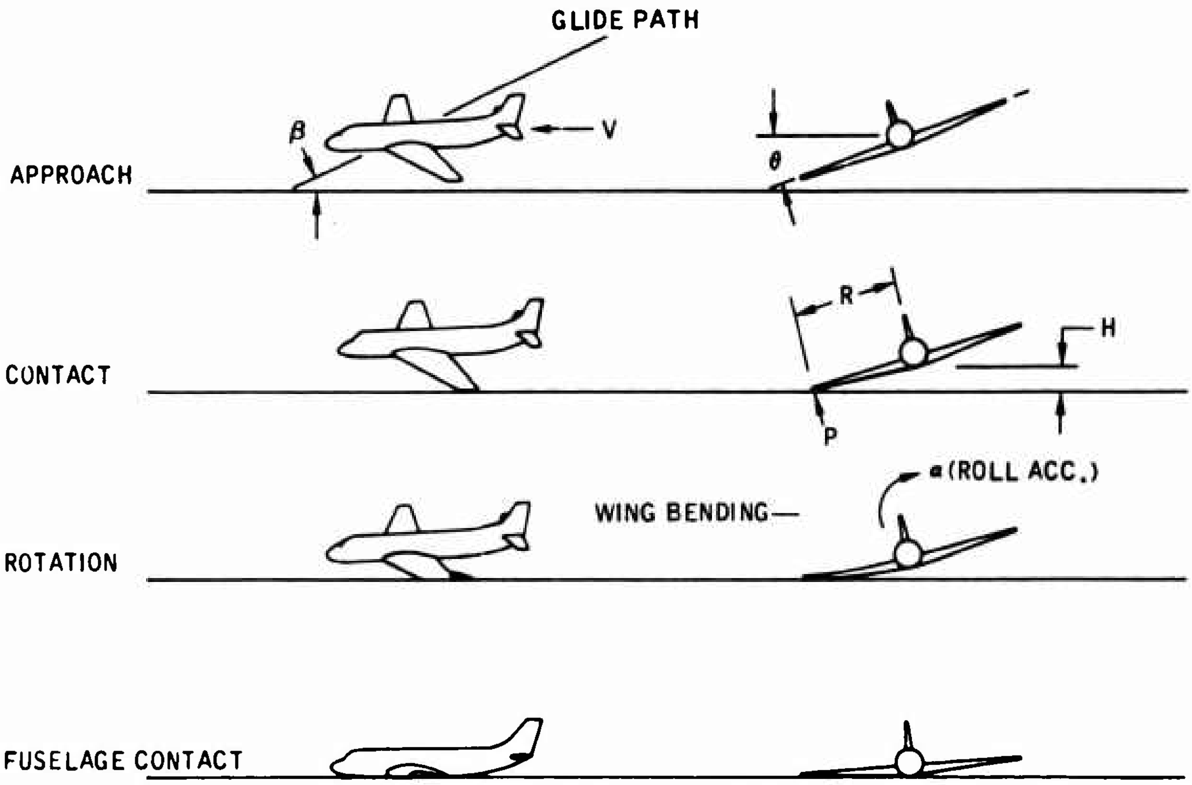
The general trends that became apparent during the study are perhaps more important than the actual numerical results. The most important factor in determining roll-angle limits is the wing flexibility of the airplane being considered. This is important for two reasons, the first and most obvious being that the wing will not break and spill fuel if it is bent out of the way. The second reason is that bending of the wing takes time — if a wing is to deflect several feet at the tip, the airplane must descend a similar distance and this descent takes time. The ground reaction will roll the airplane as a function of time squared while descent rate is a direct function of time. The actual bending of the wing is independent of descent rate (or angle of descent).

Another factor in determining roll angle limits is the amount of outer wing structure that can be crushed and worn away without affecting the fuel tanks. The crushable structure is significant in that the airplane can descend some distance without spilling fuel. At lower roll angles the wing will crush (and bend) until the fuselage contacts the ground and descent is terminated. Of equal importance is the fact that crushing the outer wing increases the time available to level the airplane.

For the two airplanes studied, wing bending is the predominate factor in determining roll limits. With the aircraft carrying fuel along the entire span of structural box, wing bending is the only significant factor. Time available for leveling the aircraft is severely limited by the amount of structure that can be crushed before a fuel tank is forced into the ground. Strengthening the outer wing does not change the available time greatly and, therefore has an insignificant effect. With the study airplanes carrying fuel along the entire span of structural box, fuel can be contained at roll attitudes of 10 to 12 degrees, independent of descent angle.

The study airplanes also were considered with no fuel carried outboard of the 80% semi-span location. In this condition, more structure is available for crushing and more time is available for leveling the airplanes. Wing bending is still the predominate factor. The study airplanes, carrying fuel out to 80% of their semi-span, can contain this fuel at roll attitudes up to 15 or 16 degrees at any descent path up to 12 degrees, which was the upper limit of the study.

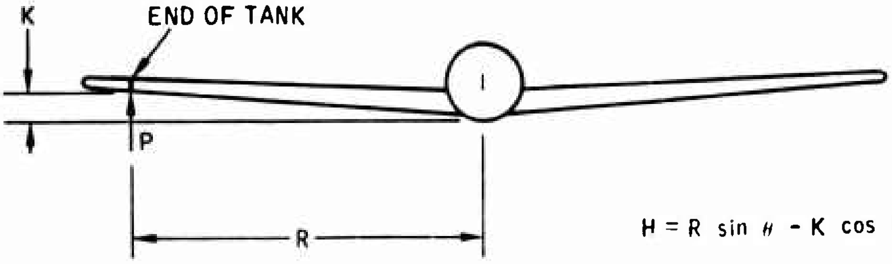
An outline of the method used in the study follows.



Rotating Moment, $T = PR = I_o \alpha$ where I_o is aircraft rolling mom of inertia

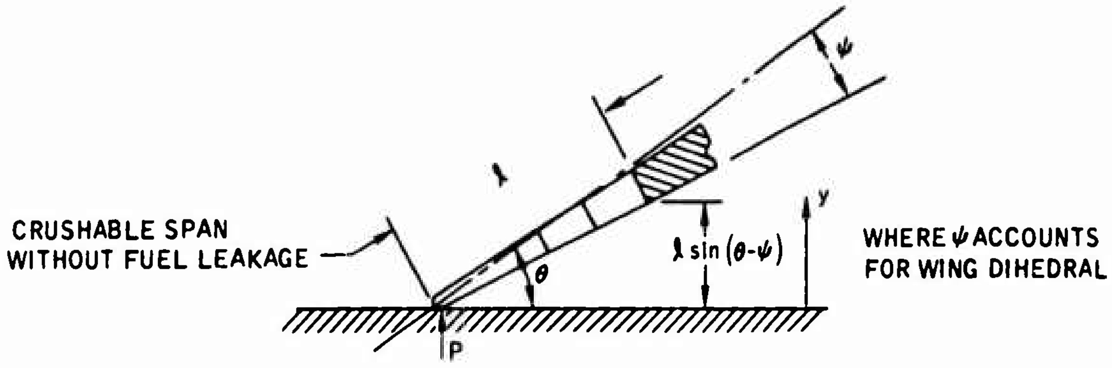
Rotating Acceleration, $\alpha = \frac{PR}{I_o}$

The load P is based on either the crushing strength of the outer wing or on the vertical bending strength of the entire wing. The load is first applied at the tip. It then moves inboard as the outer wing is crushed.

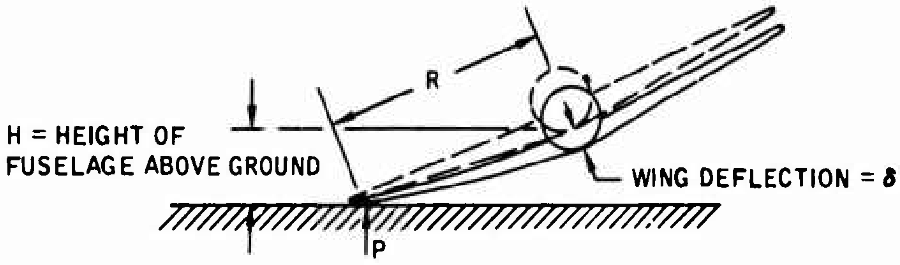


$H = R \sin \theta - K \cos \theta$ (Ref. Page A-7)

The vertical velocity of the airplane is V $\tan\beta$. The time available for rolling the airplane is $\frac{\Sigma y}{V \tan\beta}$. Where y includes the vertical components of wing bending, crushable span and roll (see sketches below).



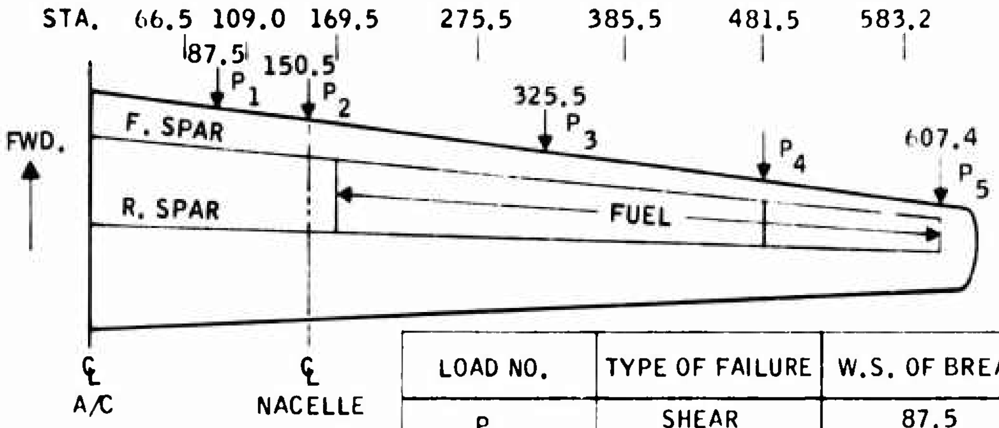
CRUSHABLE SPAN



WING BENDING

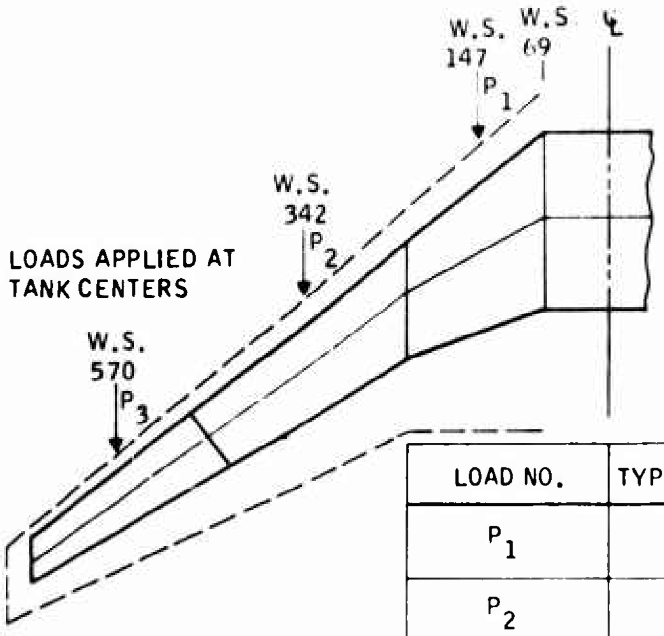
Note that P, R and S change as the tip region is ground away. I_o also varies slightly but for this study was assumed constant. If Σy is equal to or greater than H, the airplane will be righted sufficiently to prevent rupture of the fuel tanks.

A.1.3 WING STRENGTH — Figures A-2 and A-3 list the magnitude of concentrated aft load required to cause chordwise bending or shear failure of contemporary transport wings. Figure A-4 is a plot of the information shown in Figures A-2 and A-3.



LOAD NO.	TYPE OF FAILURE	W.S. OF BREAK	LOAD AMPLITUDE (LB.)
P_1	SHEAR BENDING	87.5 66.5	507,000 948,000
P_2	SHEAR BENDING	150.5 66.5	463,000 237,000
P_3	SHEAR BENDING	325.5 66.5	245,000 77,000
P_4	SHEAR BENDING	481.5 270.0	103,000 43,000
P_5	SHEAR BENDING	607.4 490.0	45,000 19,000
FULL-SPAN UNIFORM LOAD.	BENDING	66.5	103,000
HALF-SPAN UNIFORM LOAD.	BENDING	66.5	235,000

Figure A-2. Twin-Engine Transport Wing Chordwise Strength



LOAD NO.	TYPE OF FAILURE	W.S. OF BREAK	LOAD REQ. (LB.)
P_1	SHEAR BENDING	69 69	1,130,000 1,630,000
P_2	SHEAR BENDING	342 69	1,070,000 466,000
P_3	SHEAR BENDING	570 301	420,000 206,500
FULL-SPAN DISTR. LOAD	BENDING	69	500,000
HALF-SPAN DISTR. LOAD	BENDING	69	750,000

Figure A-3. Four-Engine Jet Transport Wing Chordwise Strength

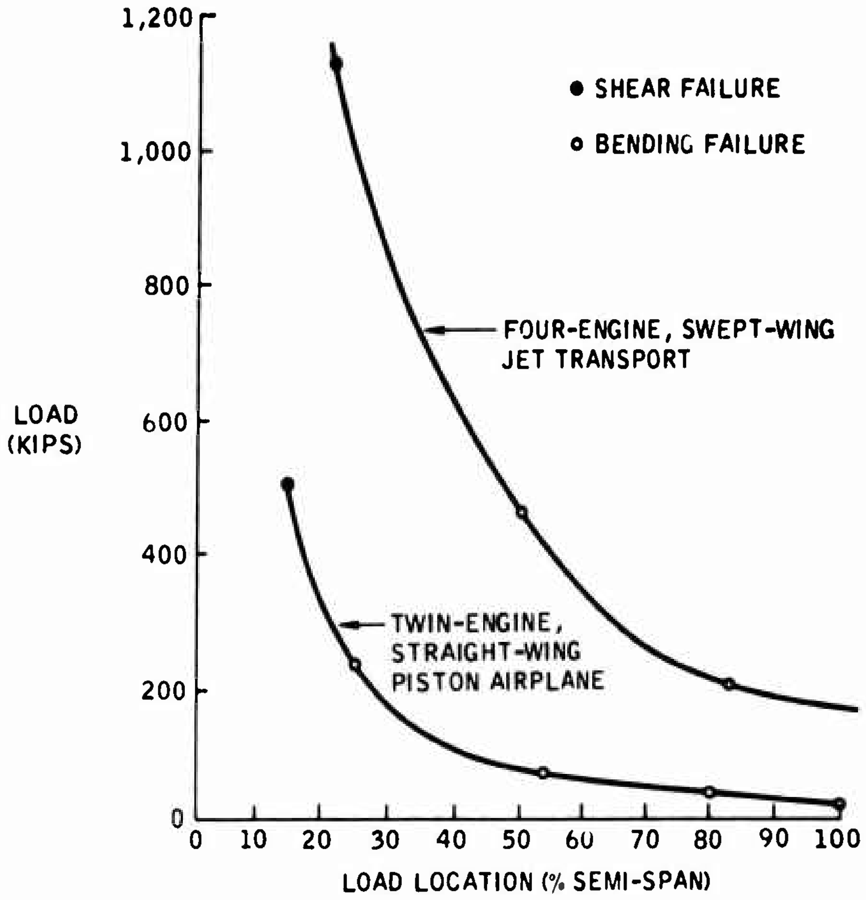


Figure A-4. Examples of Local Concentrated Loads Required to Fail Wings in Chordwise Shear or Bending

The loads shown, although indicative of over-all wing strength, may not be obtainable since:

a. Wing structure, even though designed to fuel containment principles, is seldom strong enough locally to sustain concentrated loads of the magnitude shown.

b. Few obstacles can present such concentrated resistance.

Therefore, when a wing hits something presenting a concentrated reaction, either the wing will be sliced through locally or the obstacle will be cut through. Good design for fuel containment will make the latter more probable.

Figures A-5 and A-6 indicate the relative strength-to-weight ratio for various configurations of skin panels just aft of the front spar. Panel size and skin

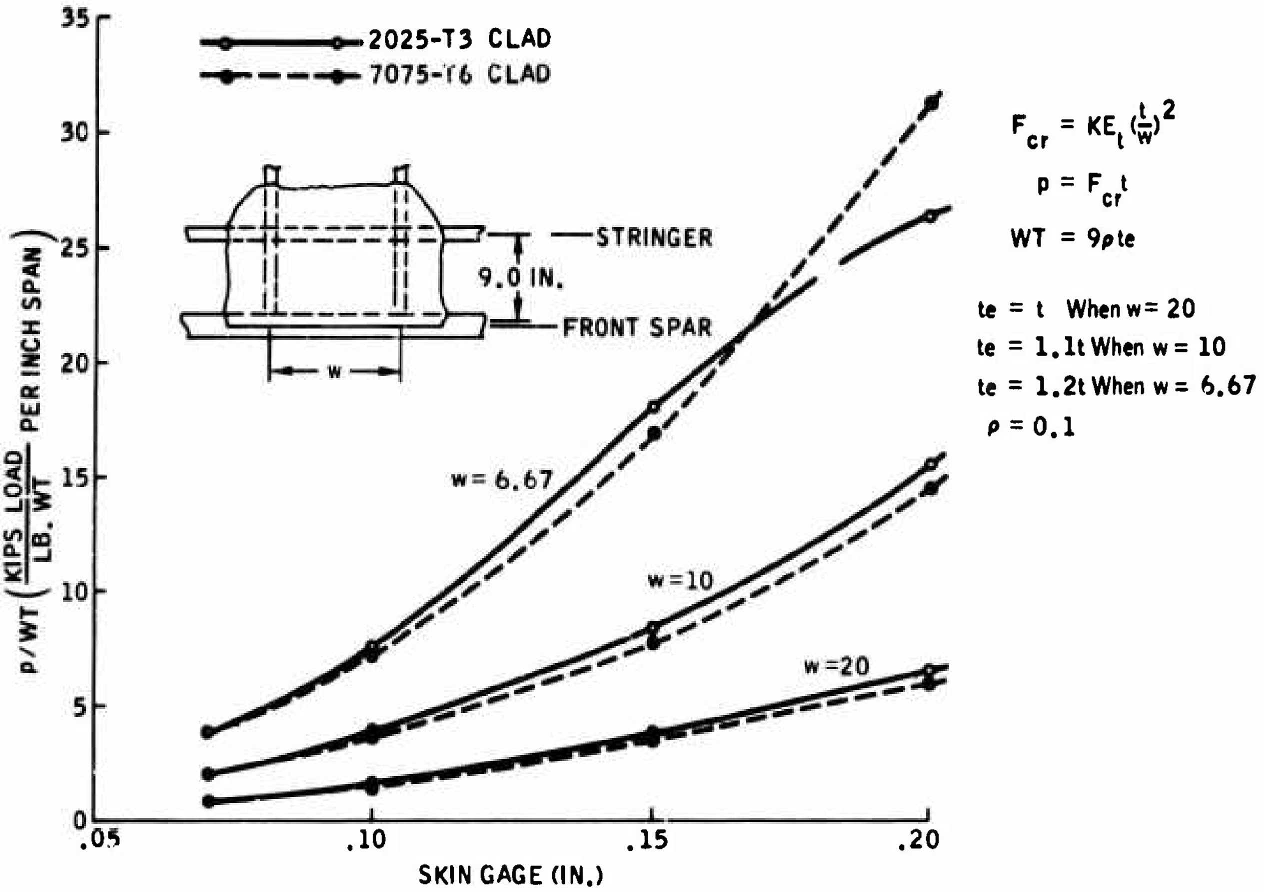
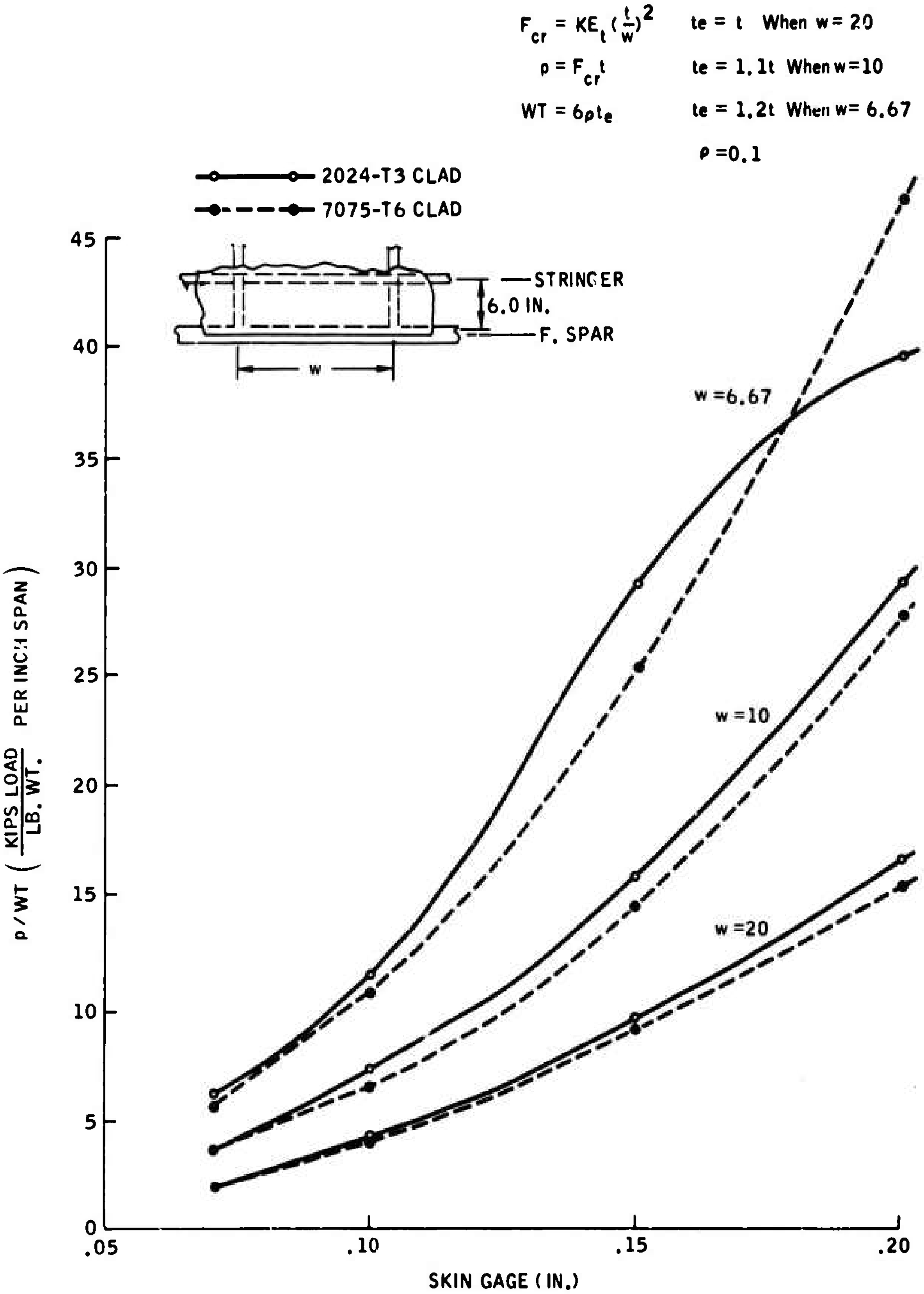


Figure A-5. Local Crushing — 9 Inch Stringer Spacing

thickness have been varied. These curves are included since the normal mode of failure during either concentrated or distributed impact loading is buckling and fracture of the skin just aft of the front spar cap coupled with pronounced bending and/or fracture of the spar caps.

A. 1. 4 DESIGN FEATURES FOR FUEL CONTAINMENT — The results of analytical work and tests involving conventional aircraft structure are summarized in Table A-I.



$F_{cr} = KE_t\left(\frac{t}{w}\right)^2$ te = t When w = 20

$p = F_{cr}t$ te = 1.1t When w=10

$WT = 6\rho t_e$ te = 1.2t When w= 6.67

$\rho = 0.1$

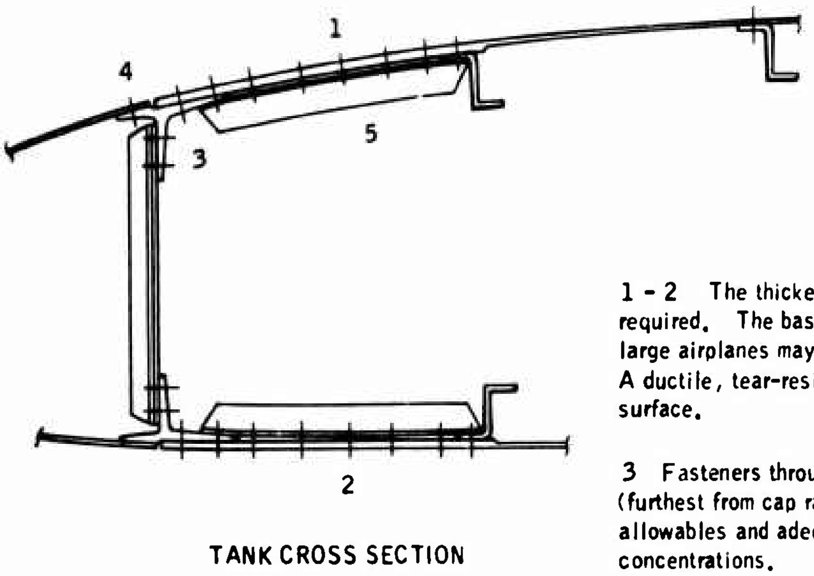
Figure A-6. Local Crushing — 6 Inch Stringer Spacing

Table A-I. Design Features for Fuel Containment

Impact Loading	Fuel Inertial Loading
a. Reinforced forward skin panels	a. Substructure designed to resist inertial fuel pressures
b. Adequate skin support structure	b. Adequate tension attachments
c. Ductile lower skin	c. Minimum number of hard points* in substructure
d. Energy absorbing wing tips	
e. Heavy front spar caps	
f. Minimum number of hard points	

*Hard points are caused by elements of structure that deflect relatively less than adjacent structure under crash loads. Such deflection discontinuities add local secondary stresses.

Some of the design features for fuel containment listed in Table A-I are illustrated in Figures A-7, A-8, and A-9. Design is conventional.



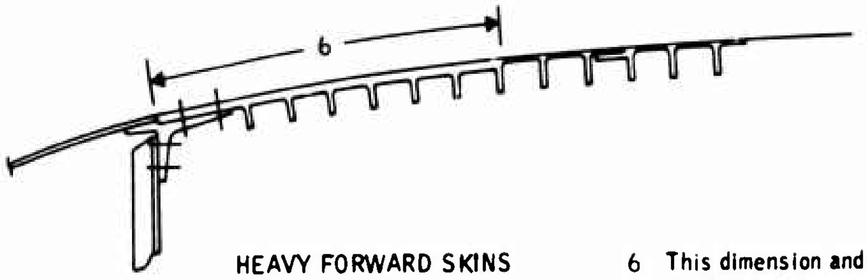
1 - 2 The thicker skin shown in these panels is not always required. The basic skins on the inboard wing sections of large airplanes may be adequate for anticipated impact loads. A ductile, tear-resistant material should be used on the lower surface.

3 Fasteners through spar caps, especially outer rows (furthest from cap radius), should have good tension allowables and adequate bearing area to reduce stress concentrations.

4 Cap material is usually dictated by primary flight loads. Additional cap material may be required in those designs having inadequate local bending strength to distribute concentrated impact loads.

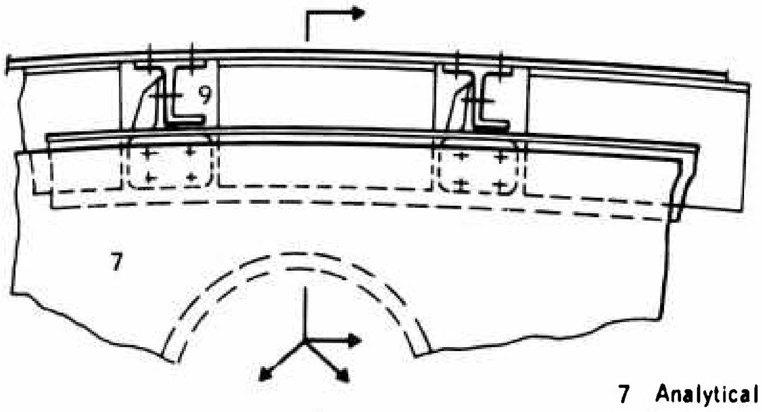
5 Stiffener spacing should be optimized for concentrated impact loading.

Figure A-7. Fuel Tank Design Features

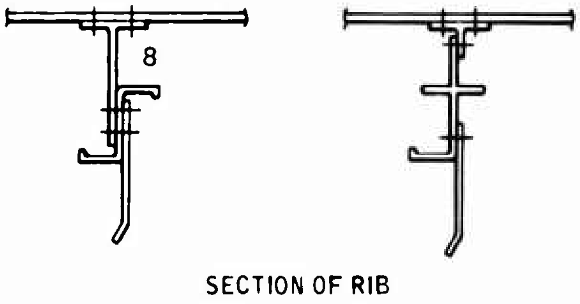


6 This dimension and the corresponding dimension in Figure A-7 is a function of the local bending and crushing strength required to distribute impact loads.

Figure A-8. Fuel Tank Design Features



OR



7 Analytical work and test results have shown that web-type ribs have greater crash resistance than truss-type ribs.

8 Tests and engineering analysis have indicated that full intercostaling (front spar to rear spar) is desirable. Intercostals should be designed for tension loads as well as shear.

9 All attachment patterns should be critically analyzed for crash conditions.

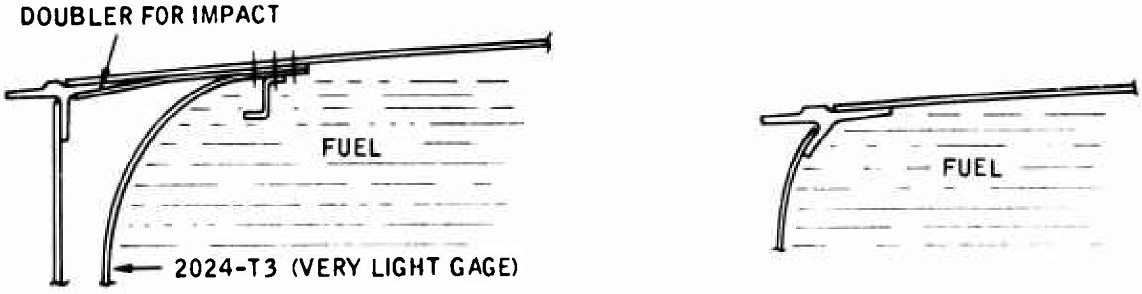
Figure A-9. Rib Design

A.2 FEASIBILITY STUDIES FOR FUEL CONTAINMENT

This section contains sketches of unconventional design features that could be considered during the early development stages of a new airplane. The notes accompanying the sketches list some advantages and disadvantages for each design.

The concepts shown in Figures A-10 through A-16 are based on the premise that the major fuel containment effort should be in the front spar and the skin panels just aft of the front spar.

Figures A-17 and A-18 illustrate two possible leading-edge tank protection devices. Weight added to the leading edge is usually "dead weight." That is; the strength of the wing box beam can seldom be decreased because of added leading edge strength.



ADVANTAGES:

1. High fuel inertial pressures can be contained in a light gage wing structure.
2. The front spar can be broken or punctured without necessarily spilling fuel.

DISADVANTAGES:

1. Lost volume for fuel is approximately 2%
2. Fuel sealing at the ribs is difficult
3. Manufacturing and inspection are complicated.

ADVANTAGES:

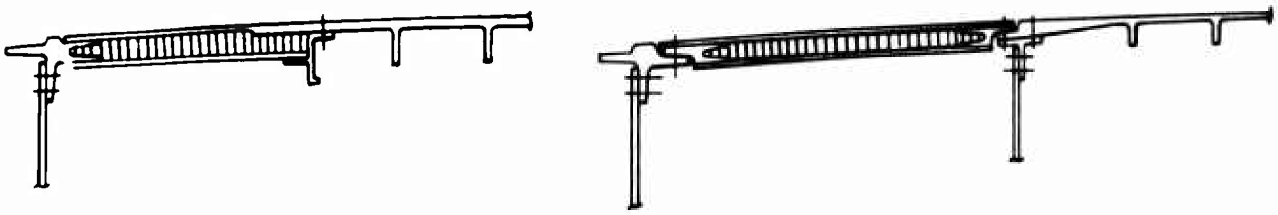
1. High fuel inertial pressures can be contained in a wing with light gage skins and spar webs.
2. The heavy spar cap furnishes good impact strength.

DISADVANTAGES:

1. Mating and riveting is difficult.
2. Rib design and web stiffening is complicated.
3. Front spar cap is heavy although usable as wing beam material.

NOTE: These concepts are primarily for those applications where the critical loading results from inertial fuel pressure.

Figure A-10. Front Spar Configurations



ADVANTAGES:

1. Good impact resistance.
2. Panels increase bending strength of wing box, therefore, over-all weight increase will be small.

DISADVANTAGES:

1. Curing problems add to manufacturing costs.
2. Manufacturing and maintenance costs are increased.

ADVANTAGES:

1. Same as at left.
2. Same as at left.
3. Panels can be removed.

DISADVANTAGES:

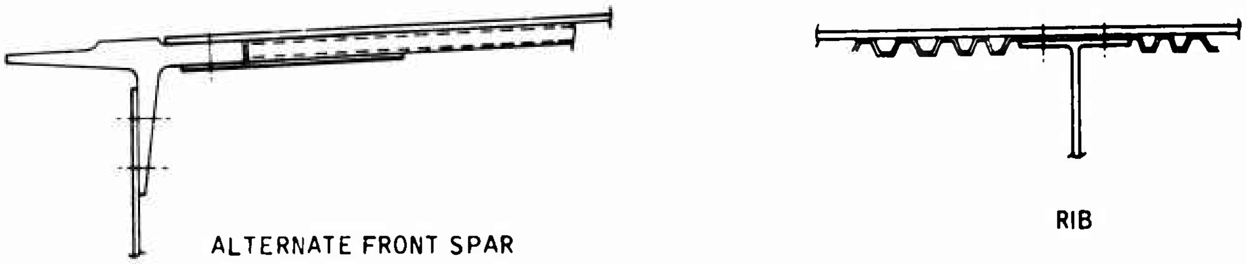
1. Manufacturing costs higher than machined skins.

NOTE: These designs have the common advantage of good impact resistance.

Figure A-11. Sandwich Construction in Forward Skin Panels

FRONT SPAR

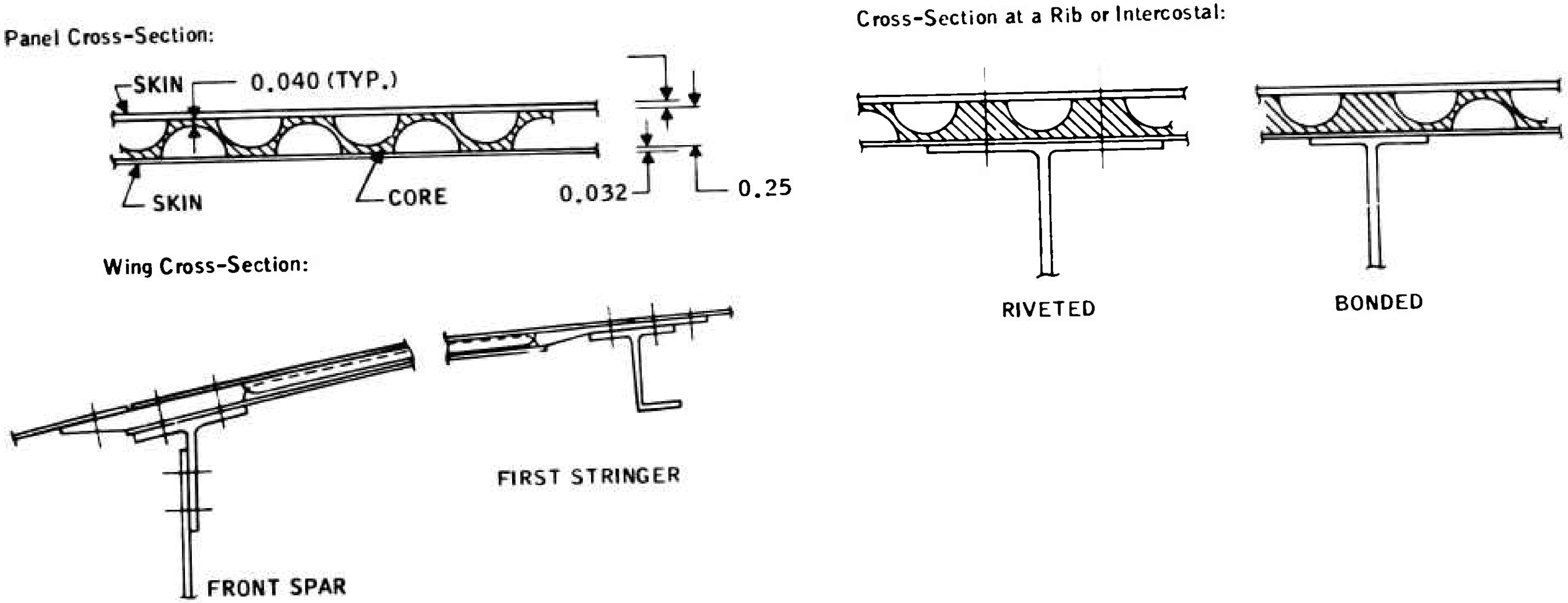
1st STRINGER



ALTERNATE FRONT SPAR

RIB

Figure A-12. Corrugated Skin Configuration


Panel Cross-Section:

Wing Cross-Section:

Cross-Section at a Rib or Intercostal:

MANUFACTURING PROCEDURE:

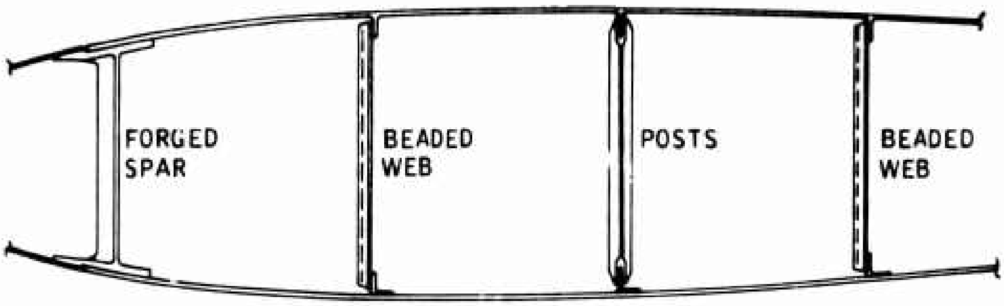
1. 1/4-In. thick 2024-SOplate is formed to wing surface contours.
2. Formed plate is heat treated and then machined.
3. 0.063 outer and 0.032 inner heat treated skins are bonded to core.

ESTIMATED WEIGHT AND STRENGTH (2024-T3 ALUMINUM ALLOY):

1. The weight per square inch of surface is approximately .017 psi.
2. The strength in the chordwise direction is approximately 10 times that of an equivalent weight, unstiffened, skin panel based on a panel size of 10-in. chord and 20-in. span.

NOTE: An imaginative designer could develop an efficient, practical fuel containment configuration, assuming definite design criteria.

Figure A-13. Sandwich Panel Study



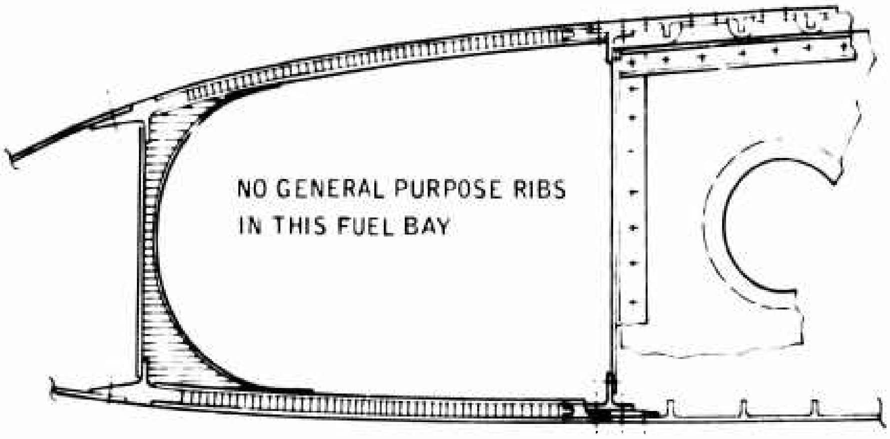
ADVANTAGES:

1. Multi-web design is inherently good for hitting posts or trees and for sliding over rocks or hard ground since the skins are thicker than on other types of construction.
2. The beaded web just aft of the front spar gives a compartmentation effect by hindering fuel movement. Note that this possible advantage may not hold for highly swept wings.

DISADVANTAGES:

1. The shear strength between the upper and lower skins is limited because of the very large rib spacing usually found in multi-web configurations. A large load on the lower surface (such as that encountered while plowing through soft earth or possibly while ditching) will tend to collapse the lower skin aft with respect to the upper surface.
2. Design allows less deviation from original layout since cutouts and local load concentrations cannot be accommodated efficiently.

Figure A-14. Multi-web Post Configuration



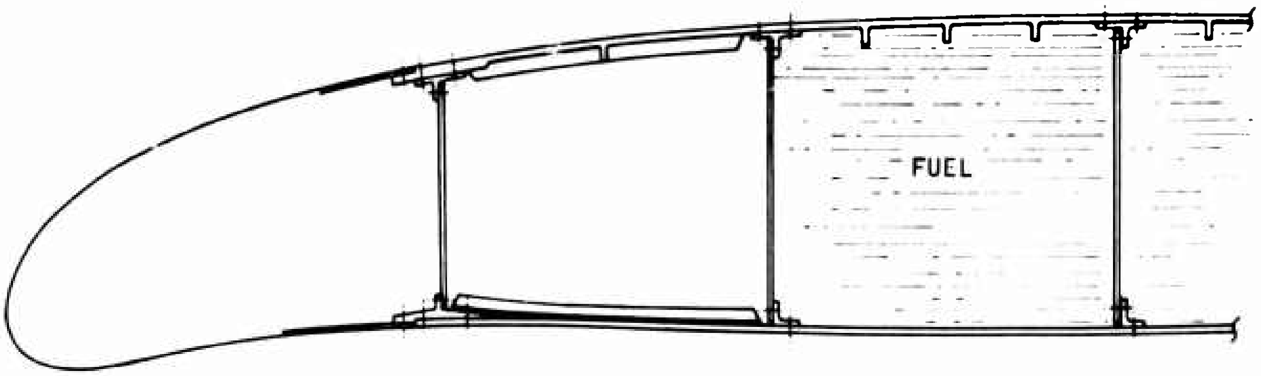
ADVANTAGES:

1. Good design for most crash-type loadings
2. The added weight is structural. The effect on over-all wing weight is therefore lessened.

DISADVANTAGES:

1. Design and fabrication is complex.
2. Manufacturing and maintenance inspection is difficult.

Figure A-15. Bolt-on Bonded Forward Bay



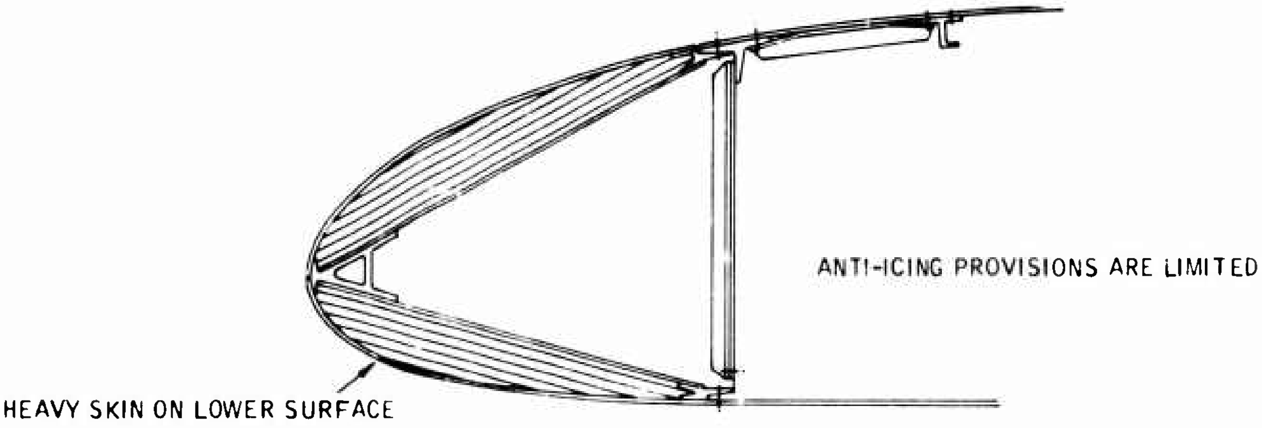
ADVANTAGES:

1. Impact in the front spar region is less critical
2. The added material is structural.

DISADVANTAGES:

1. Extra machining and inherent waste material add to the cost of the configuration shown.

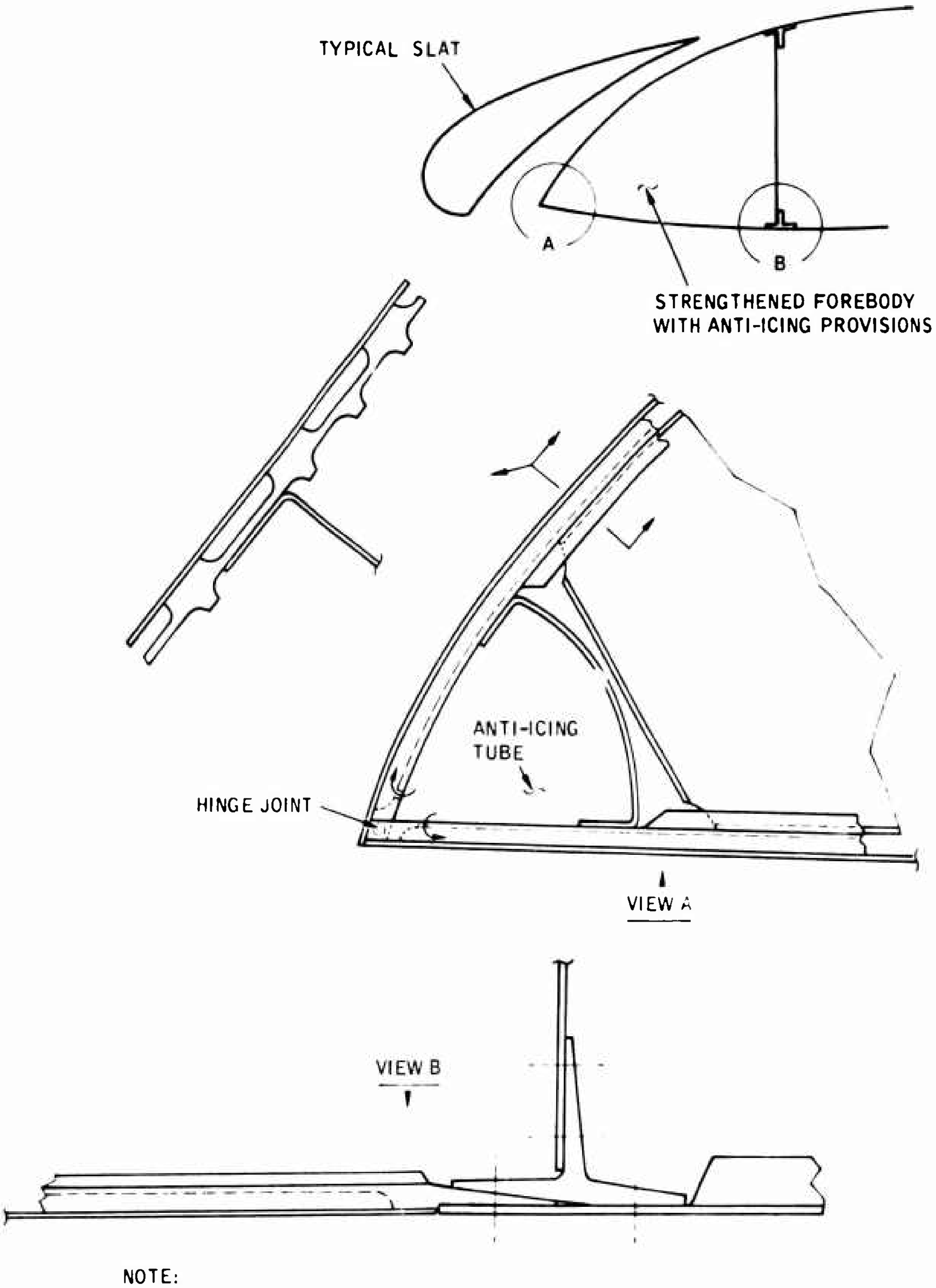
Figure A-16. Fuel Containment for Delta Wings When Fuel Space is Not Critical



NOTE:

1. Any weight added to the leading edge is dead weight. Leading edges seldom add to the strength of the wing box. Even a structural leading edge can add little to the bending strength of the wing.
2. If leading edge lift devices are used, the problem becomes one of protecting the front spar from puncture by leading edge elements rather than of the leading edge protecting the wing fuel tanks.
3. Any leading-edge protection device which absorbs impact loads must be backed up by substantial main box structure to distribute the loads.
4. Anti-icing provisions are limited if the leading edge protection devices are incorporated in an already crowded area.

Figure A-17. Leading Edge Tank Protection Devices (A)



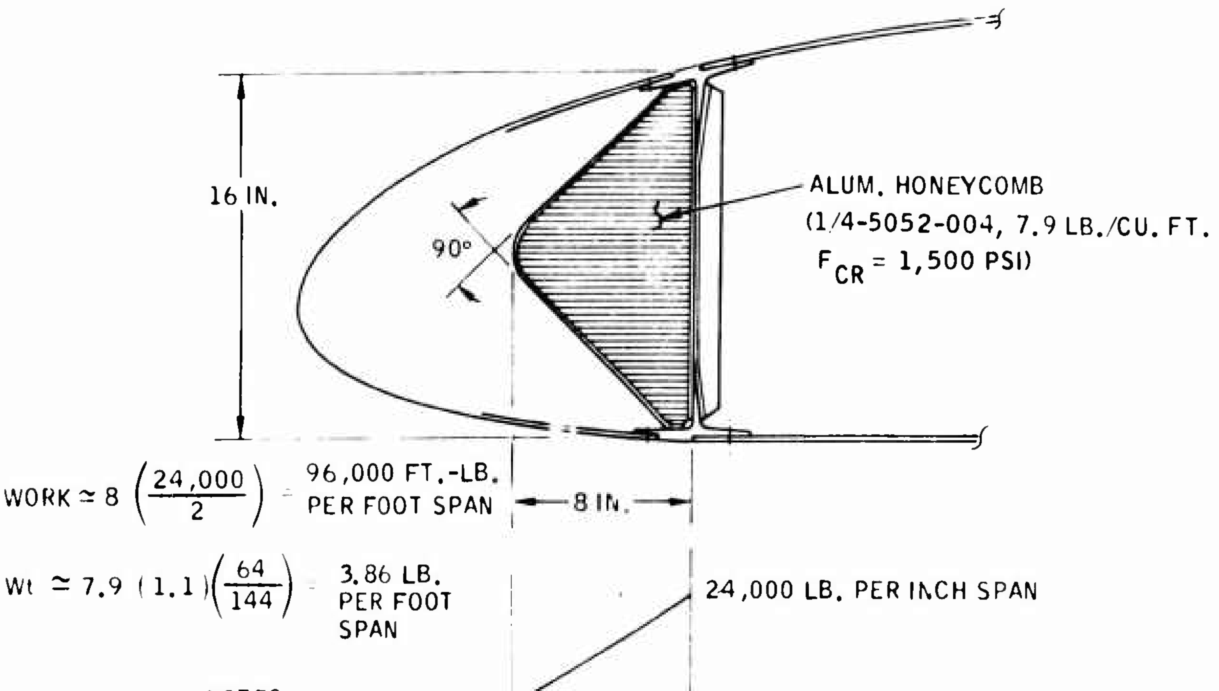
NOTE:

In this arrangement, that part of the leading edge aft of the slat is strengthened for impact loading. Provisions for anti-icing are included.

Figure A-18. Leading Edge Tank Protection Devices (B)

Several energy absorbing schemes for wing fuel tanks are sketched in Figures A-19 through A-24. Note that many of these devices do not absorb energy without some fuel spillage. Note also that the energy absorbed is negligible. The devices do, however, act as shock relievers. An object struck by the wing must be accelerated out of the way. The acceleration, and therefore impact load, will be lower with an energy absorbing device because of the greater available acceleration distance.

The important parameter in any fuel dump study is the rate of flow. Figure A-25 gives some insight into the difficulty of getting rid of fuel in a hurry. A 1,000-gal. rectangular tank measuring 18 in. x 100 in. x 128 in. was drained by a single, round, unlipped hole in the center of the bottom wall. Hole diameter was varied and the time to drain the tank was calculated for each size hole. The assumed coefficient of discharge was 0.6. Flow losses to the hole were neglected. The results are, therefore quite optimistic.



$$\text{WORK} \simeq 8\left(\frac{24{,}000}{2}\right) = \text{96,000 FT.-LB. PER FOOT SPAN}$$

$$\text{Wt} \simeq 7.9\,(1.1)\left(\frac{64}{144}\right) = \text{3.86 LB. PER FOOT SPAN}$$

NOTES:

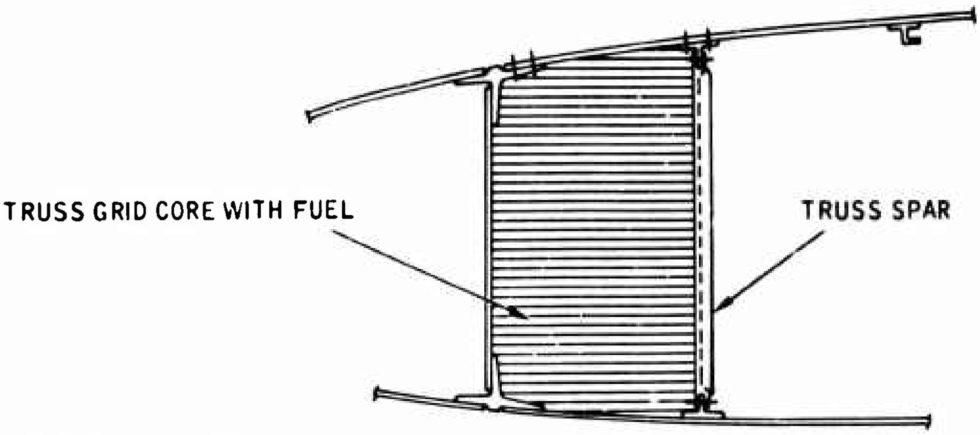
1. Ribs and/or skin must be strengthened to distribute high local loads.
2. Spar must be inspected from inside.
3. Anti-icing and high-lift devices are space limited.
4. There must be local interruptions of core for actuators, tracks, plumbing, etc.

Figure A-19. Energy-Absorbing Structures (A)

ASSUMING 4 LB./CU.FT. CORE AND 16 IN. x 10 IN. BAY SIZE

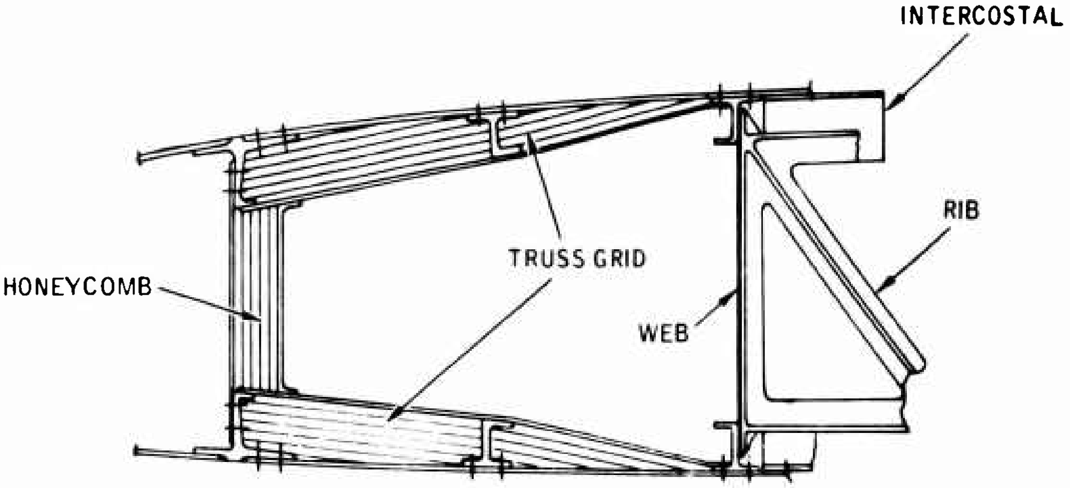
$$\text{Wt.} = 4\left(\frac{16 \times 10}{144}\right) = 4.44 \text{ LB. PER FT. OF SPAN}$$

$$\text{FUEL LOSS} = \left(\frac{4(100)}{0.1(1728)}\right) = 2.32\% \text{ OF BAY WITH CORE } (0.1 - 0.2\% \text{ OF TOTAL FUEL})$$



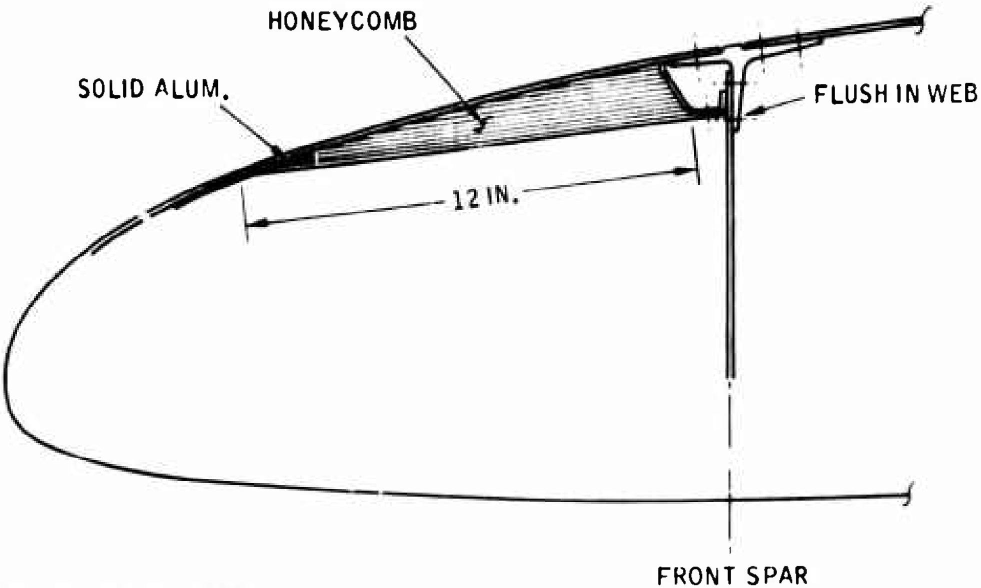
NOTES:
1. Tank purging is difficult.
2. Bacterial growth problem is compounded unless core is fiberglass.
3. Fuel may still pour out after a crash but fire can only burn as fast as fuel is supplied.
4. Bond to skins is critical for distributing impact loads.
5. Crushing energy is more than double that of configuration shown in Figure A-19, and onset rate is higher.

Figure A-20. Energy-Absorbing Structures (B)



NOTES:
1. The truss grid sandwich is energy-absorbing. The honeycomb serves as "wadding" for partial sealing during crushing of the truss grid structure.
2. All material is structural.
3. With perforated sandwich structure, fuel loss is minimized but maintenance is compounded. Therefore, it seems advantageous to seal the tank at the inner faces of the sandwich.
4. Rib design in the forward bay is complicated but number of ribs can be kept small since skins are stabilized.

Figure A-21. Energy-Absorbing Structures (C)



CRUSHING OF CORE ≃ 1,500 psi

WITH AN AVERAGE THICKNESS = 1 IN.

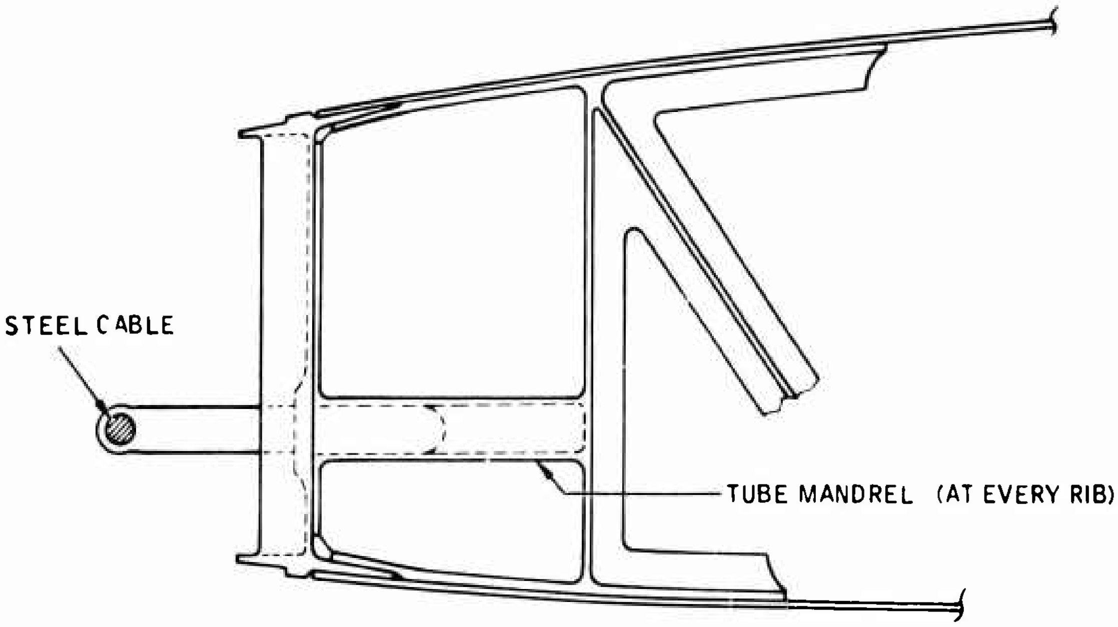
p = 2 (1,500) = 3,000 LB./IN.

WORK = 3,000(1) = 3,000 FT.-LB./IN. SPAN

FOR A 1 FT. SPAN:

WORK = 36,000 LB.- INSIGNIFICANT!

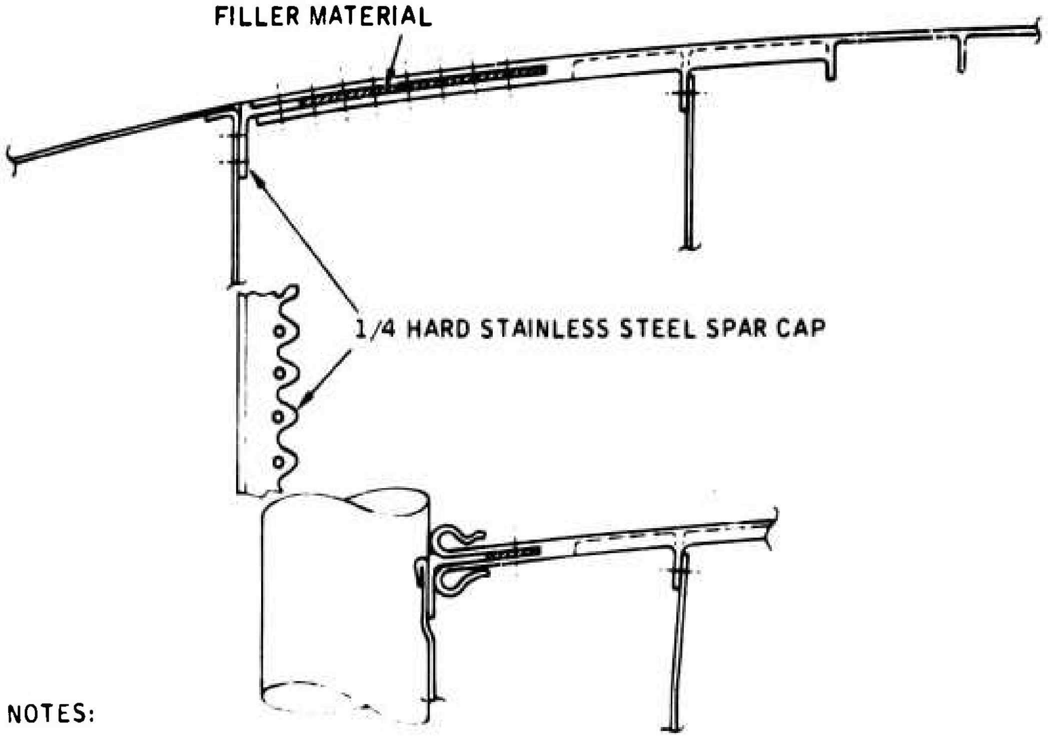
Figure A-22. Energy-Absorbing Structures (D)



NOTE:

This design is restricted to cutting down trees or poles. The added weight cannot increase the basic strength of the wing and, therefore, is dead weight.

Figure A-23. Energy-Absorbing Structures (E)



NOTES:

1. This design can absorb impact loads and energies comparable to the design shown in Figure A-19.
2. All weight except for the filler is structural in wing bending.
3. The design is difficult if the failure pattern shown is to be foolproof.

Figure A-24. Energy-Absorbing Structures (F)

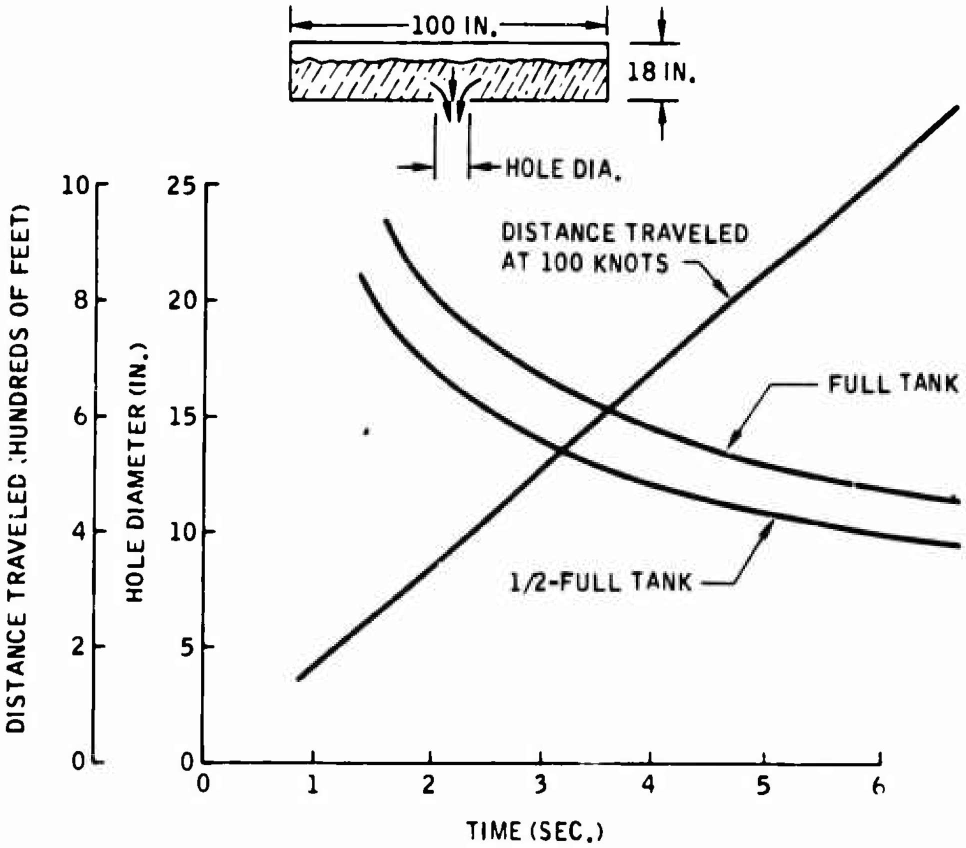


Figure A-25. Time to Empty a 1,000-Gal. Wing Tank Through a Round Unlipped Hole

BLANK PAGE

APPENDIX B | FUEL CONTAINMENT TEST PROGRAM

The fuel containment test program consisted of a series of simple spar rail bending tests followed by a series of swing tests on box sections representative of typical wing integral fuel tanks.

B.1 SPAR RAIL BENDING TESTS

B.1.1 TEST SETUP AND TEST SPECIMENS — A study was made of front spar design details that would increase the ability of a fuel tank to withstand internal pressures. The principal assumption was that the tank would balloon out enough for membrane stresses to become dominant. The purpose of the experimental effort was to check the validity of the study results. The testing consisted of static bending of various front spar rail sections.

Three-foot lengths of sheet aluminum with gages representative of wing skins and front spar webs were riveted (or bolted) to short sections of extruded angles. The specimens represented a narrow (approximately three inch) span of wing that included spar web, spar cap and skin. The specimens were pulled in a testing machine (Figure B-1), inducing tension and bending in the angle simulating the spar rail — an effect similar to that experienced by a fuel tank when internal fuel pressures "balloon" the tank.

B.1.2 TEST RESULTS — Seventeen specimens were pulled until failure. Results indicated that the higher strength 7075-T6 rail material appears better from a load-capacity standpoint than the more ductile 2024-T4. Load was applied slowly during these tests and results might have been different had the loading been applied suddenly. Some experimenters (Ref. 36) believe that, for gradually applied loads, stress resistance (ultimate allowable stress) is the criterion that establishes the strength of a structure and that fracture toughness (the total area under the stress-strain curve) determines the strength of a structure under suddenly applied loads. However, these tests indicate that the ultimate allowable tensile stress of a material is the gage of its ability to contain internal pressures under a membrane type loading. The following design details which promote the containment of high internal pressures also were demonstrated by the spar rail bending tests:

a. The front spar web should be on the forward side of the spar cap vertical leg.

b. Web and skin attachments to spar caps must have good tension allowables.

c. Symmetry of gages in the front spar region should be a design goal.

Note that swing test results and analytical work have indicated that the above membrane-type pressure loading is seldom the most critical design condition.

B. 2 SWING TEST RESULTS

B. 2. 1 TEST SETUP — The swing test was a pendulum action with a 6-ft. section of fuel tank being hoisted along a 50-ft. arc to a given height and then allowed to swing free on suspension straps to the low point of the arc (Figure B-2). At this low point, the tank was arrested either by energy absorbing straps (Figures B-3 and B-4), or impacted against some obstacle such as a section of telephone pole (Figures B-5 and B-6) or an inclined bank (Figure B-7). Each method of stopping the tank simulated some kind of loading that might be experienced by the fuel tanks of an airplane during a crash.

B. 2. 2 TEST SPECIMENS — All specimens had a 6-ft. span, 4-ft. chord and 16-in. constant depth. One-and one-fourth inch thick aluminum plates closed off the ends of the tanks and furnished pickup points for the suspension straps, arresting hooks, and the hoist point. All tanks were sealed by joint filleting with EC 1293 compound. Fuel in the tanks was simulated with water.

Six tank specimens were tested. Tanks 1 and 2 were of simplified construction with very light truss ribs and no stringers. Tanks 3 through 6 were representative of wing structure found in a four-engine jet transport, with varying amounts of strengthening to withstand impact loads. Tank No. 3 had no reinforcing and closely represented typical wing structure. Tank No. 4 included external doublers between the front spar rail and first stringer aft. Tanks 5 and 6 were identical and differed from Tank 4 in that the ribs were web type and fully intercostaled to the skins and the front spar to first stringer doublers were sandwiched between the spar rail and skin and extended the full length of the tank (end plate to end plate). A more detailed description of these specimens is given in Table B-I. Figures B-10, B-16, and B-34 are photographs of the interiors of Tanks 1, 3 and 5. All specimens were fabricated from aluminum alloy and all structural design was conventional.

B. 2. 3 INSTRUMENTATION — The tanks were instrumented to record deceleration and fuel pressure vs. time. Deceleration was measured by two Statham C-50-120 accelerometers having a linear range of ±50g and a flat response of 0-330 cps. One accelerometer was mounted on the right-hand end plate (Figure B-5) on the forward edge of the door cutout. The other was mounted on the rear spar of the tank at the tank centerline. Deceleration was measured only in the direction of travel.

Water pressure was measured with a CEC 4-312 strain gage pressure transducer having a linear range to 50 psi with a flat response from 0 to 120 cps. The transducer was mounted in a hole in the right-hand end plate (Figure B-5) with the transducer diaphram recessed in the end plate. The diaphram was mounted normal to the direction of deceleration.

The accelerometers and pressure transducer were excited by Pacific Telemetry carrier amplifiers capable of 2, 000 cps response. The amplifiers were shock-mounted on the tank in the vicinity of the rear spar (Figure B-7). The amplifiers were supplied with regulated 28v dc which in turn supplied the transducer and accelerometers with 10 kc carrier signals.

The amplifier output signals were directly proportional to the transducer (or accelerometer) output and were used to frequency modulate IRIG voltage-controlled oscillators which were mounted about 120 ft. from the amplifier. The VCO frequency was 22K cps modulated ±7.5% giving a data frequency response of 330 cps. The VCO modulated output then was recorded on a DEC Datatape magnetic tape recorder (Figure B-8) with a tape speed of 15 in./sec. Loads required to stop the swinging tanks also were measured as a function of time.

Tank arresting loads were measured by two strain gaged links in the arresting strap arrangement (Figures B-3 and B-4). Each link was gaged with four 350 ohm, bonded wire, resistance strain gages. The gages were mounted and wired into a full bridge in a manner that measured axial loads only. The links were calibrated in a universal test machine. Precision shunt resistors were used to correlate calibration data with test data.

Tank-log impact loads were measured by a load platform to which the section of log had been bolted (Figure B-5). The platform was supported by four steel ring dynamometers, one at each corner. The ring dynamometers were strain-gaged and oriented so that all side loads were cancelled and only loads normal to the platform were measured. Each ring dynamometer contained four 60 ohm, bonded wire, resistant strain gages. The gages were wired into a full bridge in a manner to average the output of the four dynamometers. The platform, with log in place, was calibrated in a universal test machine at various attitudes and positions of symmetry. Precision shunt resistors were used to correlate calibration data with actual test data.

Maximum tank velocity also was measured during the first few tests. The measuring setup involved two microswitch trip levers located a known distance apart along the path of tank movement (Figure B-9). The instant of trip was recorded on the oscillograph trace as a function of time. Results from early tests indicated that the actual velocity was very near the calculated velocity assuming no aerodynamic or friction damping. All data was presented as calibrated oscillograph traces against a vertical grid of lines representing 0.01 sec. of time by the system shown in Figure B-8. Data samples are shown in Figures B-39 through B-50.

B.2.4 LOG IMPACT TESTS — In these tests, tank specimens were impacted against sections of a large-diameter telephone pole (Figure B-5) mounted on a strain-gaged platform dynamometer which measured impact load versus time. Other instrumentation recorded tank deceleration and fuel pressure versus time. All specimens except Tank No. 6 were eventually ruptured by this test method.

A summary of log impact test results is shown in Table B-II. Note that rupturing loads varied from 34,000 lb. for Tank No. 1 to 97,500 lb. for Tank No. 5. Peak g loading varied from 14.4 to 58.5 for the same tanks. It is felt that the higher g loading produced unduly severe internal pressures that damaged the internal tank structure to a degree that the allowable impact loads were lowered. Maximum fuel pressures, including slosh effects, encountered during survivable crashes of transport aircraft are expected to be considerably less than those experienced during these tests.

B.2.5 ARRESTED STOP TESTS — In these tests, tank specimens were arrested at the low point of their swing by energy-absorbing stainless steel straps. A hook arrangement attached to the end plates of the tanks (Figure B-3) picked up linkage (including the stainless steel straps) that was anchored to the floor of the test building. The linkage was instrumented to record load versus time. Other instrumentation, mounted in the end plates or on the test specimen, recorded deceleration and fuel pressure versus time.

Arrested drop tests were conducted on each of the first five tank specimens (Table B-I). Drop height varied from 5 ft. to a maximum of 36-1/3 ft. Maximum loading experienced during the 36-1/3-ft. drop was 44.8 g and 45.4 psi. This maximum loading test was made with Tank No. 4. Tank damage resulting from arrested stop tests usually was confined to the interior of the tank. This damage often was extensive (Figure B-23). Note from Figure B-23 that deflections were large — two of the rib diagonals ended up on the opposite side of the rib rail to which they had been attached. Although 16-mm, high-speed movies and post-test still photographs indicate very large tank wall deflections and extensive internal damage, fuel leakage usually was very slight; the exception was Drop No. 18 from 36-1/3 ft. In this test, six rivets along a rib intercostal near the rear spar failed in tension and fuel leaked through the rivet holes (Figure B-20).

The large "ballooning" deflections noted above affect the fuel pressures resulting from deceleration. The recorded fuel pressures are therefore lower than the calculated fuel head static pressures based purely upon deceleration.

B.2.6 INCLINED MOUND IMPACT TESTS — In these tests, Tank No. 6 was impacted against 30-degree slopes of either sand or sand and rock. Nine drops, from heights of 5 to 25 ft., were made against a contained sand pile (Figure B-7) that was comparatively dry for five drops (5 to 15 ft. drop heights) and very wet for four drops (15 to 25 ft. drop heights). Five drops, from heights of 5 to 25 ft., were made against a similar pile of sand and rock of a mixture of 50-50. Rock size was 1-1/2 in. diameter. The tank was 3/4 full of water.

Specimen performance against the three types of inclined surface was very similar. Stopping distance was quite large, amounting to more than a chord length for all drops from higher than 15 ft. The specimen tended to pitch up as the stopping distance increased with the maximum pitchup estimated at 20 degrees. In all cases, the recorded deceleration built up to a rounded peak and then dropped off gradually (Figure B-47). Pressure built up gradually as deceleration increased; then as deceleration dropped off, it abruptly peaked as the sloshing fuel was stopped by the front spar. The time to maximum g loading was approximately 0.026 sec. with the time to maximum recorded pressure of 0.05 to 0.08 sec., decreasing with impact velocity. Total stopping time was about the same (0.11 sec.) for all drops. A study of peak decelerations and pressures (Table II) also indicates little difference between impacting against the three simulated soils. For example, at the 15-ft. drop height level, the peak recorded fuel pressures were 18.0, 21.7 and 24.1 psi for dry sand, wet sand and moist sand-rock. Maximum recorded pressure was 28.9 psi for a 25-ft. drop against sand-rock.

The only damage to the specimen was a flattened leading edge. Testing was suspended at the 25-ft. drop height level since: (1) a loading pattern appeared to have been established, (2) significant loading changes were unlikely from the higher available drop heights, and (3) the specimen could be profitably used for the following test series.

B.2.7 POLE BREAKING TESTS — In these tests, Tank No. 6 was impacted against lengths of telephone pole and piling which were simply supported at both ends (Figure B-6). Span between supports was seven feet with the impact point at midspan. A sand-gravel pile served to stop the tank after it had passed through the pole.

Pole sections were 8-ft. lengths cut from tapered telephone poles and piling. In the first series, six sections of Grade A used western pine telephone pole were broken. Pole diameter at midspan varied from 6.6 to 13.8 in. Next, a 16.5-in.-diameter section of red cedar used telephone pole was broken. The final series used freshly treated Douglas fir piling. The piling was cut into six, eight-foot lengths with diameters at midspan varying from 13.2 to 17.4 in. All poles were broken without significant tank damage. As shown in Table II, maximum recorded decelerations was 54.6 g and maximum recorded pressure was 38.4 psi.

After the above series, a log was buried in the sand-gravel pile such that an end would face the falling test tank. The log, lying horizontal in the sand, was placed at a height that would allow the lower spar cap to strike the center of the end of the log. The buried log was a 40-in. length of the 14.8-in. diameter Douglas fir piling and the tank drop height was 35 ft. As expected, the lower spar rail split the log lengthwise. Half remained buried in the sand under the tank while the other half buried in the tank, pushing a section of leading edge and front spar web back to the rear spar.

Before the above tests were begun, a static bending test was made of a section of the western pine telephone pole. The specimen was 4-1/2 ft. long with a midspan diameter of 7.1 in. Rupture stress was 7,470 psi. At this stress level, the static load required to break the 17.4-in. diameter pole would have been 221,000 lb. Log impact tests (Section B.2.4) indicate that the tank would fail at an impact load of approximately 100,000 lb. Since the tank did not fail during the pole breaking tests, it is believed that the poles may not act as homogeneous cylindrical sections, but split lengthwise in shear to form individual bending sections whose cumulative strength was less than that of a homogeneous cylindrical section. Also the impact area of the spar rails against the pole was small and the bearing stress greatly exceeded the allowable stress for cross-grain compression. This loading may have contributed significantly to failure of the poles.

The above tests differ from actual airplane-telephone pole impact conditions in several ways:

a. Test impact velocity was rather low (27.3 mph). The load required to accelerate a large section of pole and push it out of the way may be as large as that required to break the pole.

b. Pole sections were short, requiring larger loads to produce failure.

c. Pole support (simple support at both ends) was not representative of actual support.

d. Leading edge of the tank was normal to the pole. Most aircraft have some degree of front spar sweep which should help to tear and cut a pole or tree.

Test results do, however, give an indication of the great strength that can be built into an aircraft wing.

B. 2. 8 FUEL SLOSH TESTS — The results of eight drop tests can be applied to the evaluation of slosh effects (Table B-III). Five of these tests were log impacts (Section B. 2. 4) and three were arrested stops (Section B. 2. 5). Drops were made with 1/2 full, 3/4 full and full tanks. Tank specimens were similar, the main difference being that some specimens used truss-type ribs and others had web-type ribs. All impact tests were completely compatible concerning specimen configuration.

Impact test results were conclusive in demonstrating that the full-tank condition is more critical than that of the partially filled tank (Table B-III and Figure B-50).

Arrested stop tests also demonstrated that a full tank condition is critical although the tests were complicated by inconsistencies in tank velocity and structural stiffness. Figure B-49 shows instrumentation traces of arresting load and fuel pressure versus time for the three tests. The slosh effects on pressure are shown quite clearly for 1/2-full and 3/4-full tanks. Both of these tests were made with tanks that were much stiffer structurally than the tank used for the full fuel condition. Note also that the energy input level for the 3/4-full test was double that for the other two, causing relatively higher pressure pulses for the 3/4-full test.

B. 2. 9 INTERPRETATION OF TEST RESULTS — Containment of fuel pressures resulting from deceleration does not appear to be a critical design condition for tanks which also must be designed to cut through trees and plow through dirt and rocks. However, design features which delay breakup of tank support structure due to internal pressure, also promote resistance to concentrated or distributed impact loading by (1) maintaining tank shape, (2) by supporting the walls for buckling loads, and (3) by redistributing the loads. The tests indicated the importance of the following design features for delaying breakup of internal structure due to inertial fuel pressures:

a. Provide attachments which develop the full strength of all structural components. For example, in the design of a truss bulkhead, rivets of sufficient size and number should be used to develop the full tension strength of the bulkhead diagonals.

b. Rib to skin structure (intercostals) should be designed for pressure loads (tension) as well as the usual shear loads.

c. Web-type ribs resist large internal pressures better than truss-type ribs.

It is desirable that wing fuel tanks not rupture under the effects of impact loads having sufficient magnitude to tear the wing from the aircraft. The tests and analysis indicated that, for concentrated impact loads on conventional structure, such a goal is not obtainable without large weight increases. However, other tests (pole breaking) have indicated that many large obstacles can be cleared from the path of the fuel tanks by wings with reasonable strengthening. Some of these features, in order of importance as indicated by the tests, are:

a. The skin-stringer panels just aft of the front spar caps must be stiffened in a chordwise direction to act as a good foundation for the front spar caps which usually serve as the first firm contact against an obstacle. This is best done by increasing the local skin gage.

b. Skin support structure such as stringers, intercostals and ribs should hold the skins in place under internal inertial pressures.

c. The front spar caps should be strengthened, primarily by making the fore and aft legs thicker and wider.

d. Local "hard spots" in the skin support structure should be avoided (Figures B-18 and B-24).

The inclined mound tests have indicated that a wing fuel tank designed for concentrated impact loading will also effectively resist distributed impact. One fact not demonstrated by the tests is that wing tanks may be more susceptible to puncture during distributed impact loading.

The tests also indicated that fuel slosh was not critical within the bounds of the test parameters. The tests, however, cannot be extrapolated to state that fuel slosh is never a critical design condition. For a given deceleration, slosh becomes more important as chord and kinetic energy are increased. Other factors such as wing sweep, tank stiffness and baffling (ribs, etc.) also affect slosh loads.

B. 2. 10 TEST SPECIMEN WEIGHT COMPARISON — The No. 3 test tank design was similar to the wing of a four-engine jet transport. The basic tank design was strengthened locally as weaknesses showed up during the test program. Total weight added in the final design of Tank No. 6 was 28 lb. Considering that the structural box of a wing may be two-thirds of the total wing dry weight, the above 28-lb. increase amounts to approximately a 10% wing weight increase. The added structure, in this case, was not a minimum weight design. For example:

a. The doublers added to the skins just aft of the front spar would ordinarily be integral with the skin and therefore be lighter and more efficient. The doublers, which accounted for 16 lb. of the weight increase, add significantly to the primary bending strength of the wing box. This weight, therefore, serves a double purpose — most of the weight added here can be recovered elsewhere.

b. When the ribs were changed from the truss type to the web type, no lightening holes were cut in the webs. The test specimen ribs were reinforced for much higher pressures than would be anticipated for a complete airplane. Thus, the weight increase for ribs in the test specimens is quite conservative.

A reasonable wing weight increase for maximum fuel containment might be 3%. Substantial increases in fuel containment potential can be obtained for 1 or 2% weight increases.

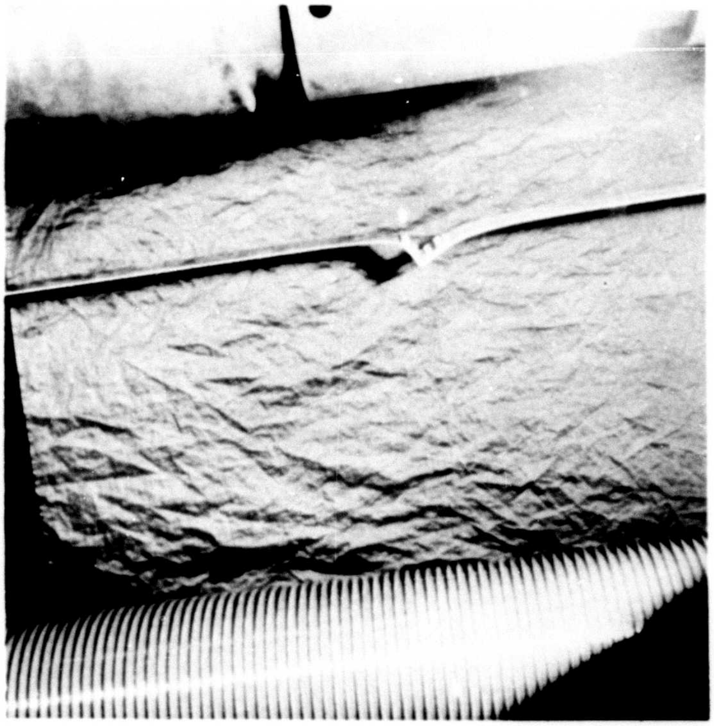


Figure B-1. Spar Rail Bending Tests. Specimens were pulled in tension until failure.

Figure B-2. Swing Test Setup. Tank specimens were suspended by 50-ft. straps. Specimens were arrested by stainless steel straps or were impacted against a log, pole, or sand.

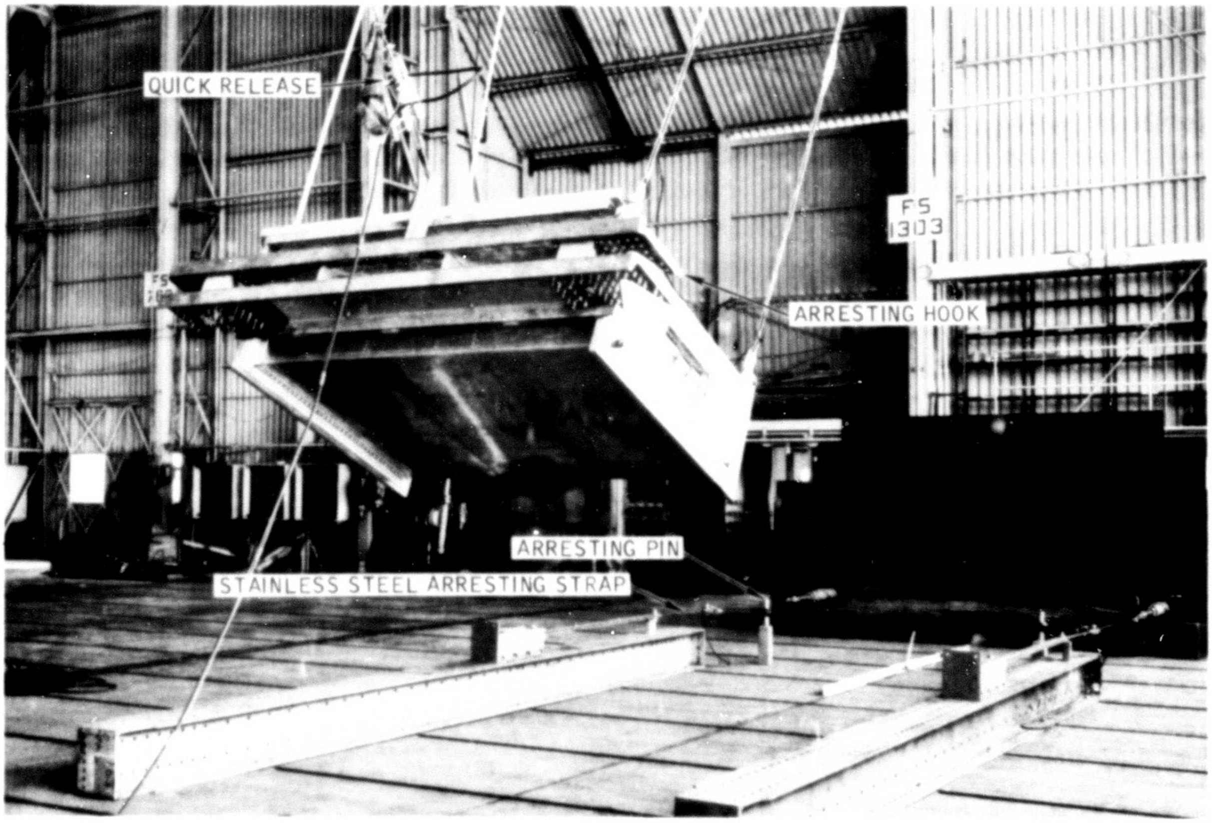


Figure B-3. Arrested Stop Arrangement. Hooks attached to tank specimens caught pin-ended links that included stainless steel arresting straps. Straps were stretched to approximately 120% of their original length during the stop (10 to 20 in. elongation).

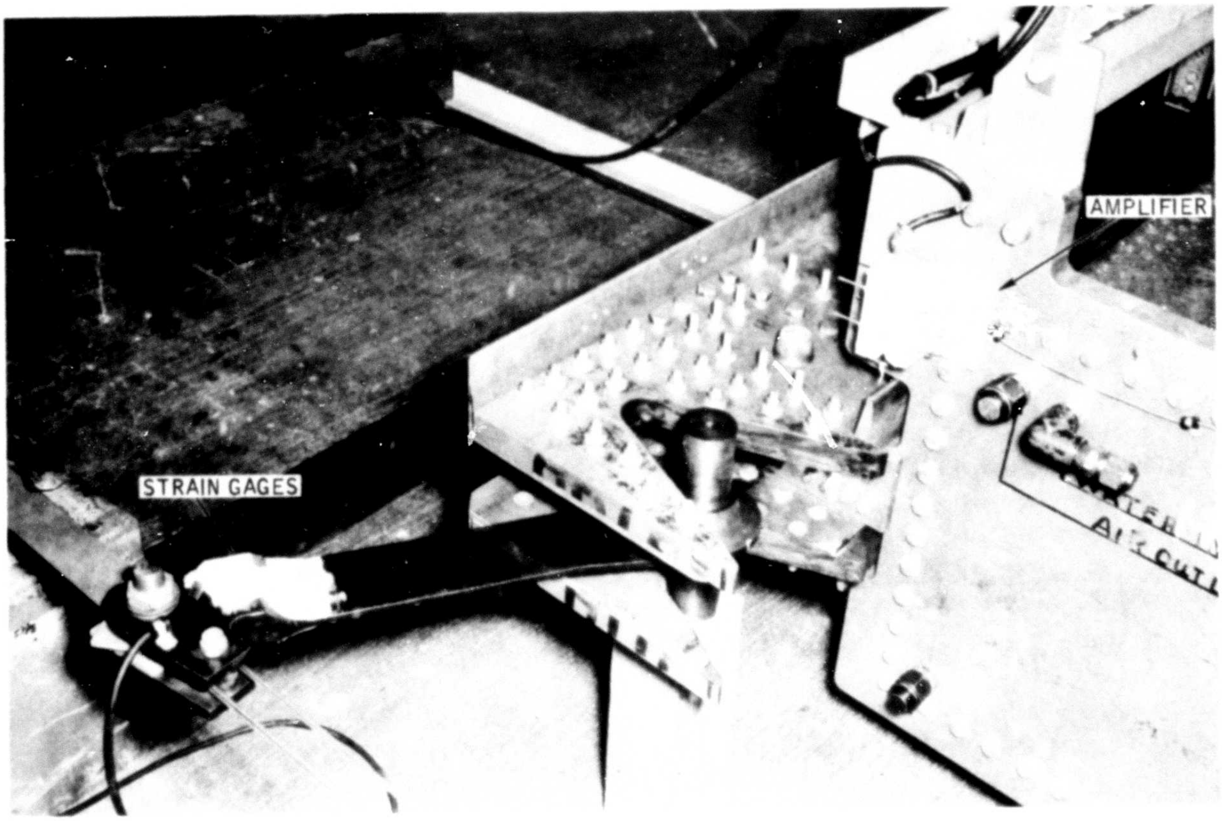


Figure B-4. Hook and Pin Arresting Apparatus. Note strain-gage installation on link.

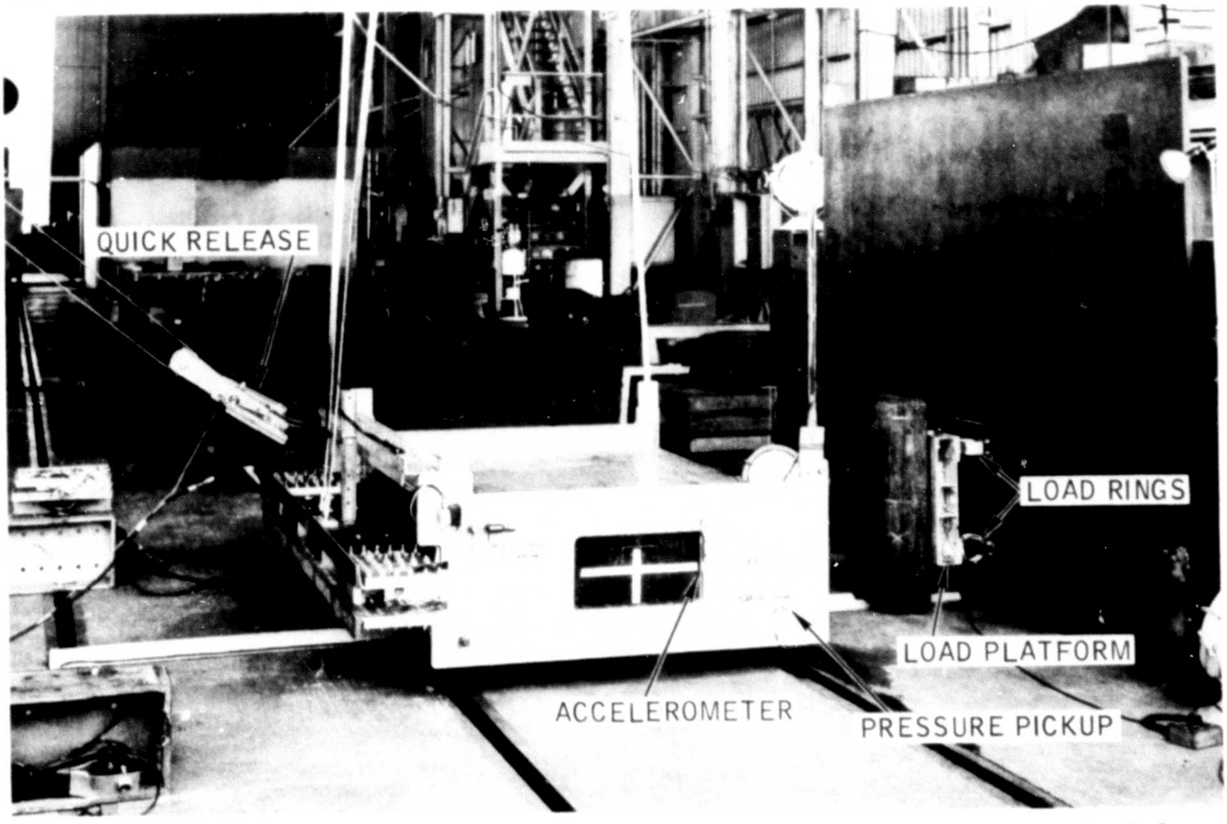


Figure B-5. Log Impact Arrangement. Note aluminum platform to which log is bolted; calibrated strain rings support platform.

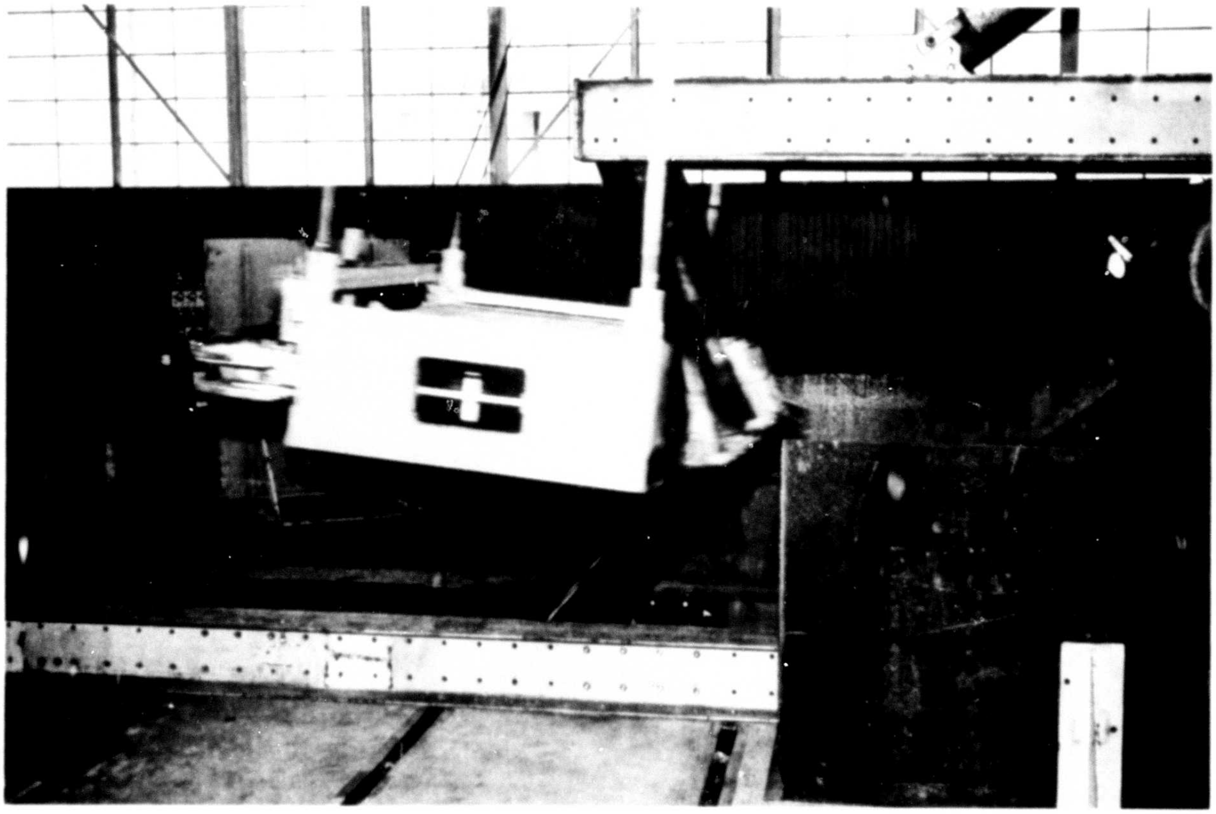


Figure B-6. Pole Breaking Test. Tank speciment breaks an 8-ft. section of pole supported at both ends.

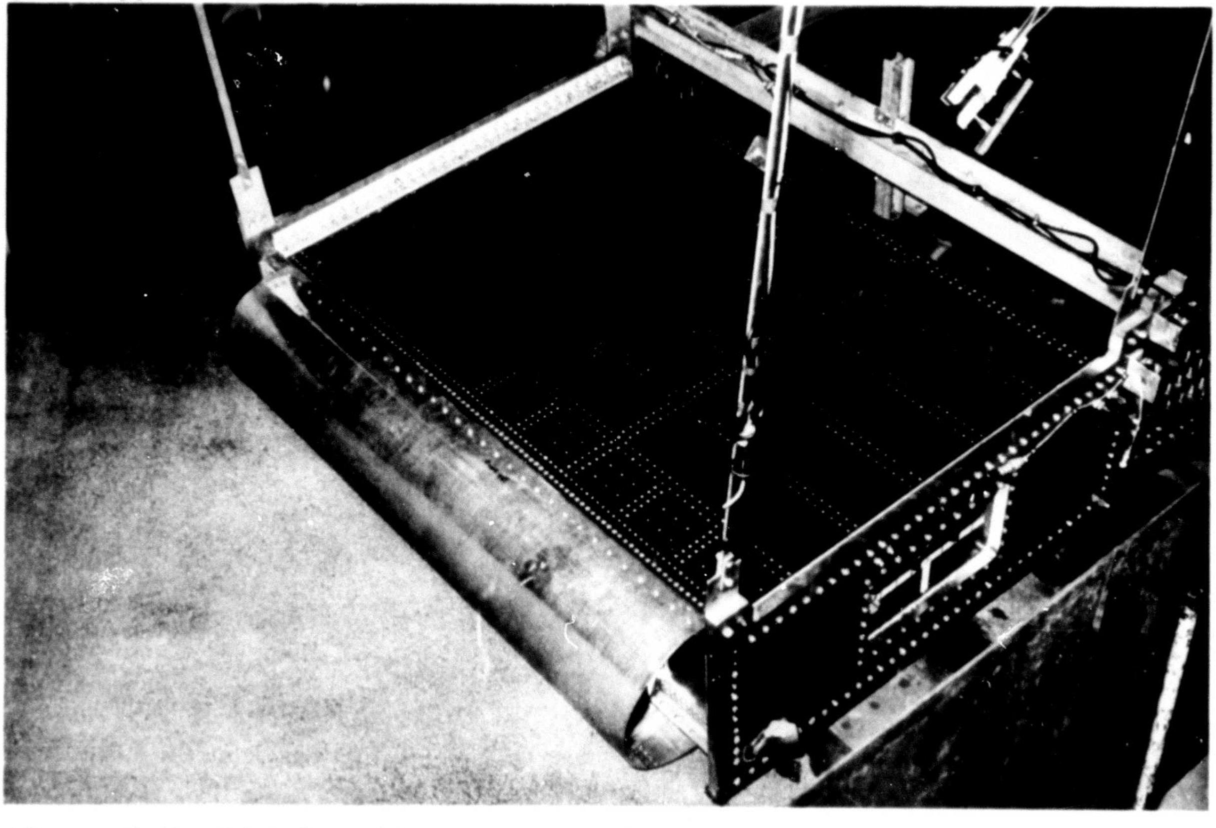


Figure B-7. Distributed Impact. Mound was arranged on a 30-deg. slope; impact against piles of dry and wet sand and sand/rock were compared.

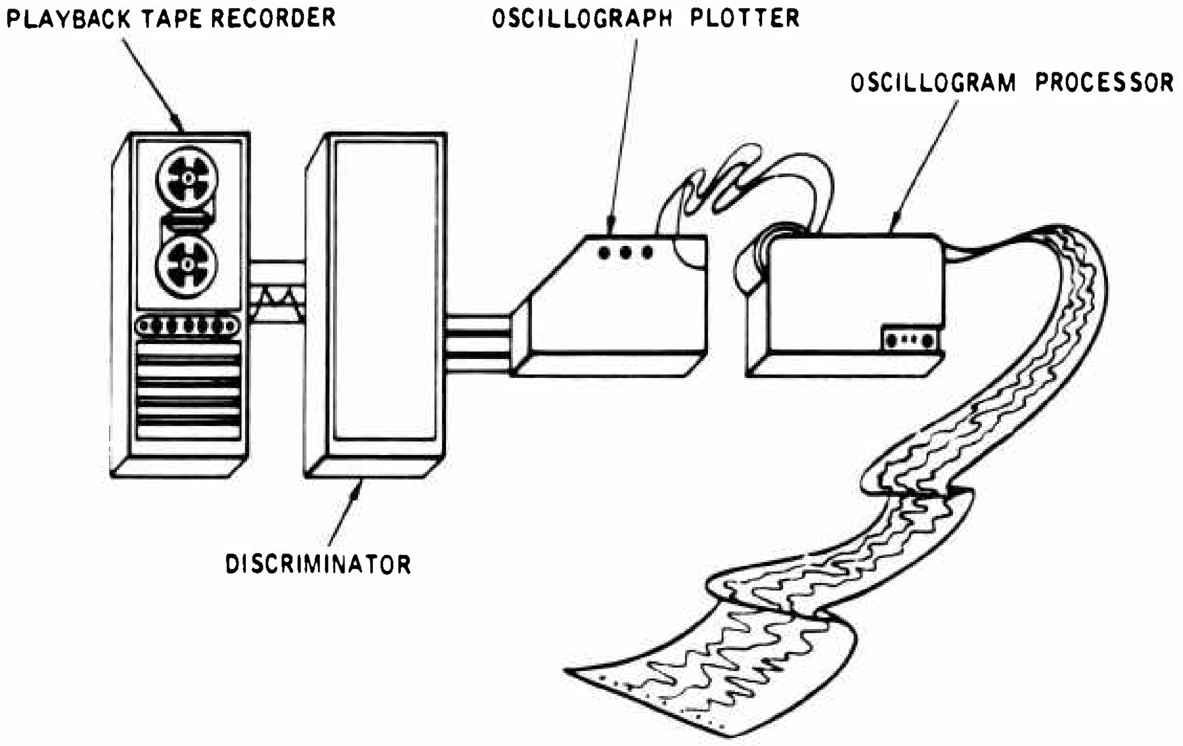


Figure B-8. Data Processing System

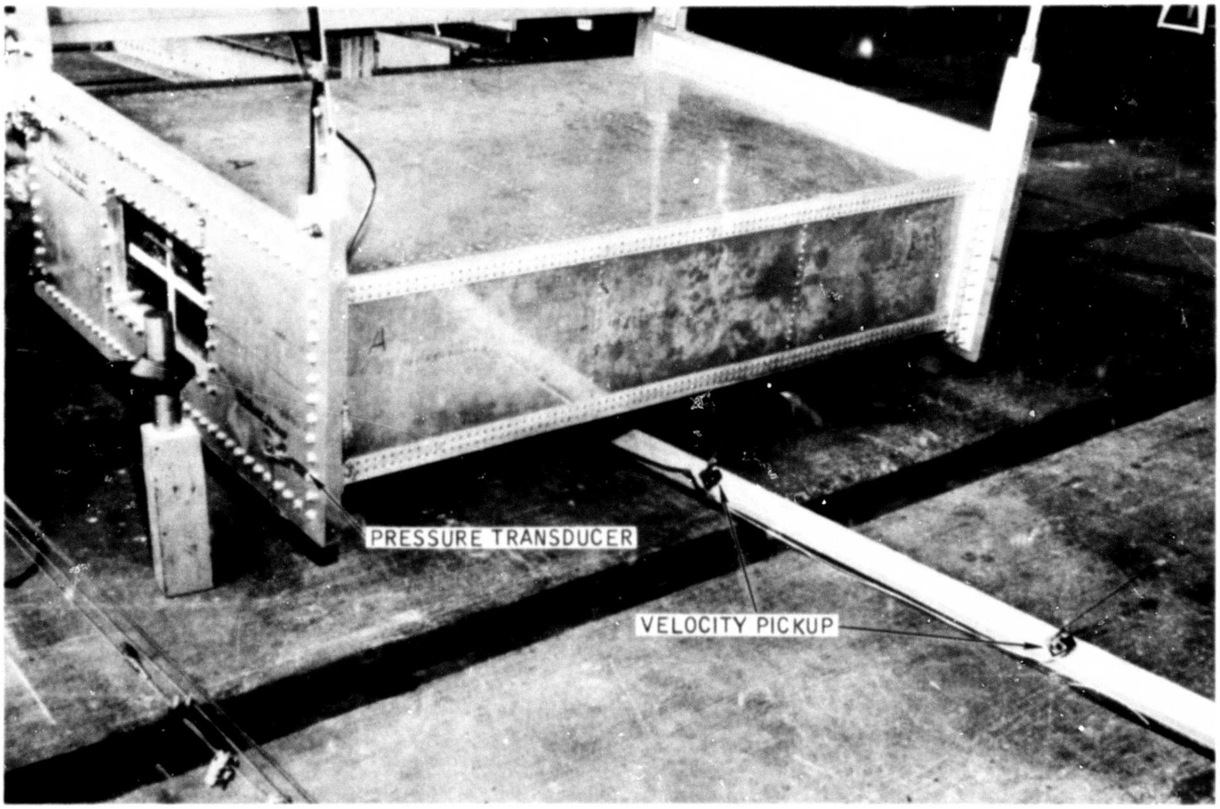


Figure B-9. Test Tank No. 1

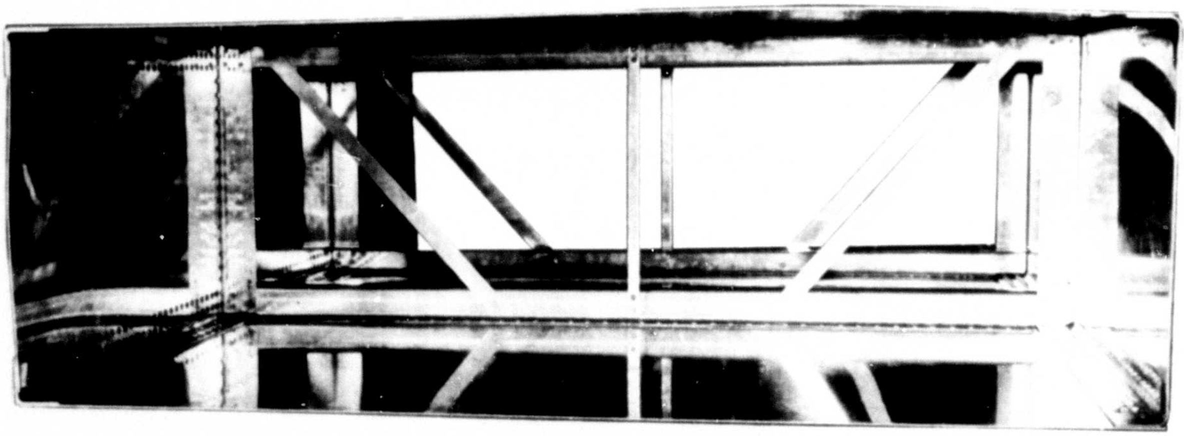
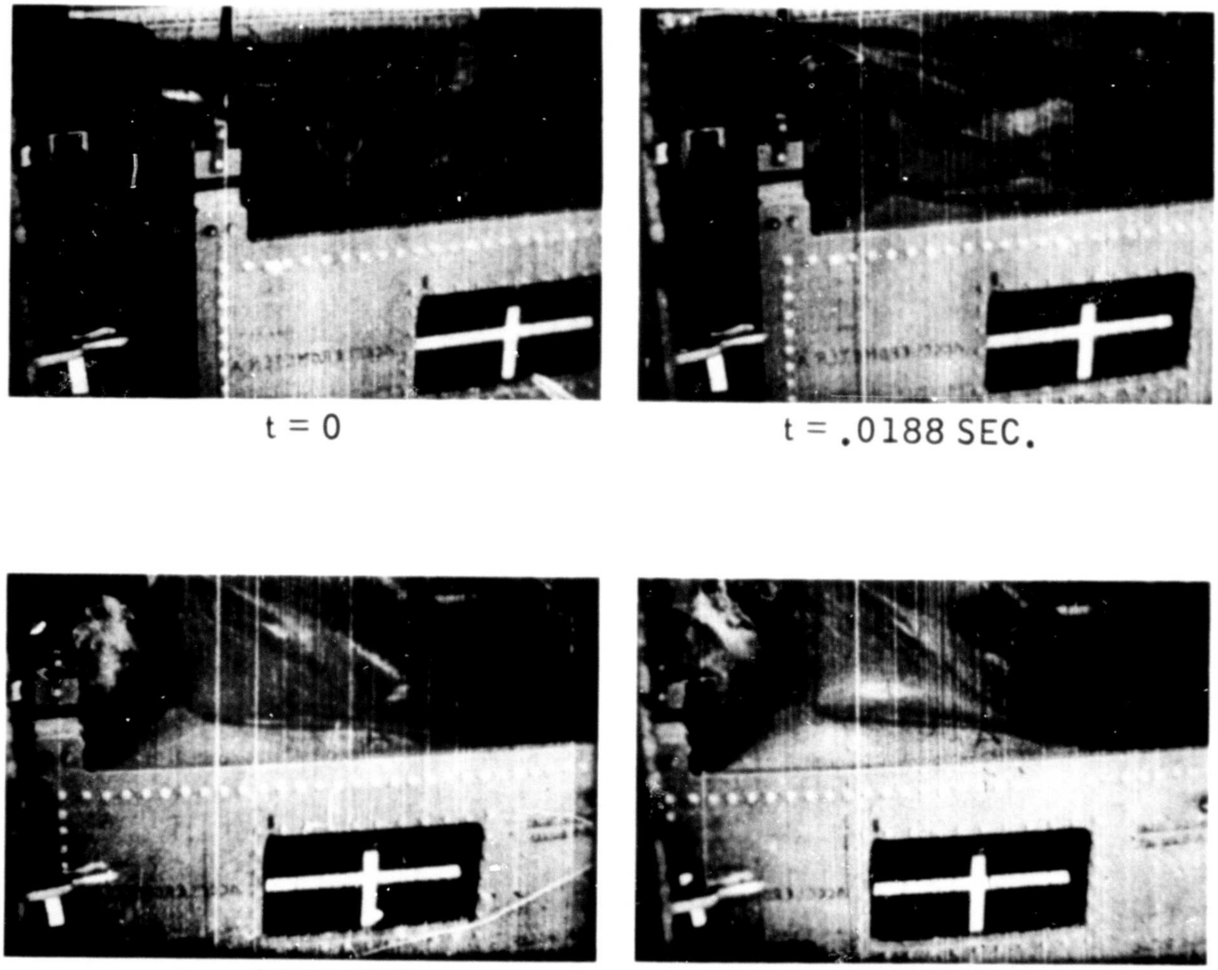


Figure B-10. Test Tank No. 1. This was a light, simple tank specimen measuring 16" x 48" x 72". Filled with water, 48" chord simulated 60" chord fuel filled tank.



t = 0

t = .0188 SEC.

t = .0375 SEC.

t = .0563 SEC.

Figure B-11. Drop No. 4, Log Impact, Tank No. 1. Max. velocity 25.4 fps, peak load 34,100 lb.

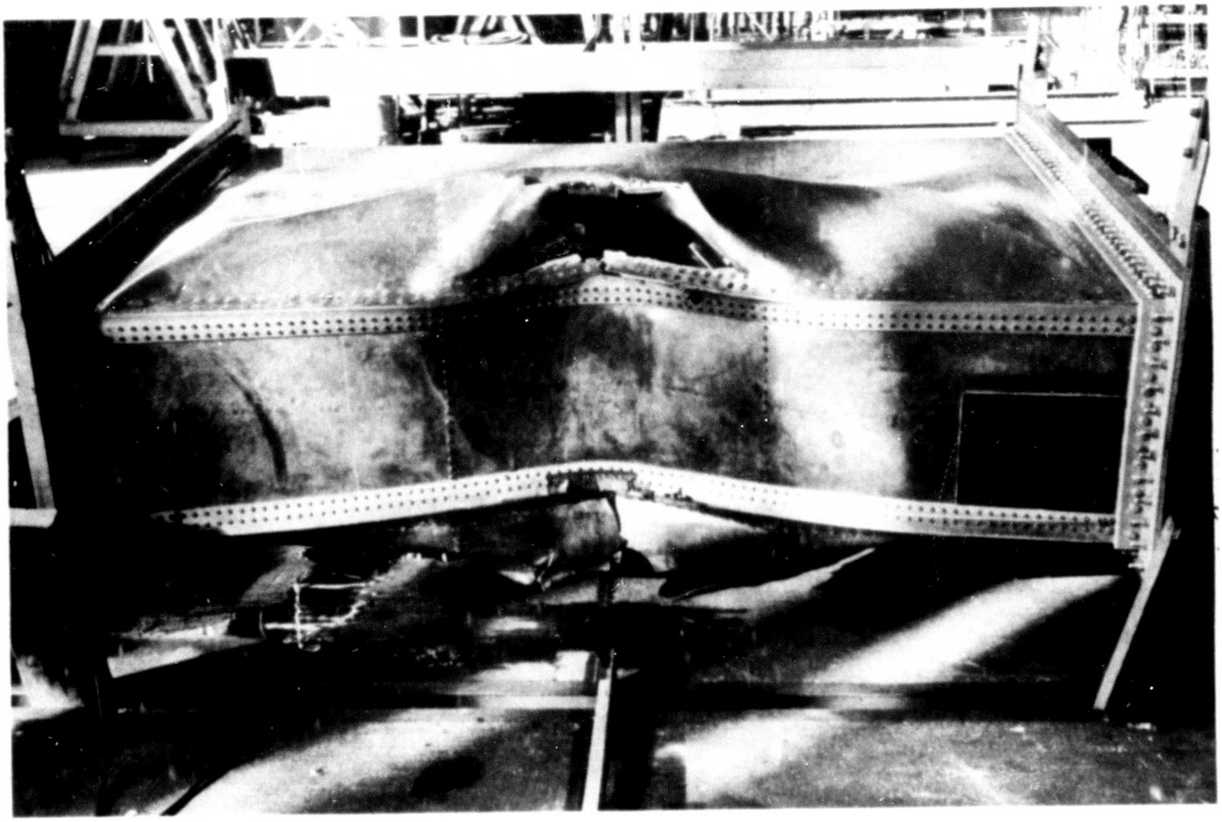


Figure B-12. Failure of No. 1 Test Tank. Result of Drop No. 4 — log impact test, 10-ft. drop height, impact load 34,100 lb.

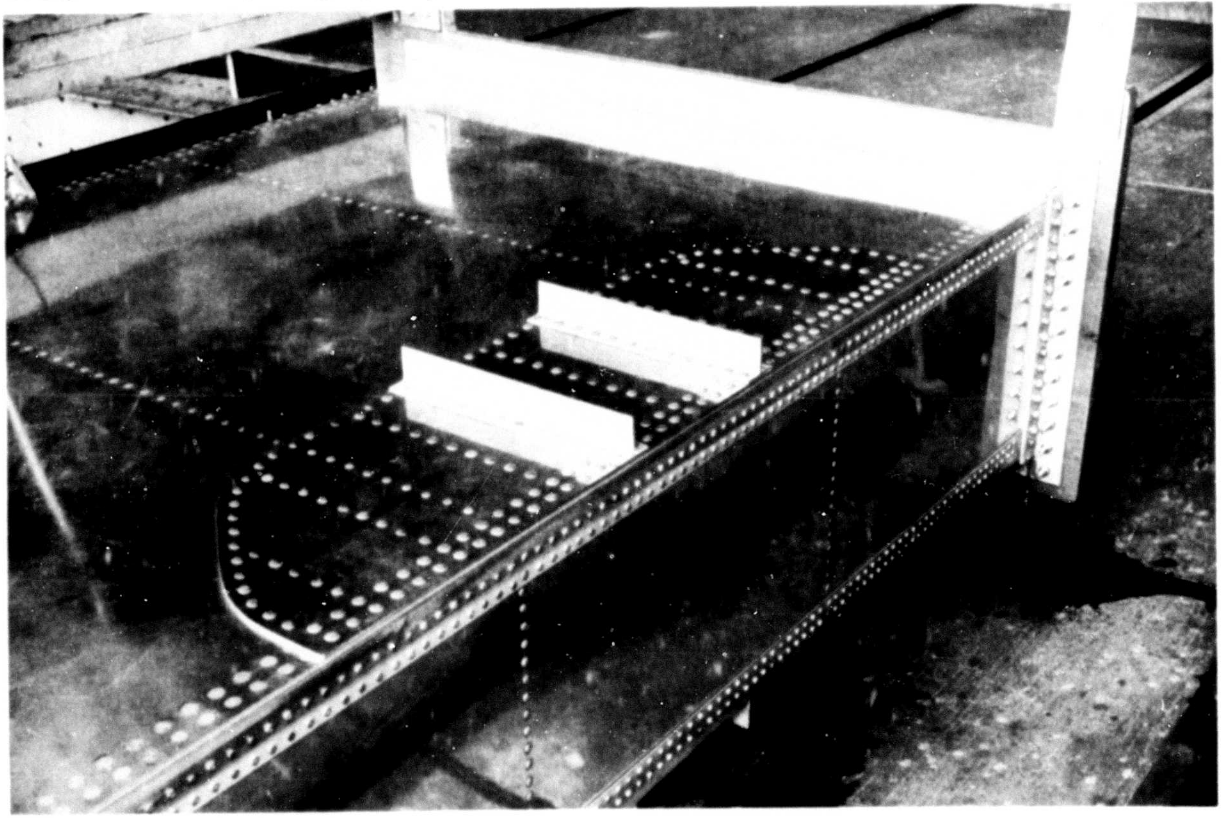


Figure B-13. Test Tank No. 2. Specimen was identical to Tank No. 1 except for skin stiffening on upper and lower surfaces.

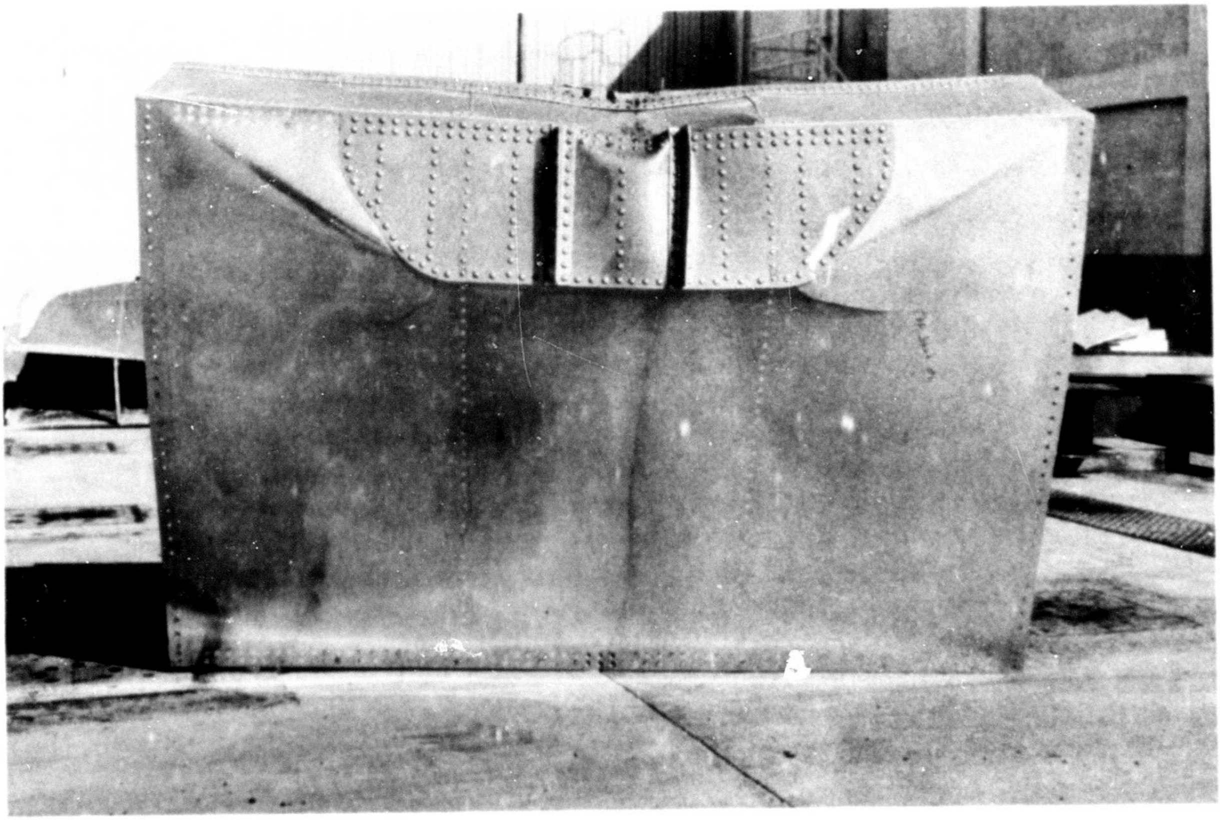


Figure B-14. Failure of Tank No. 2. Failure of upper surface after Drop 10, log impact — 6-ft. drop height, impact load 52,700 lb.

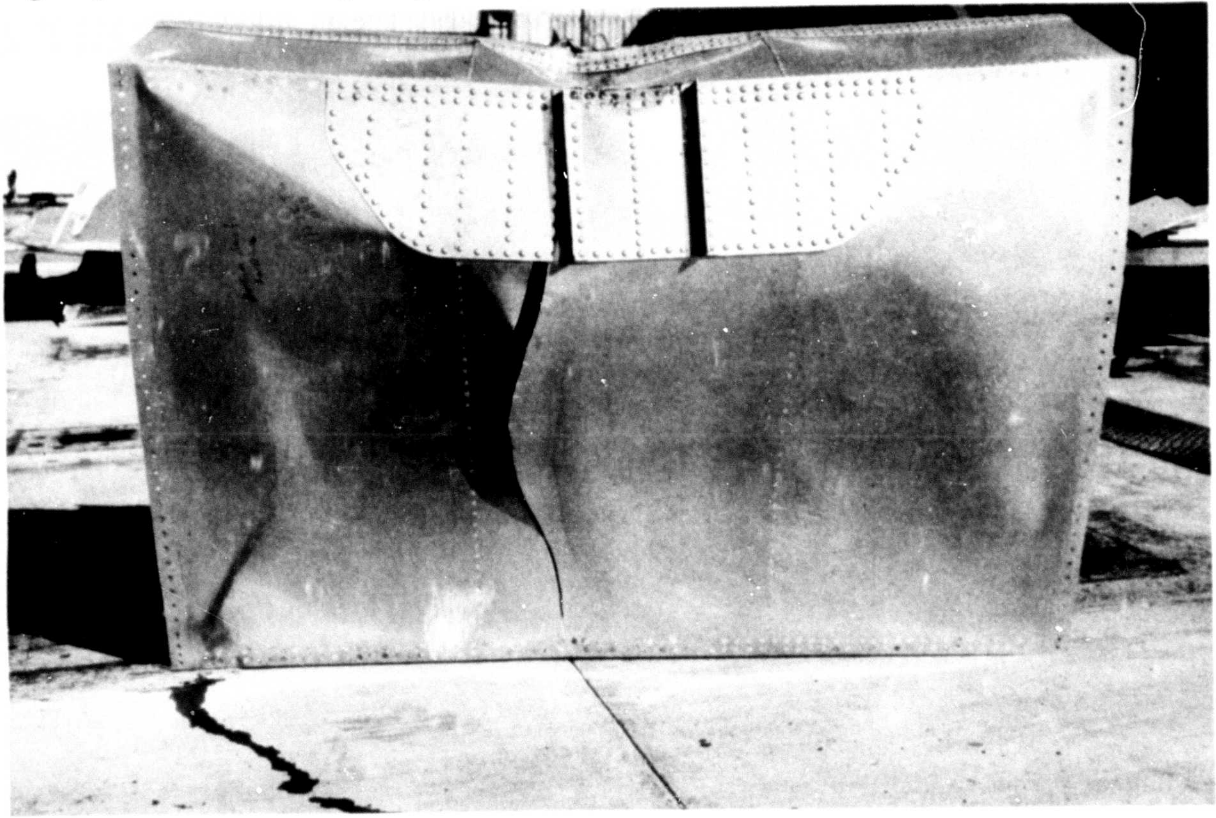


Figure B-15. Failure of Tank No. 2. Lower surface shown; note bending failure of doubler.

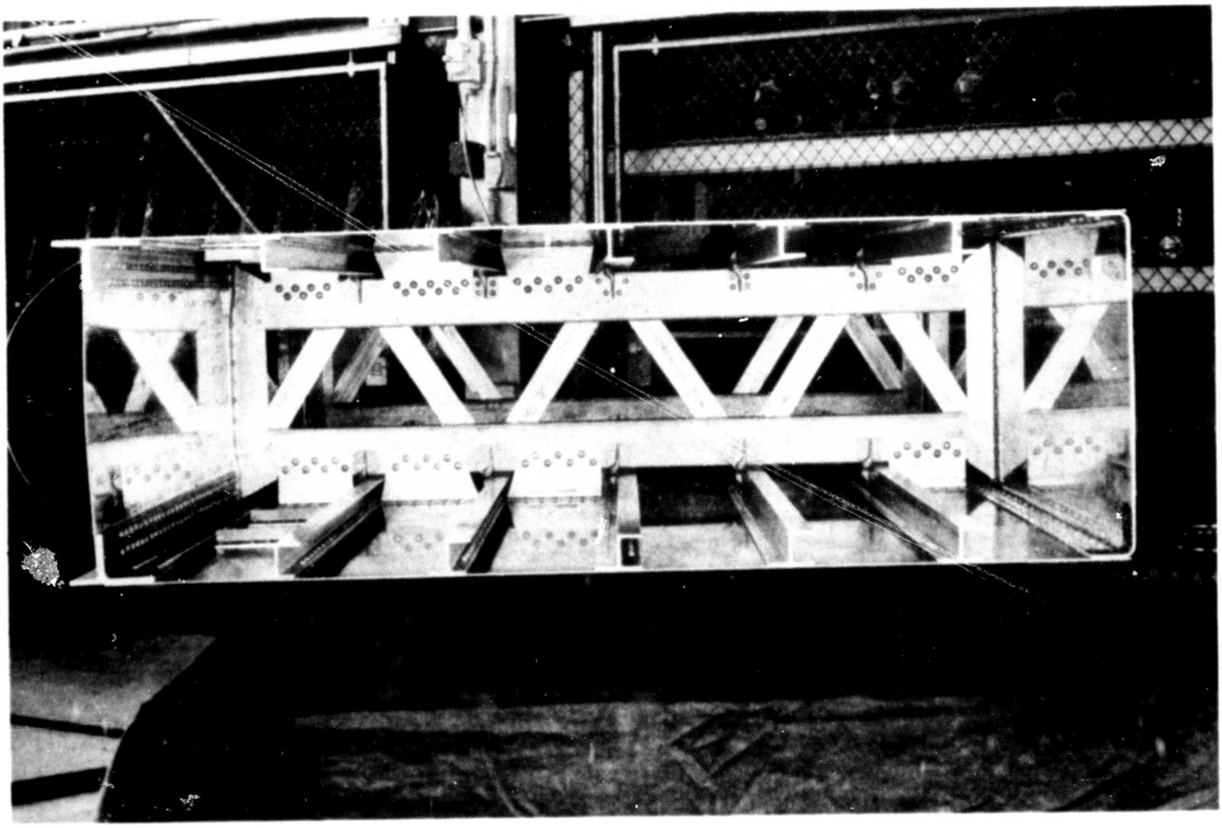
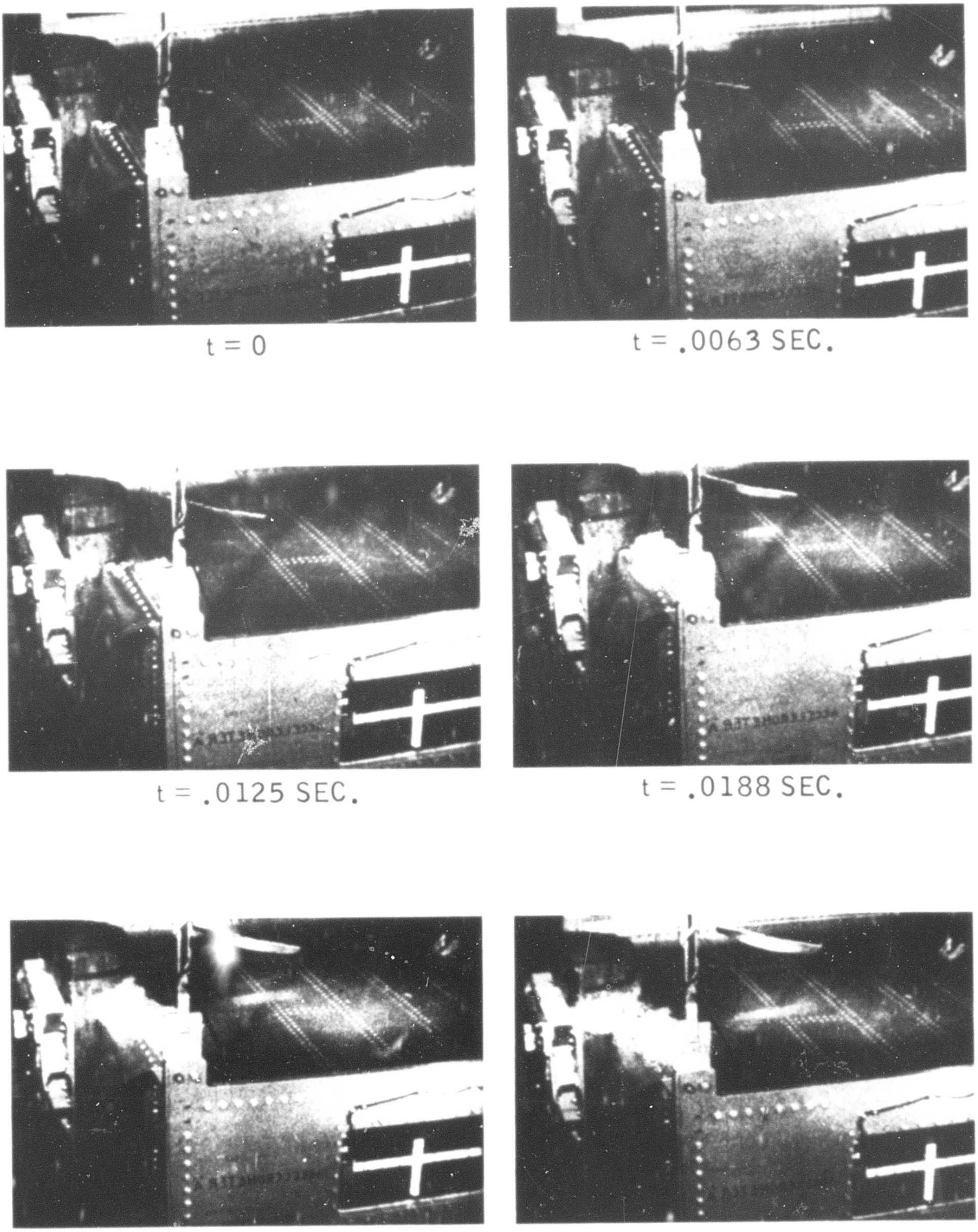


Figure B-16. Test Tank No. 3. Tank structure was similar to wing of existing jet transport.



t = 0

t = .0063 SEC.

t = .0125 SEC.

t = .0188 SEC.

t = .0250 SEC.

t = .0313 SEC.

Figure B-17. Drop No. 12. Log impact, Tank No. 3, max. velocity 17.9 fps, peak load 70,070 lb.

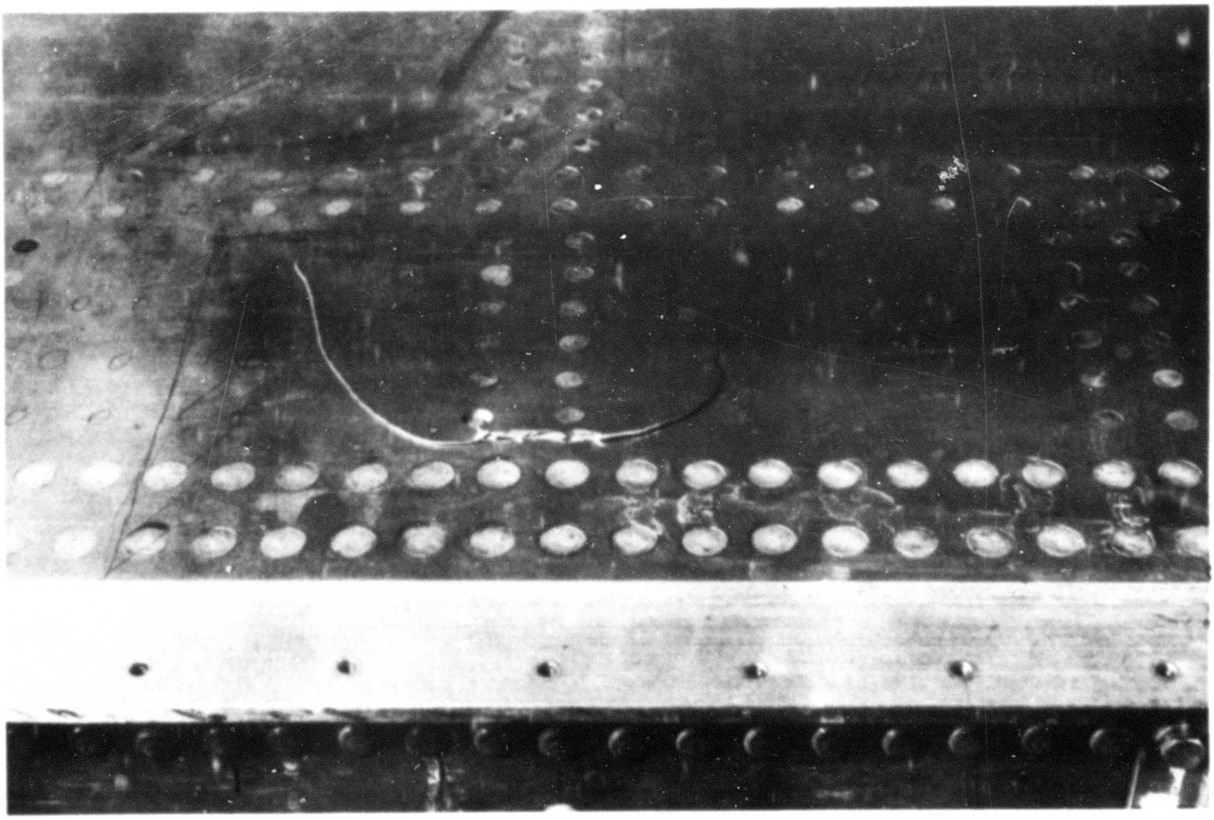


Figure B-18. Failure of Test Tank No. 3. Drop No. 12 upper skin rupture at front spar resulted from log impact test from 5-ft. drop height. Similar fracture appeared at other rib, lower skin did not fail. Impact load was 70,070 lb.

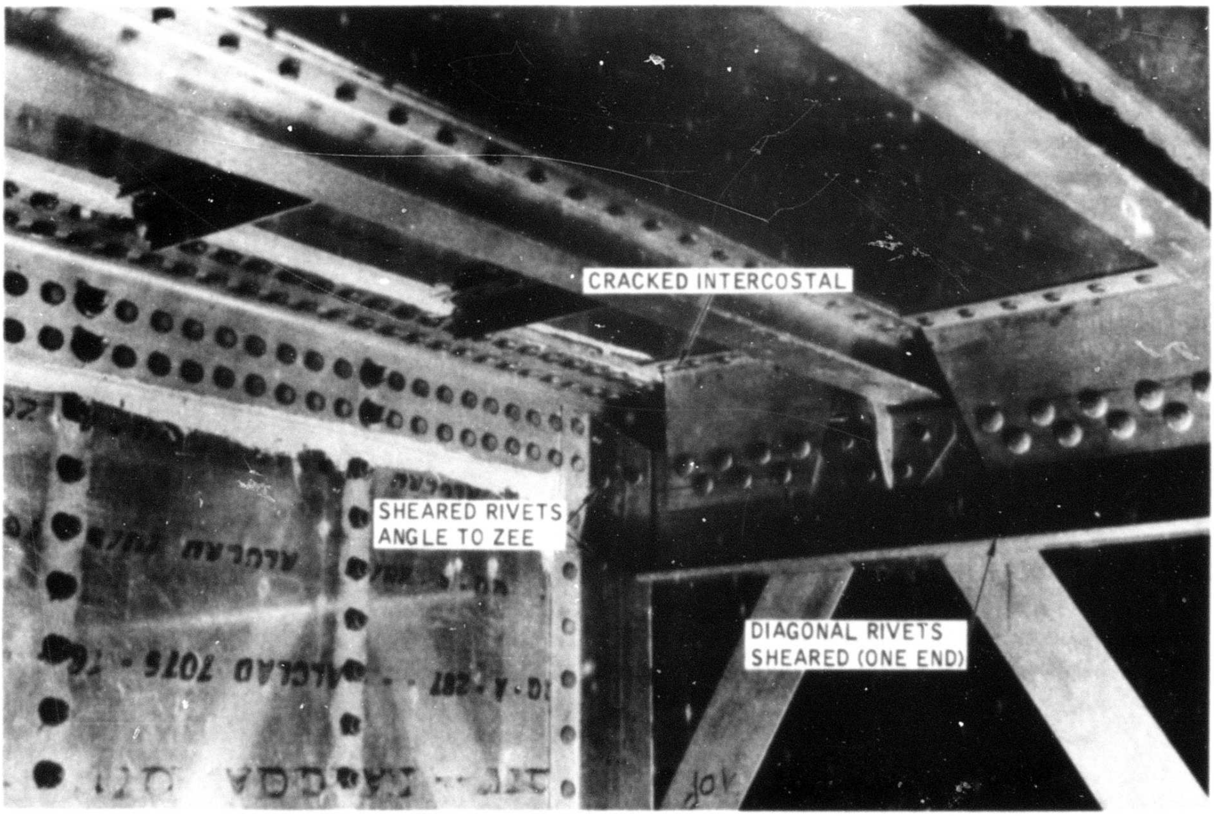
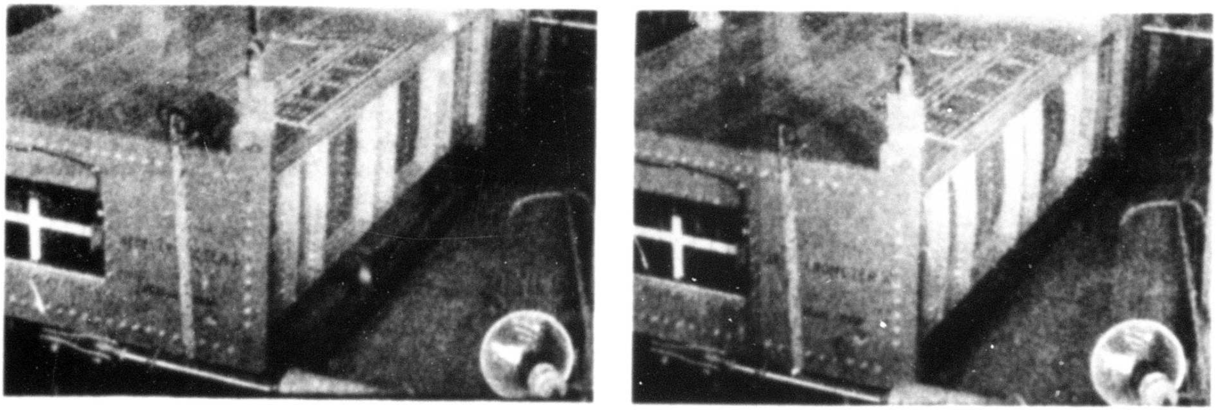


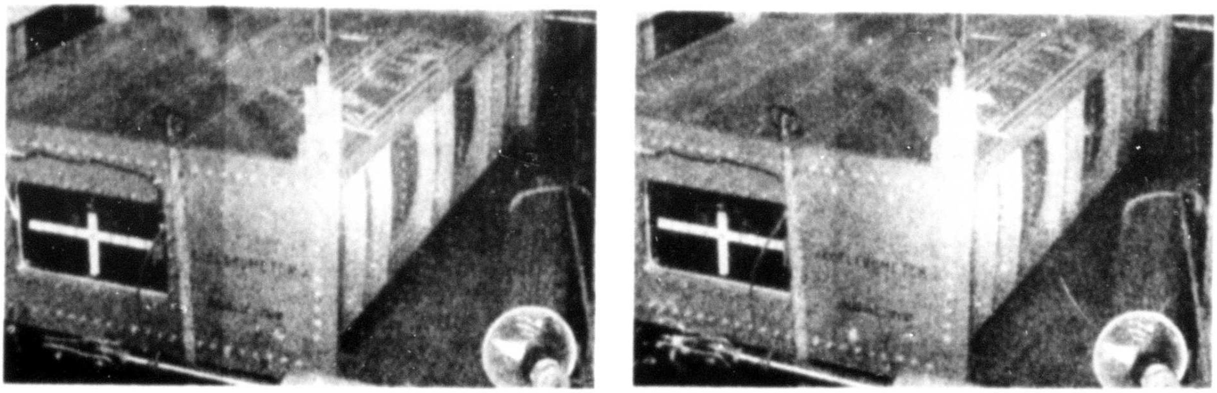
Figure B-19. Internal Failure of Test Tank No. 3.

Figure B-20. External Damage to Test Tank No. 4. Tank was rebuilt from Tank No. 3. Steel rivets were added internally and skin doublers were added to the upper and lower surfaces (Figure B-24). Six rivets popped during Drop No. 18 — a 40-g arrested stop.



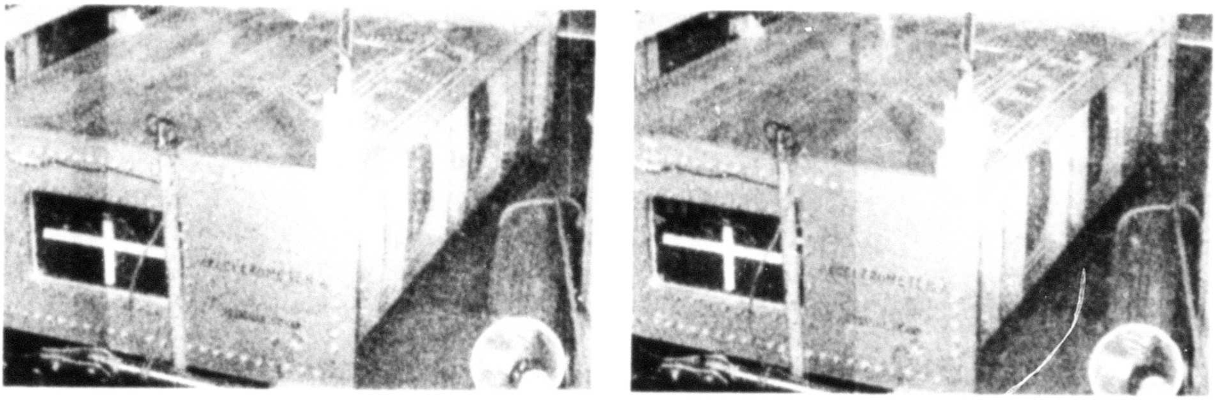
t = 0 SEC.

t = .0094 SEC.



t = .0188 SEC.

t = .0281 SEC.



t = .0375 SEC.

t = .0469 SEC.

Figure B-21. Drop No. 18. 40-g arrested stop, Tank No. 4, impact velocity 48.4 fps, peak load 97,600 lb.

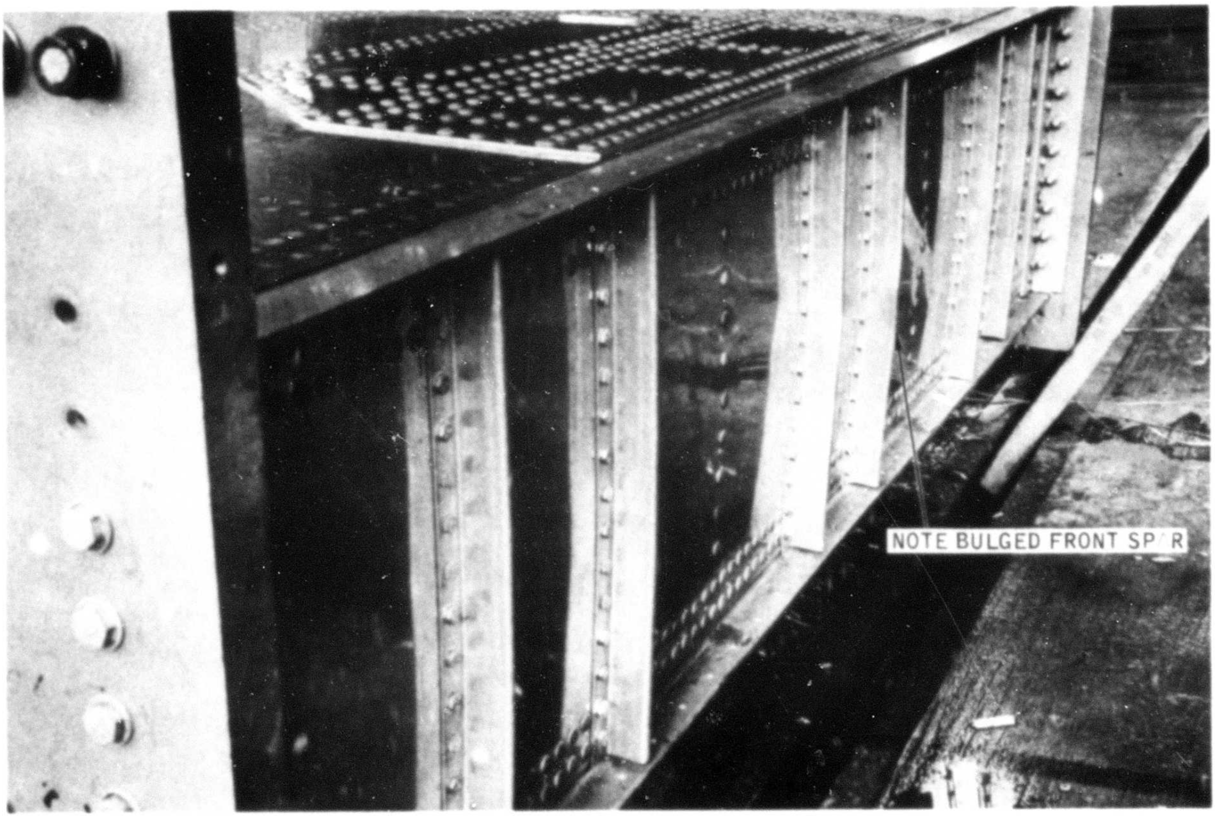


Figure B-22. Further External Damage to Tank No. 4. This shows bulge of front spar as a result of Drop No. 18 — a 40-g arrested stop. Only leakage was that shown in Figure B-20.

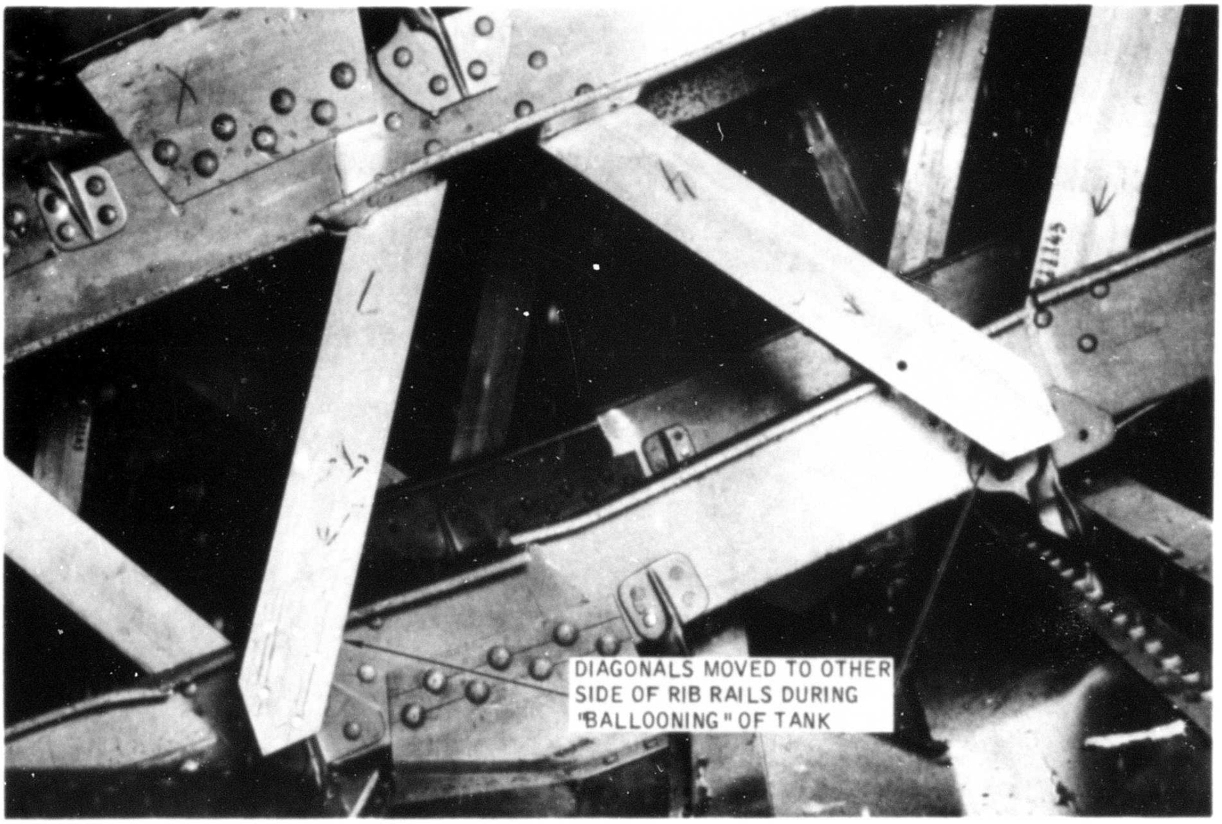


Figure B-23. Internal Damage to Tank No. 4. This shows further damage resulting from 40-g arrested stop. Note extreme deflections that must have occurred to allow two diagonals to switch from inboard to outboard side of rib rails.

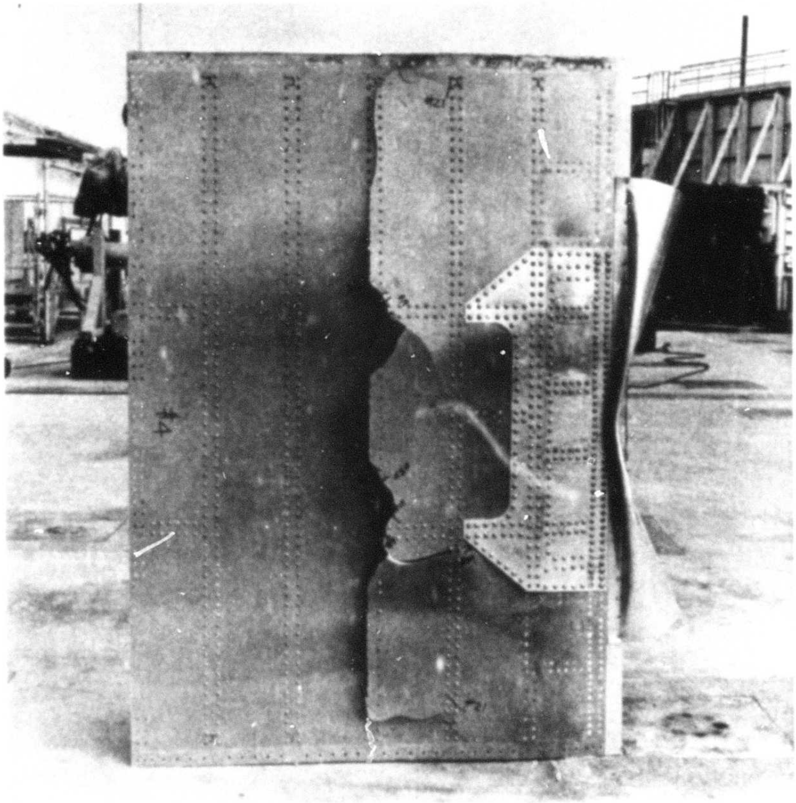


Figure B-24. Complete Failure of Test Tank No. 4. The six popped rivets shown in Figure B-20 were replaced and a log impact series of tests was begun. This shows progressive failure resulting from Drops 19, 20 and 21. Initial skin failure was 2-in. crack at an aft end of third-bay intercostal. Max. impact load was 94,100 lb.

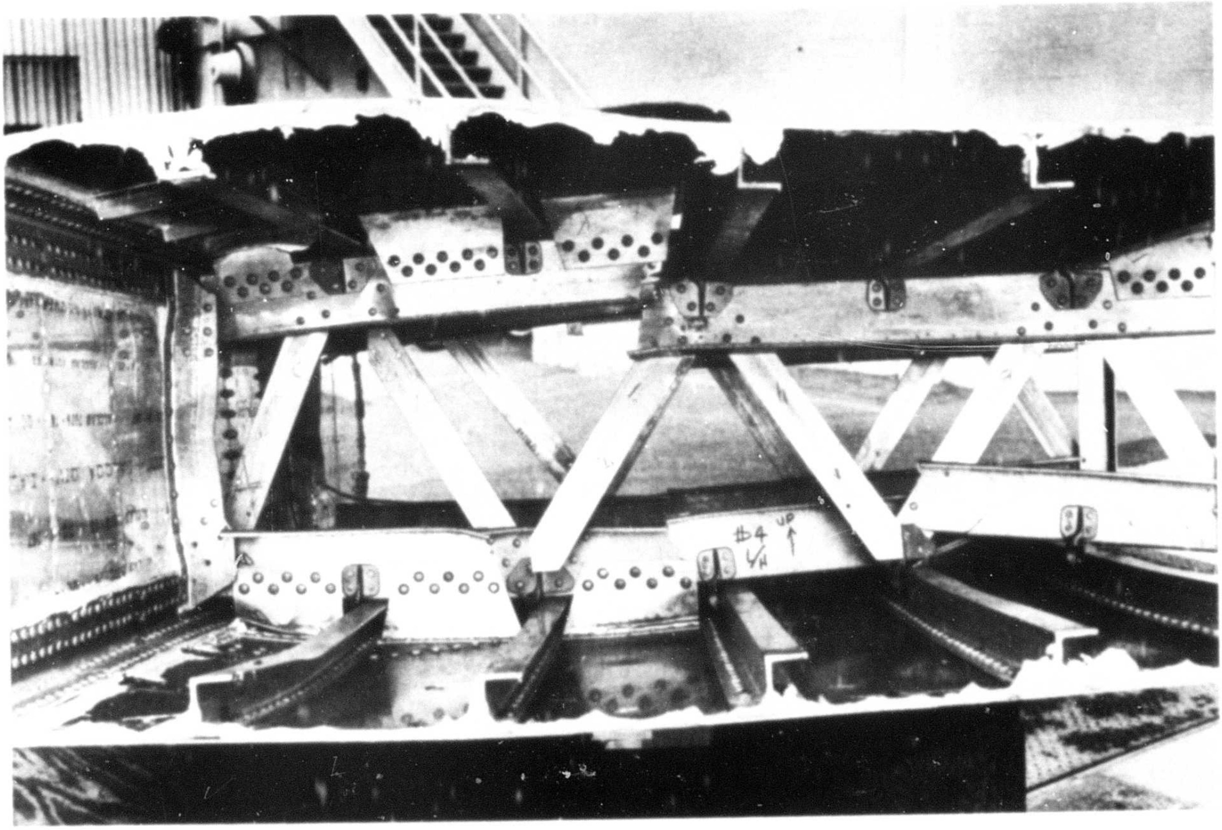


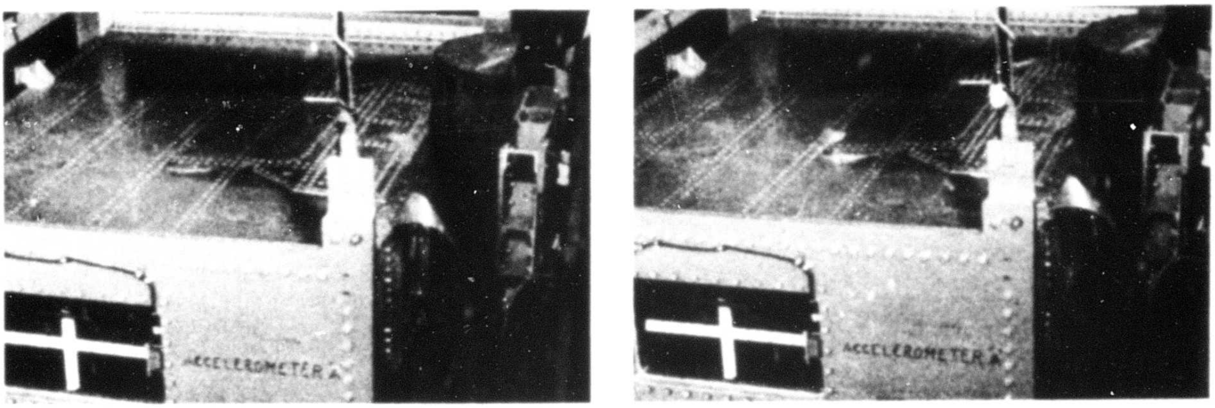
Figure B-25. Final Internal Damage to Tank No. 4

t = 0 t = .0094 SEC.

t = .0135 SEC. t = .0167 SEC.

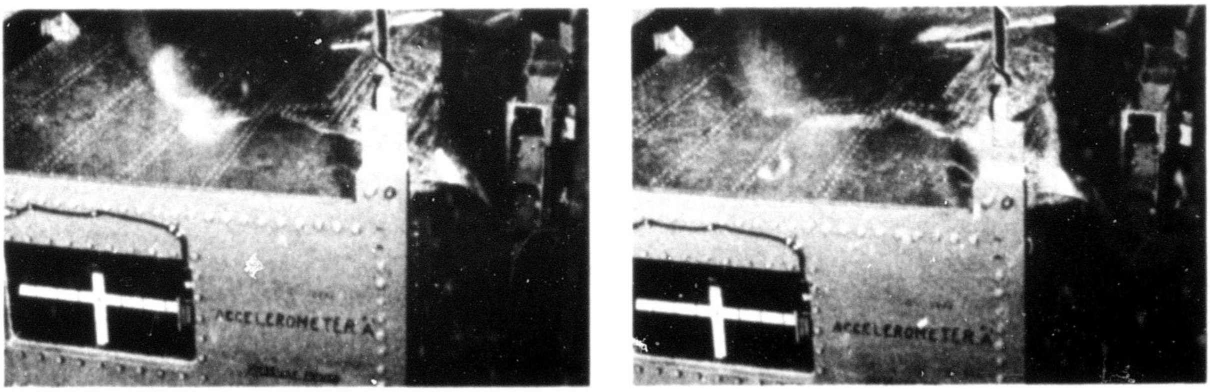
t = .0198 SEC. t = .0229 SEC.

Figure B-26. Drop No. 19. Log impact, Tank No. 4, impact velocity 17.9 fps, peak load 70,200 lb.



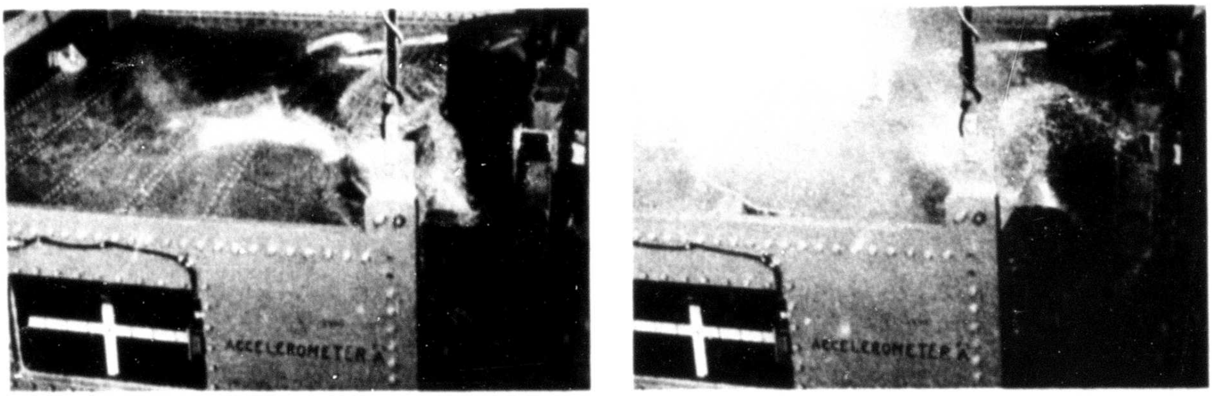
t = 0

t = .0031 SEC.



t = .0063 SEC.

t = .0094 SEC.



t = .0125 SEC.

t = .0250 SEC.

Figure B-27. Drop No. 21. Log impact, Tank No. 4, impact velocity 24 fps, peak load 94,100 lb.

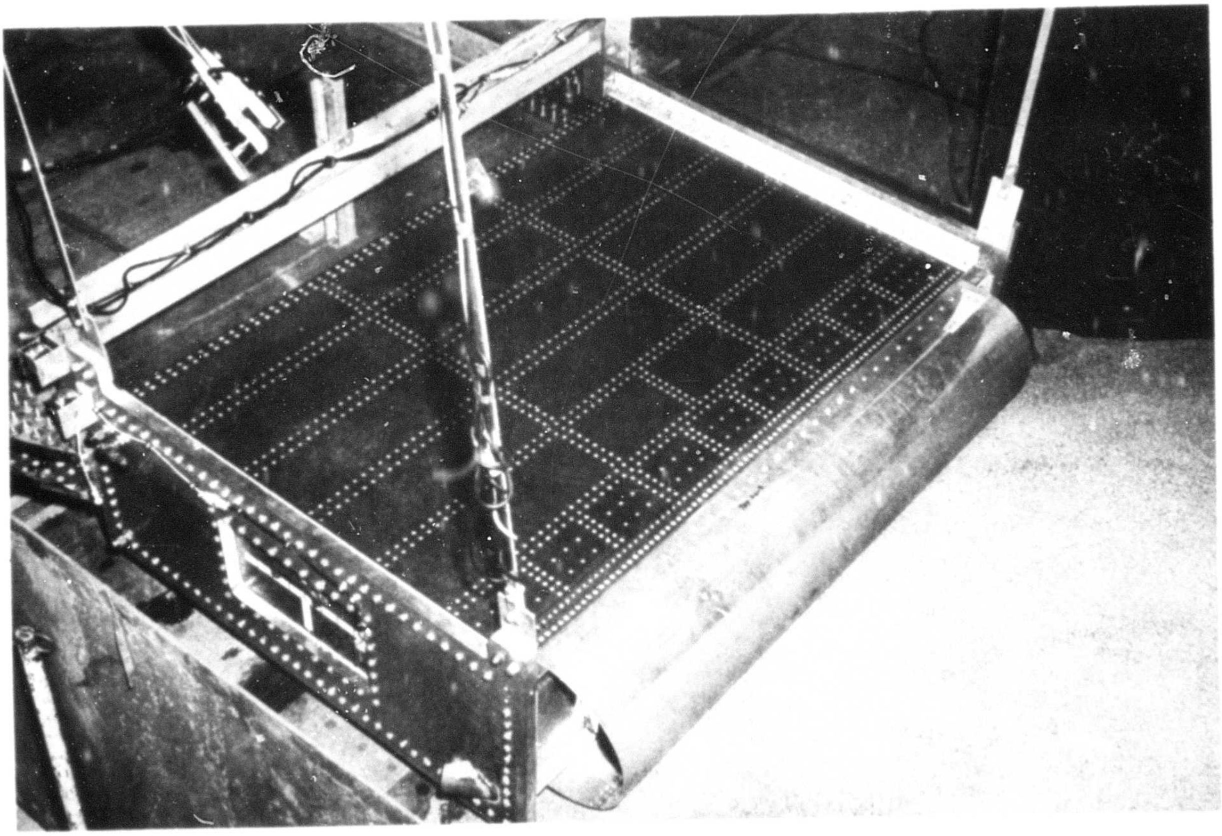
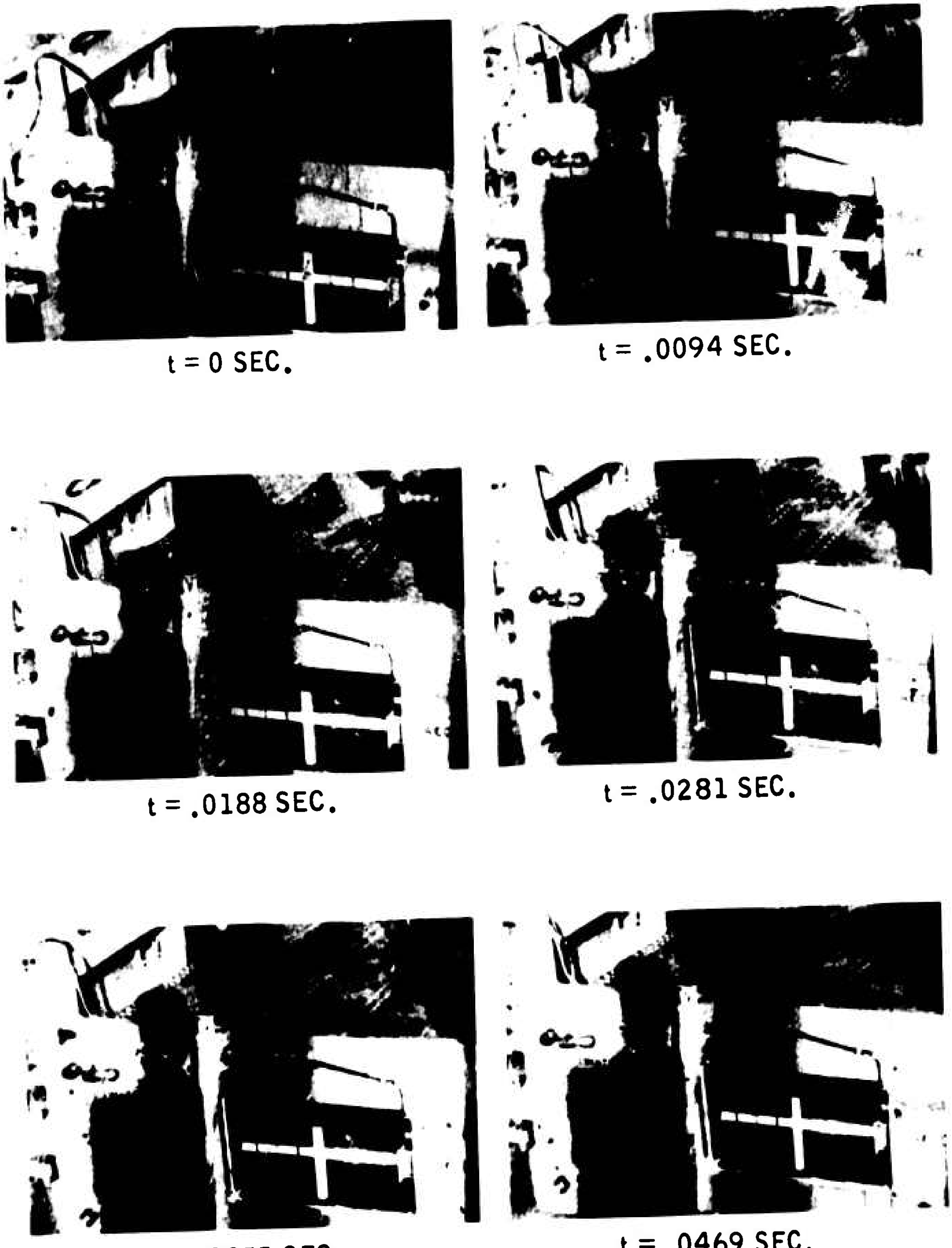


Figure B-28. Test Tank No. 6. Tests tanks 5 and 6 were identical and incorporated better features of previous tanks, plus web-type ribs.



t = 0 SEC.

t = .0094 SEC.

t = .0188 SEC.

t = .0281 SEC.

t = .0375 SEC.

t = .0469 SEC.

Figure B-29. Drop No. 25. Log impact, tank No. 5, impact velocity 27.8 fps, peak load 97,000 lb.

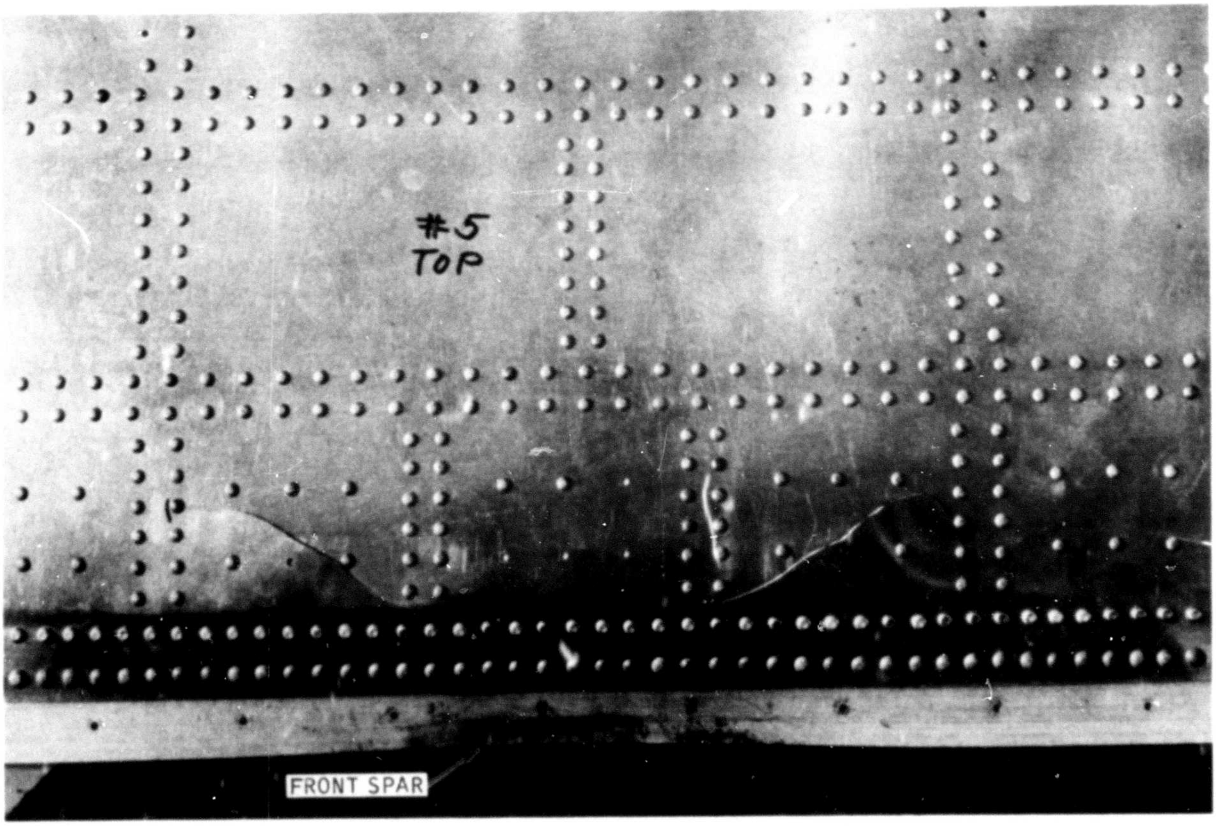


Figure B-30. Upper Skin Fracture, Tank No. 5. Result of Drop No. 25: log impact test from drop height of 12 ft.; impact load was 97,000 lb.

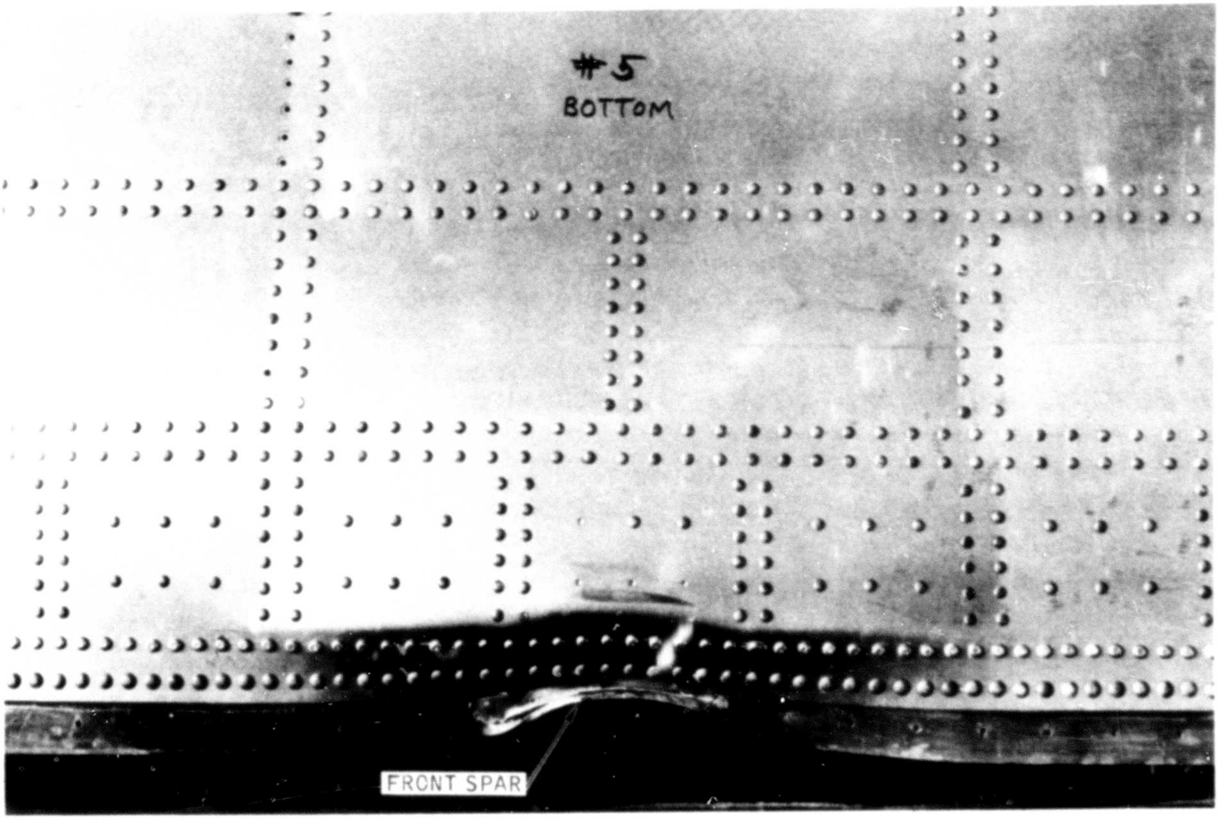


Figure B-31. Lower Surface of Tank No. 5. Results of Drop 25, impact load was 97,000 lb.

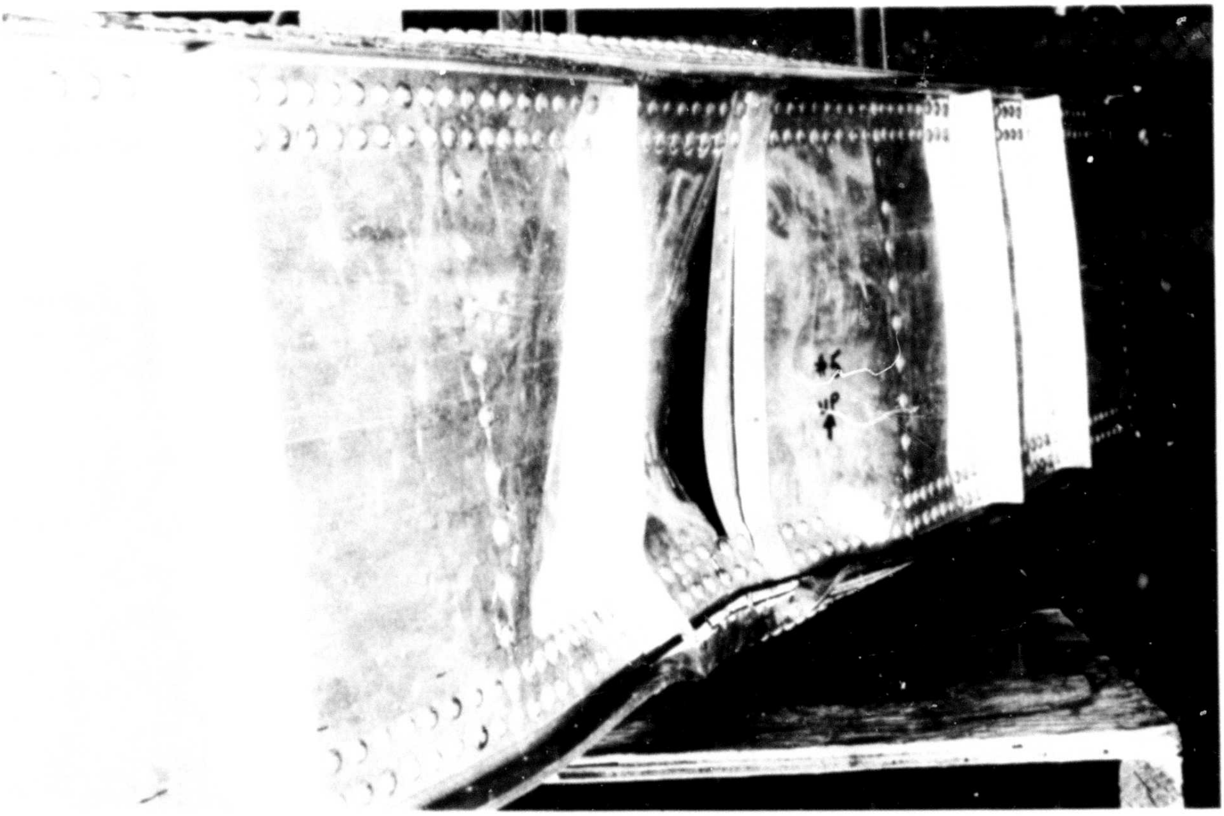


Figure B-32. Front Spar of Tank No. 5. Result of Drop 25, most fuel leakage was from this fracture.

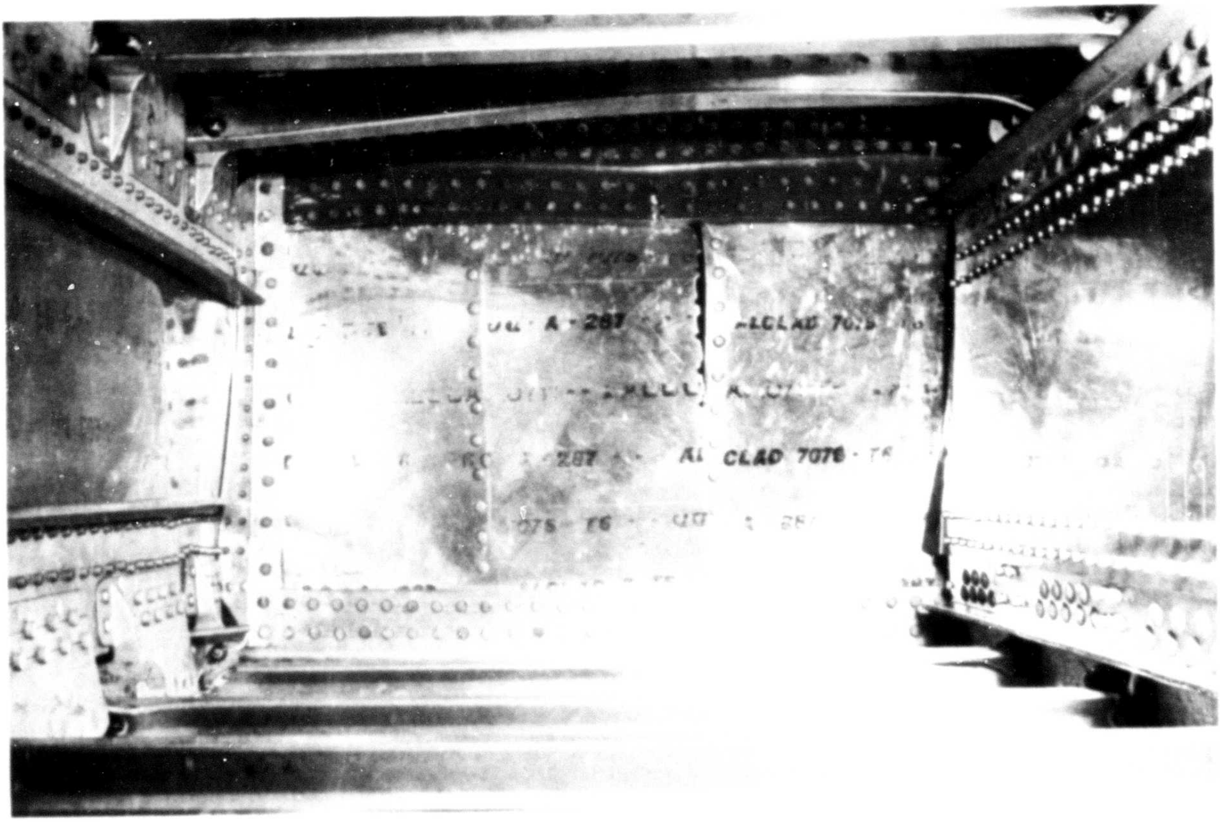


Figure B-33. Front Spar Failure of Tank No. 5. Internal view of damage shown in Figure B-32.

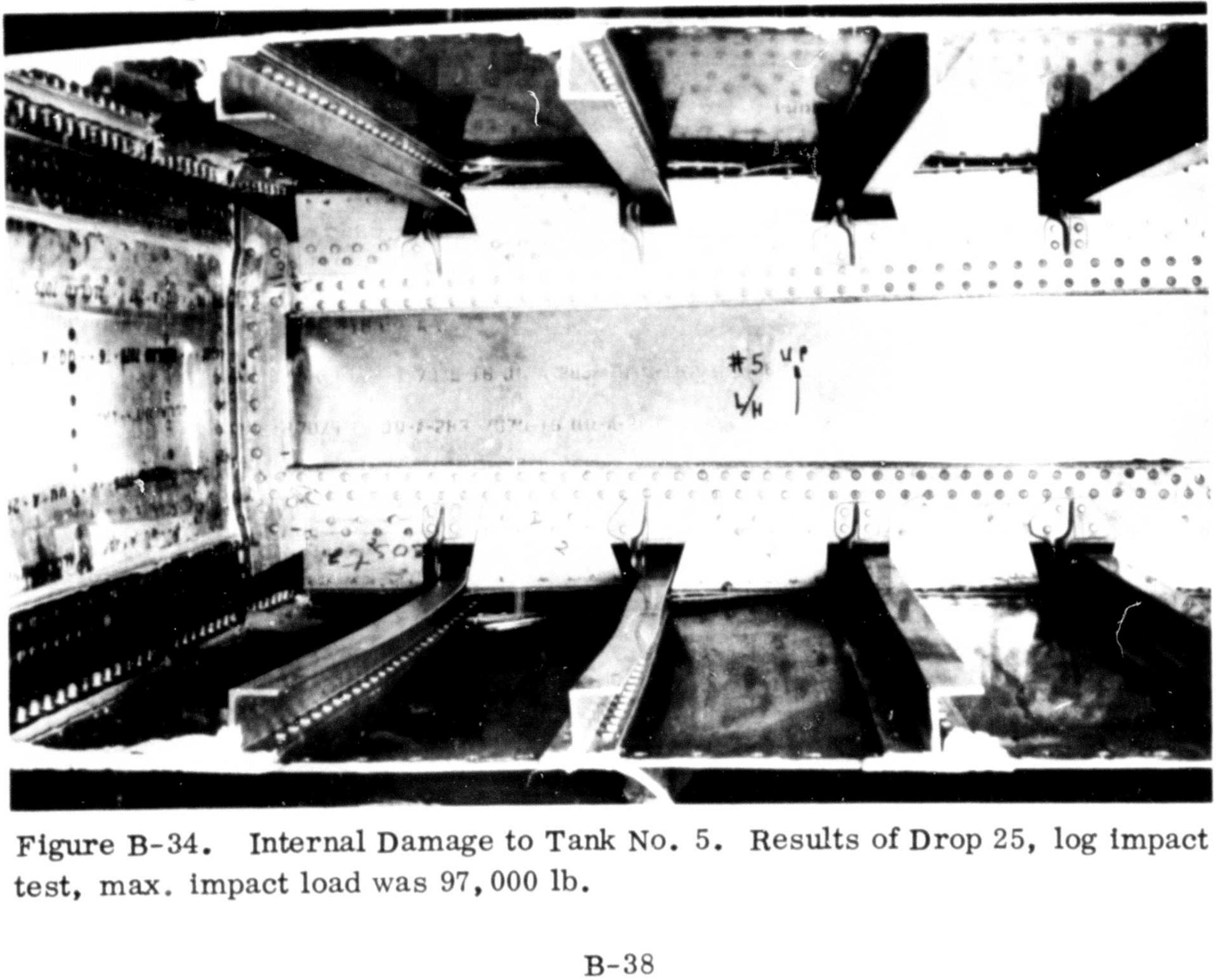


Figure B-34. Internal Damage to Tank No. 5. Results of Drop 25, log impact test, max. impact load was 97,000 lb.

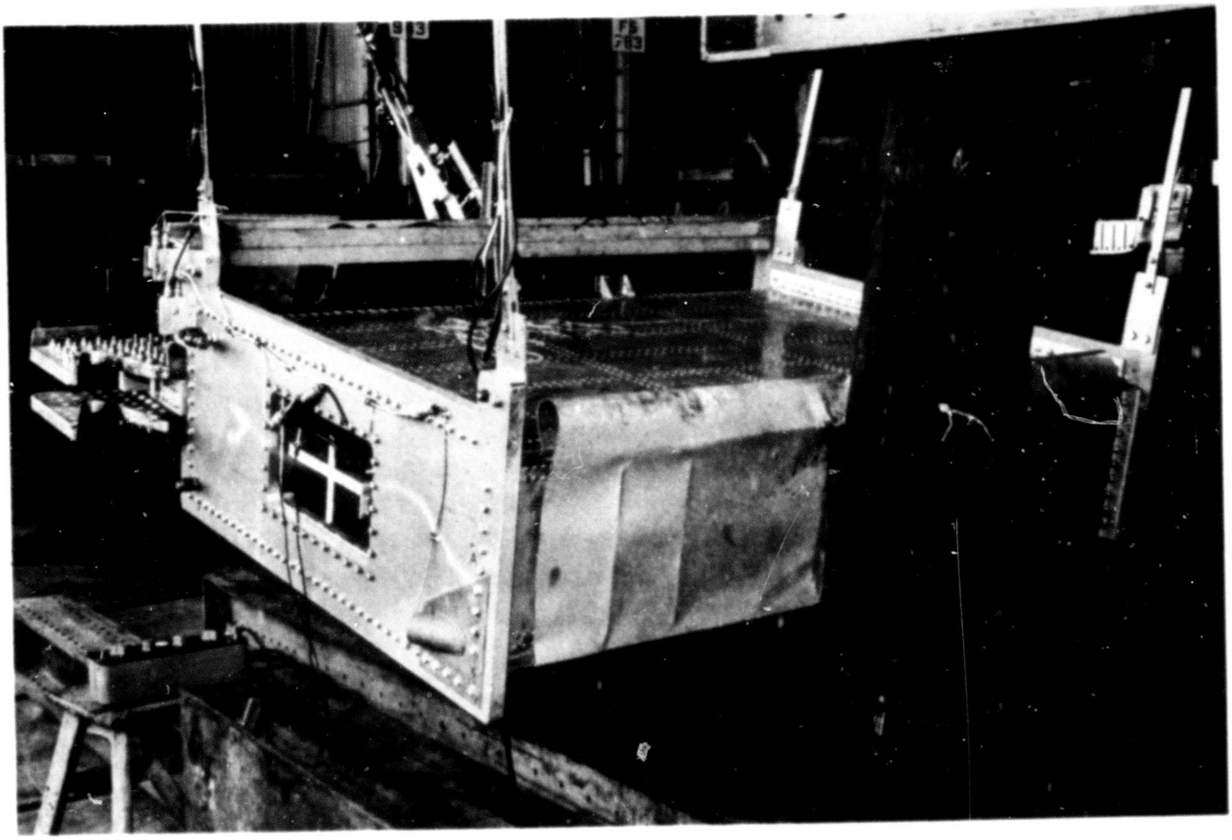
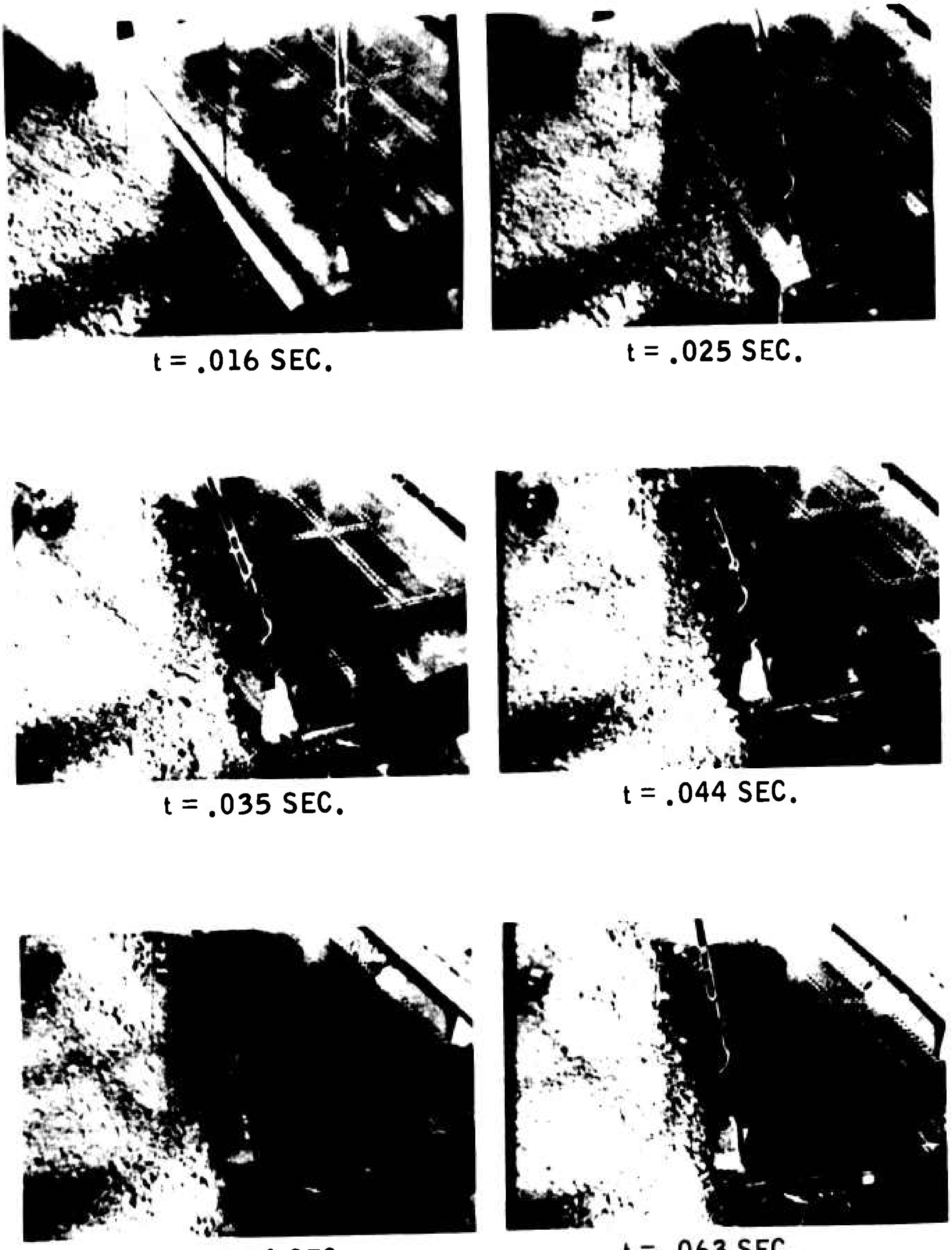


Figure B-35. Test Tank No. 6. Tank is shown prior to Drop 47 after sustaining a series of sand and sand-rock pile tests and after having broken several poles. This tank eventually broke a 17.4-in. diameter piling.



t = .016 SEC.

t = .025 SEC.

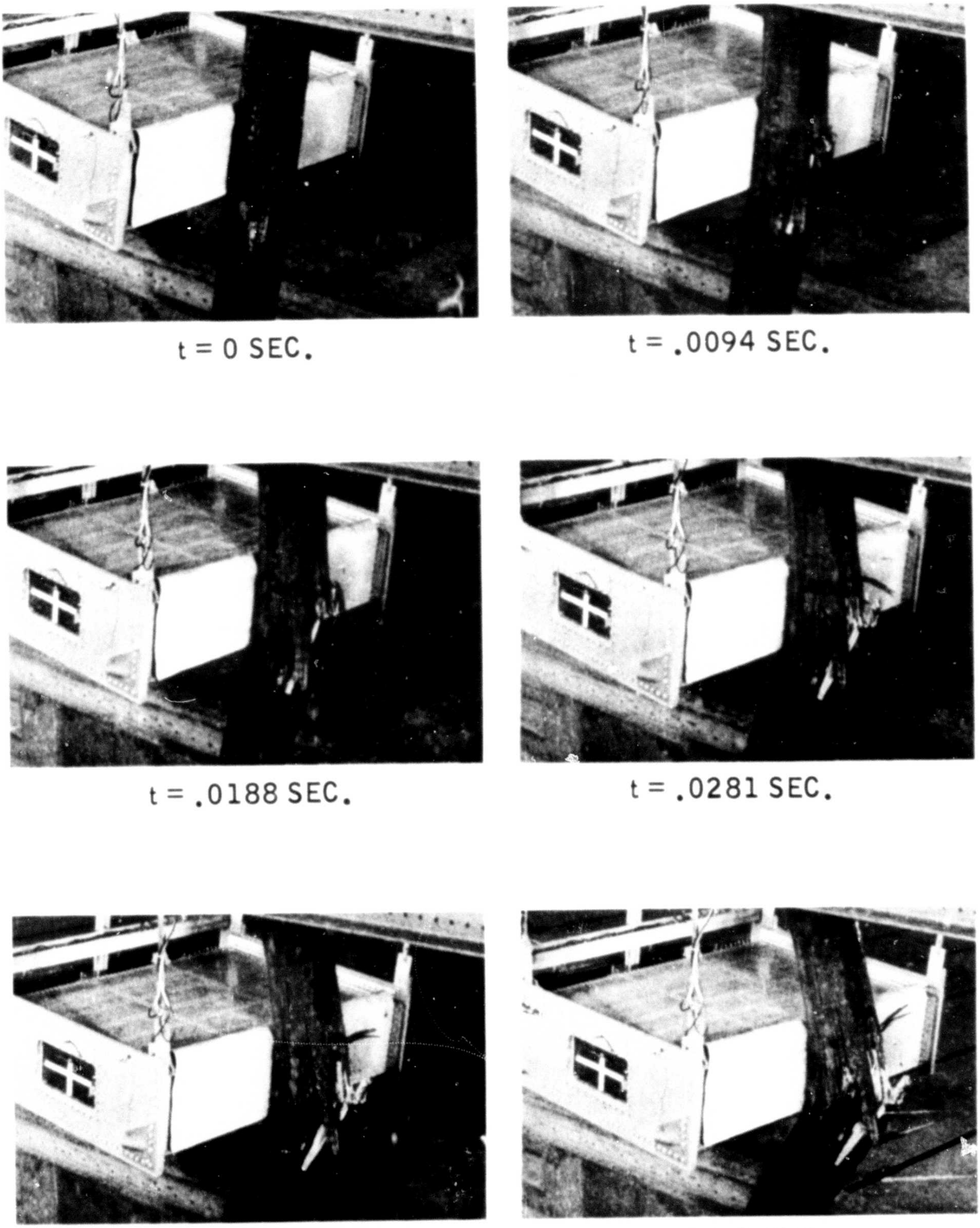
t = .035 SEC.

t = .044 SEC.

t = .054 SEC.

t = .063 SEC.

Figure B-36. Drop No. 39. Tank No. 6, 30-degree sand/rock pile, 40.1-fps impact velocity.



t = 0 SEC.

t = .0094 SEC.

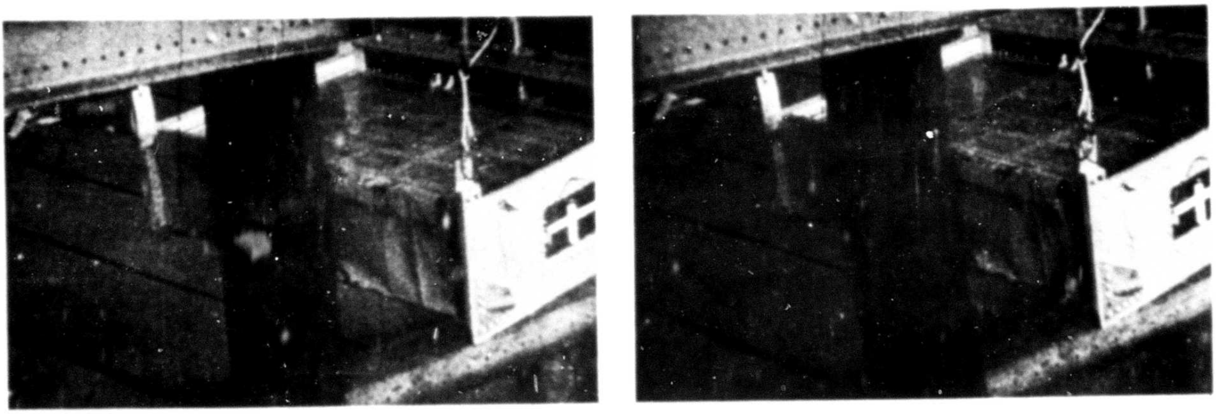
t = .0188 SEC.

t = .0281 SEC.

t = .0375 SEC.

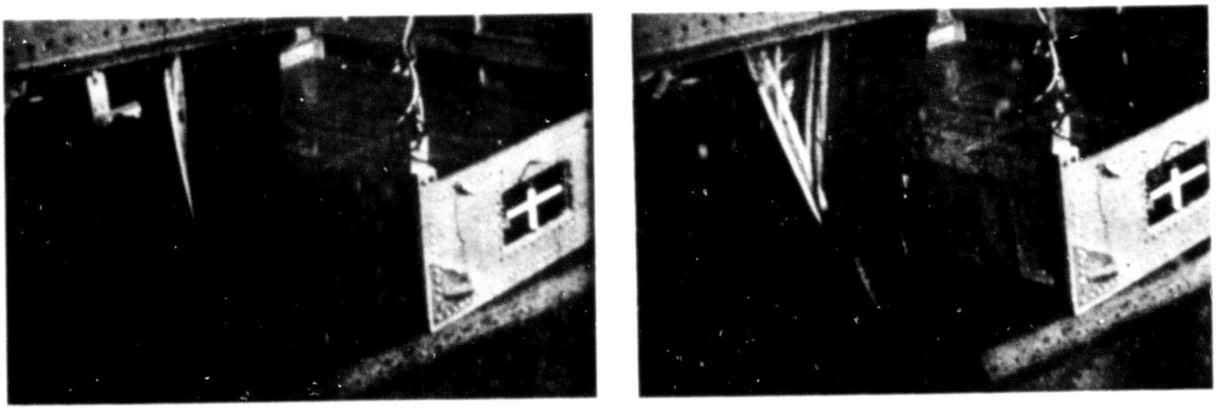
t = .0469 SEC.

Figure B-37. Drop No. 50. Tank No. 6, 16-in. diameter pole, 41-6 fps impact velocity.



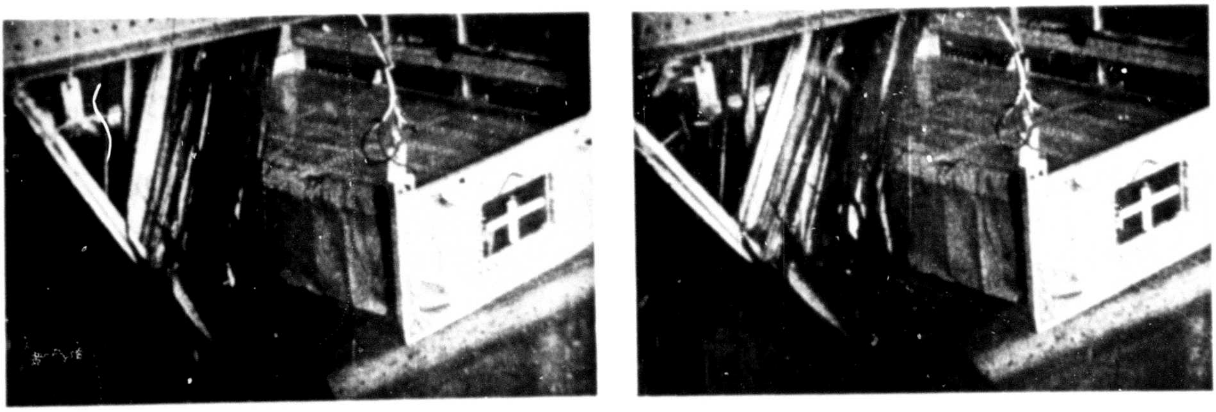
t = 0

t = .0031 SEC.



t = .0063 SEC.

t = .0094 SEC.



t = .0135 SEC.

t = .0167 SEC.

Figure B-38. Drop No. 52. Tank No. 6, 17.4-in. diameter piling, 47.4-fps impact velocity.

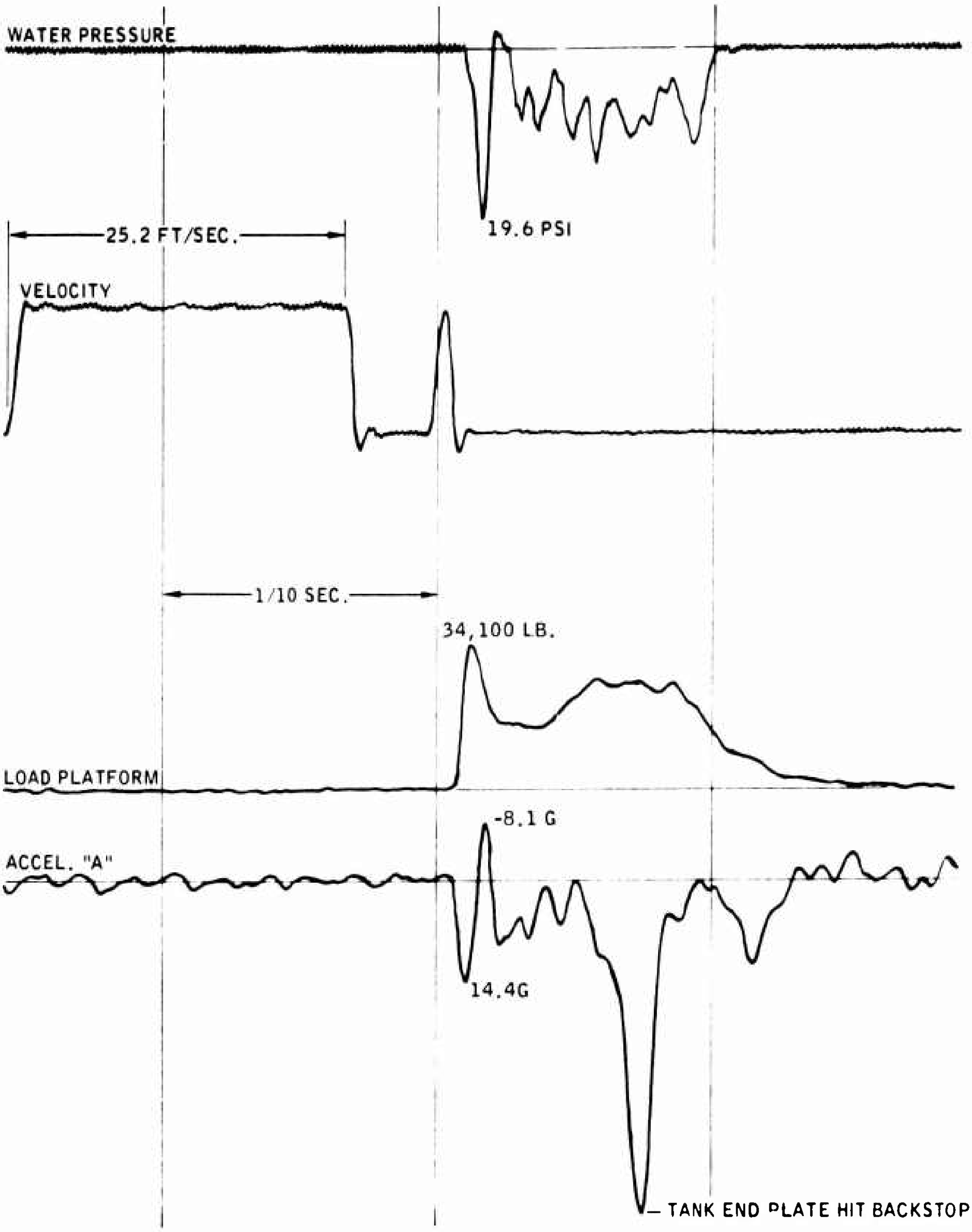


Figure B-39. Drop No. 4, 10-ft. Log Impact

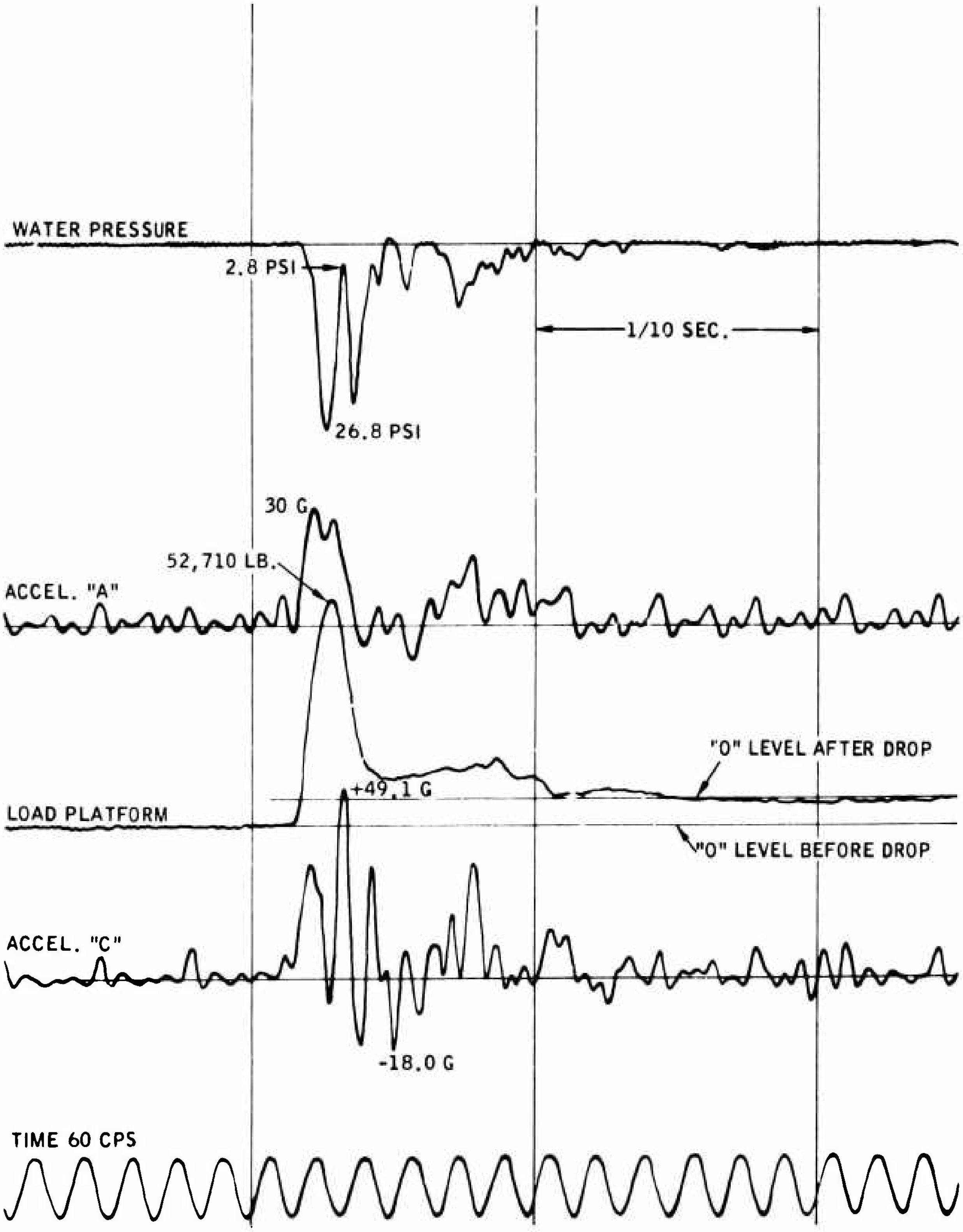


Figure B-40. Drop No. 10, 6-ft. Log Impact

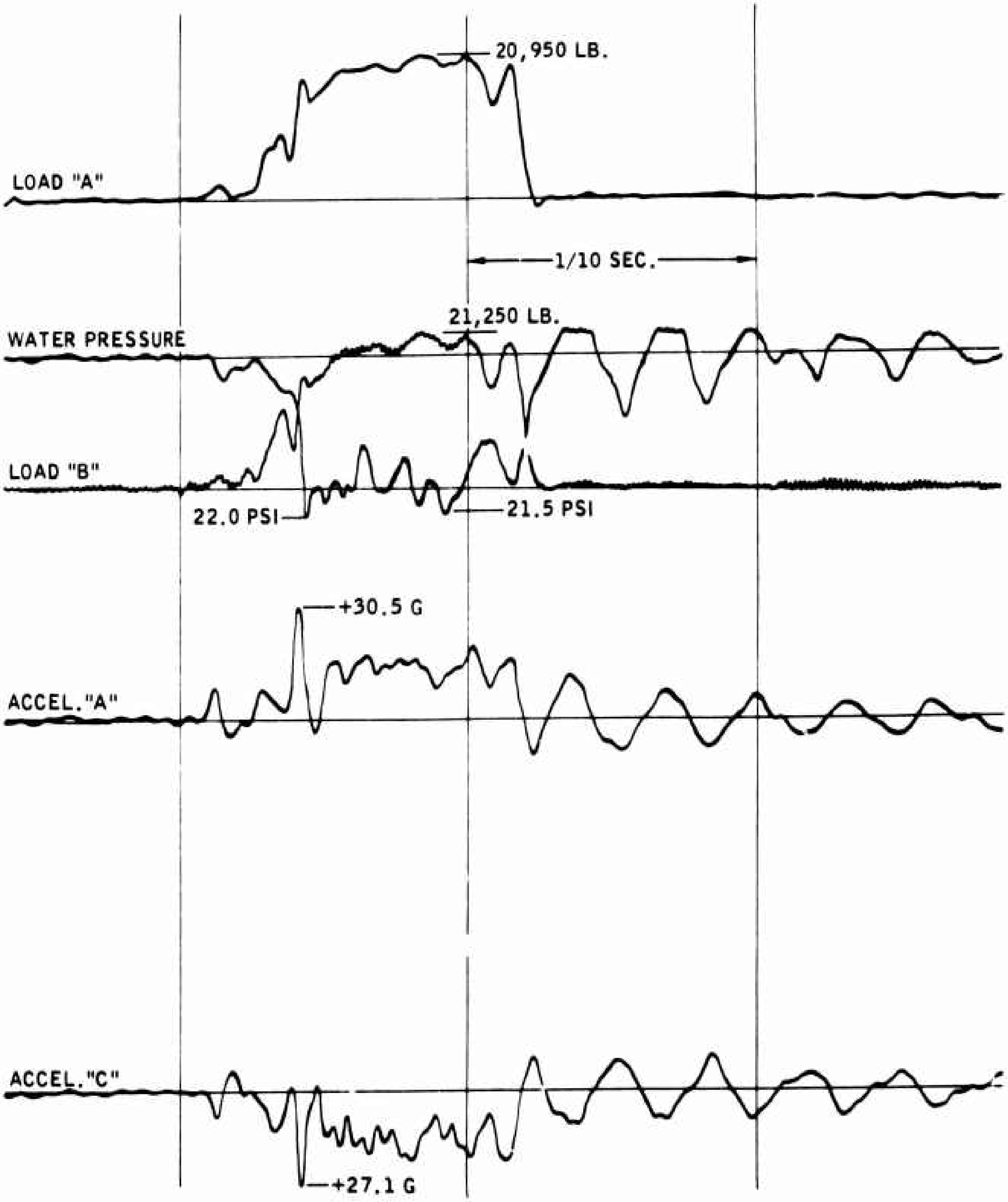


Figure B-41. Drop No. 11, 15-ft. Arrested

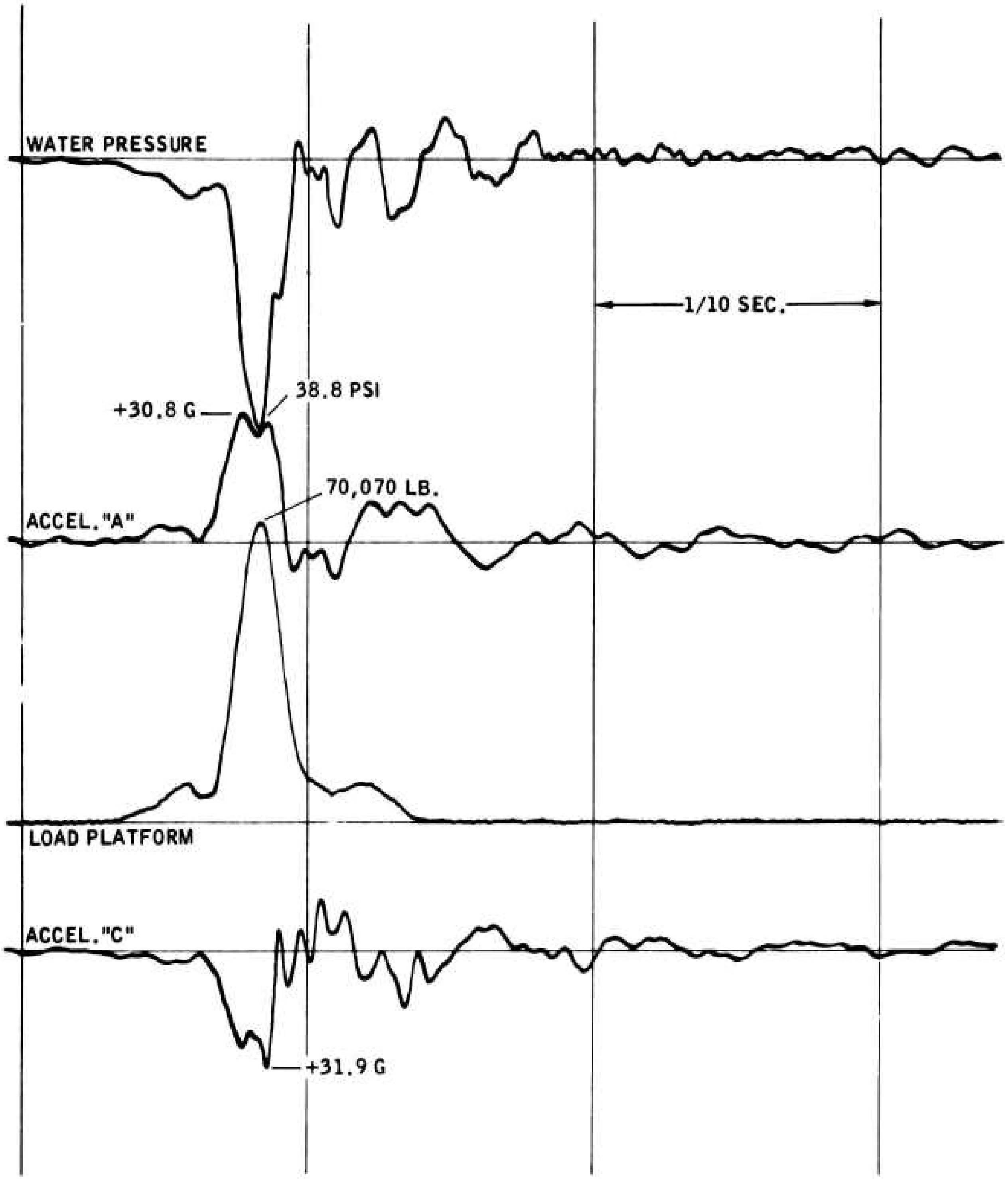


Figure B-42. Drop No. 12, 5-ft. Log Impact

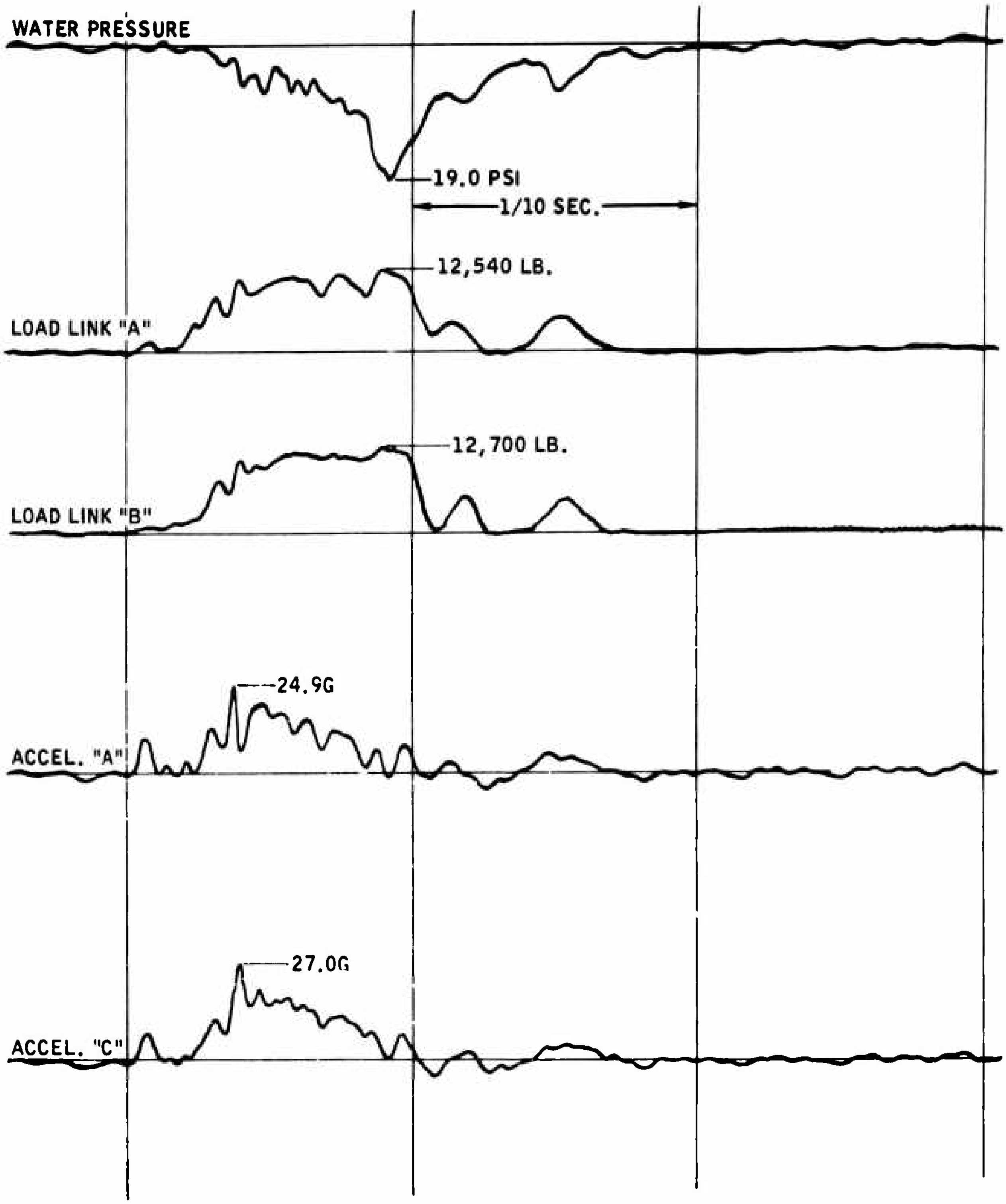


Figure B-43. Drop No. 13, 15-ft. Arrested, Half-Full Tank

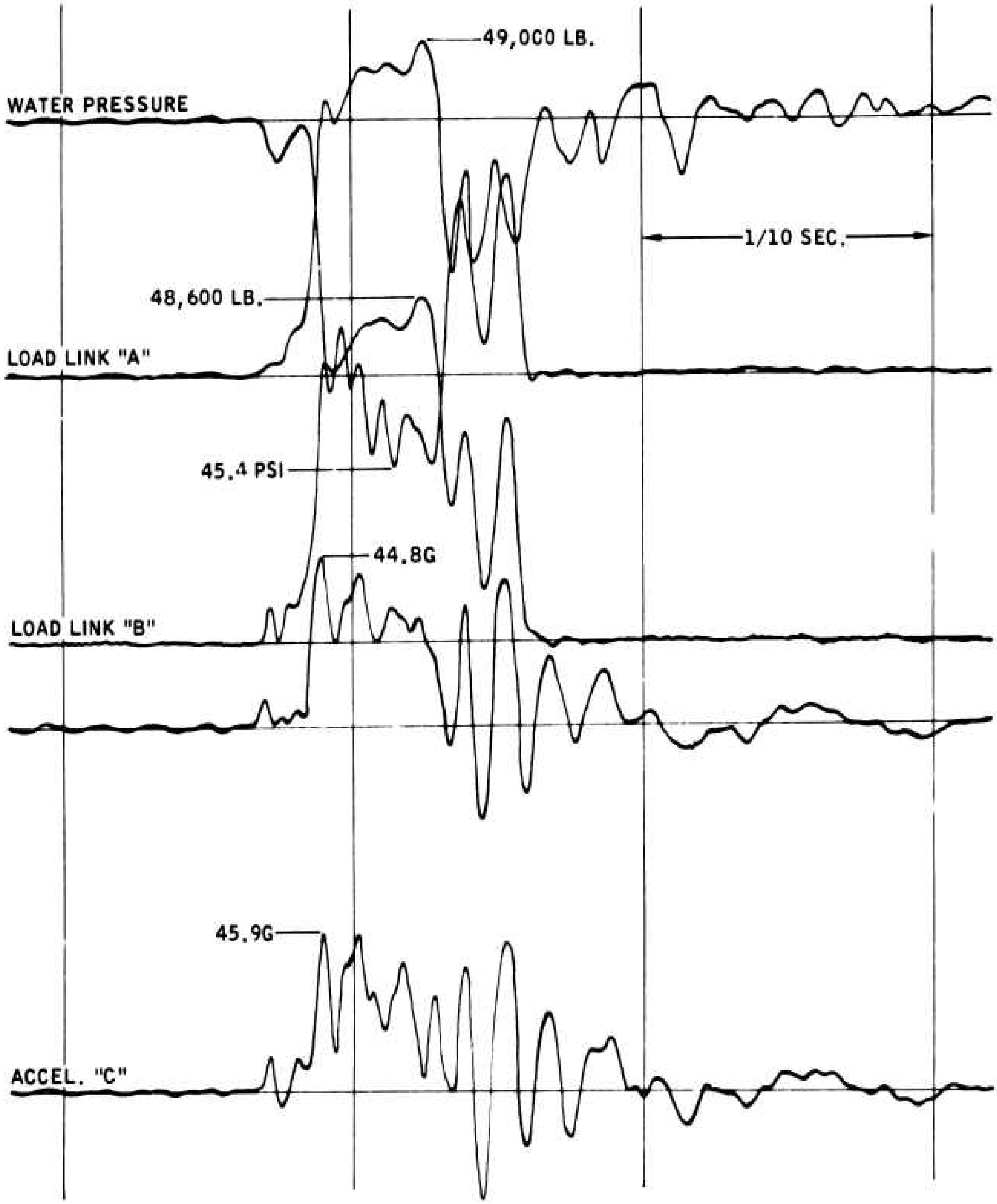


Figure B-44. Drop No. 18, 36-ft. 4-in. Arrested

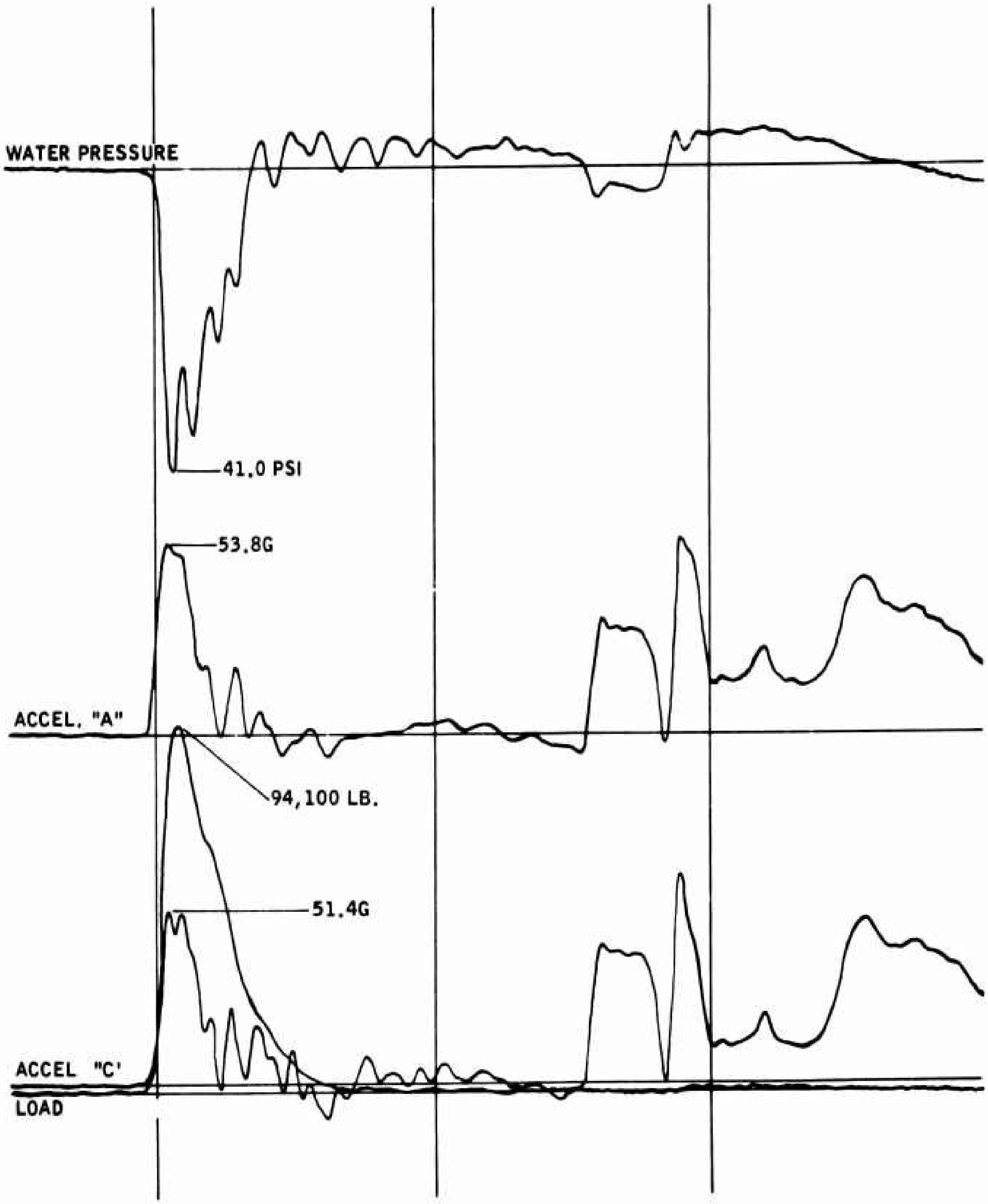


Figure B-45. Drop No. 21, 9-ft. Log Impact

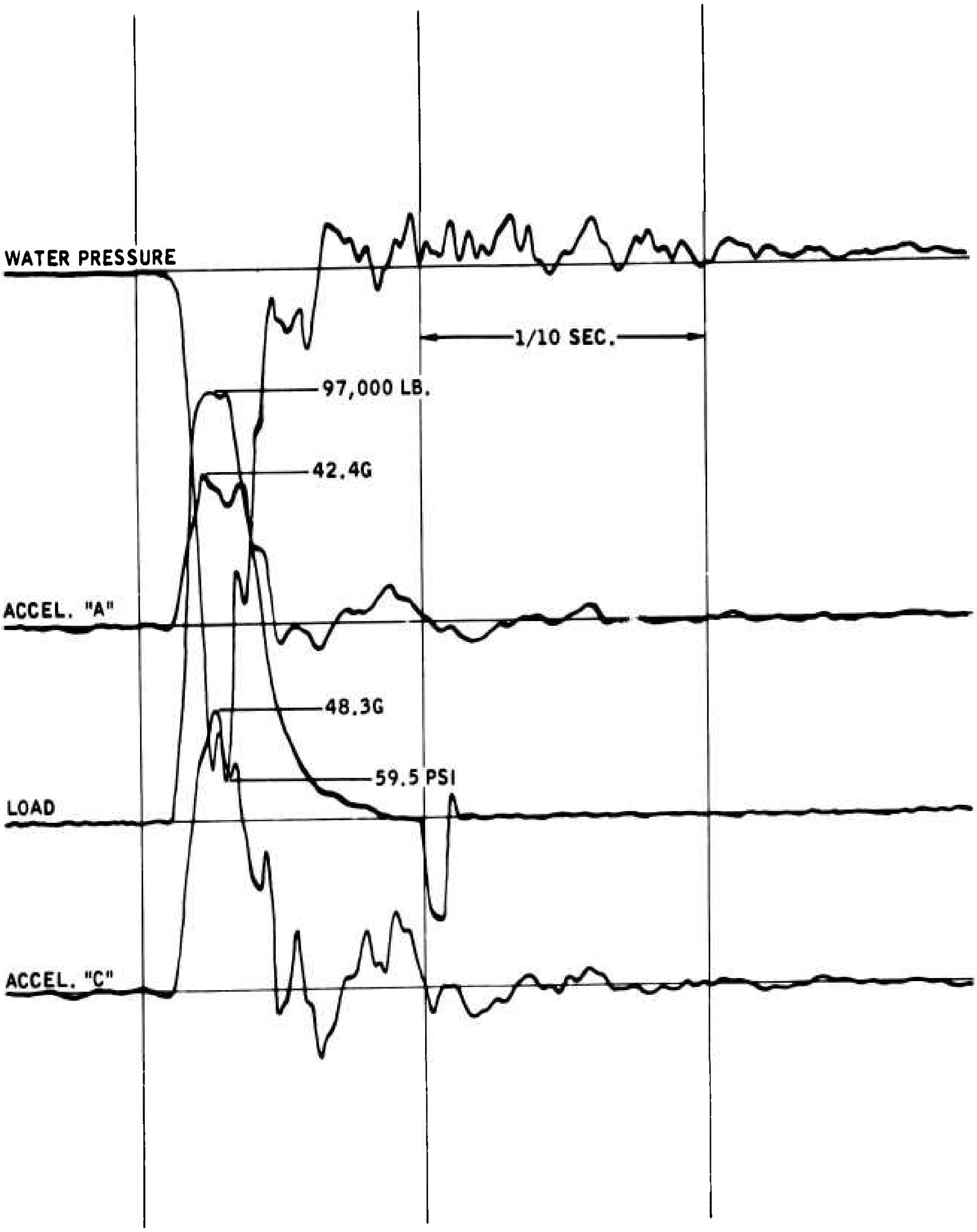


Figure B-46. Drop No. 25, 12-ft. Log Impact

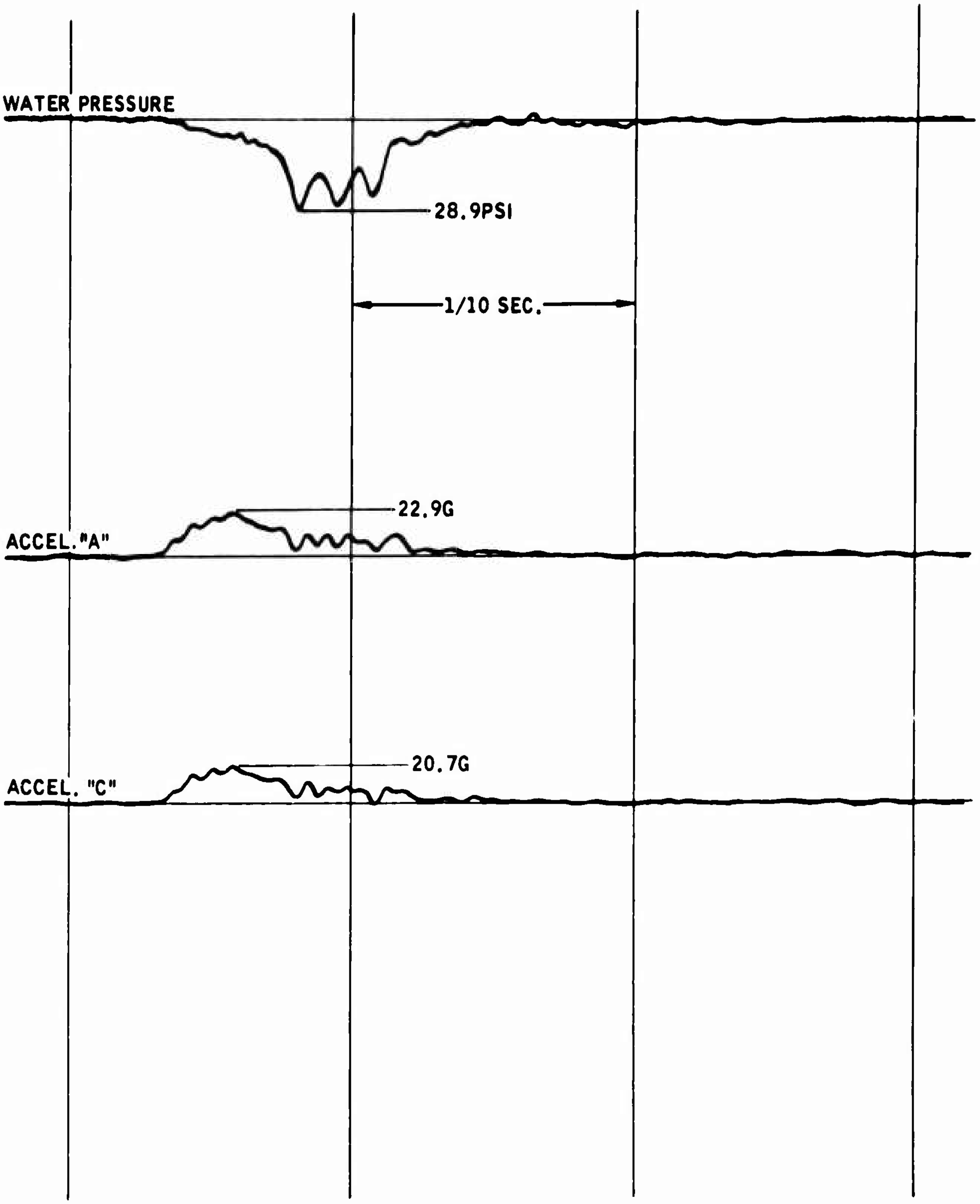


Figure B-47. Drop No. 39, 25-ft. Sand-Rock Impact, 3/4 Full

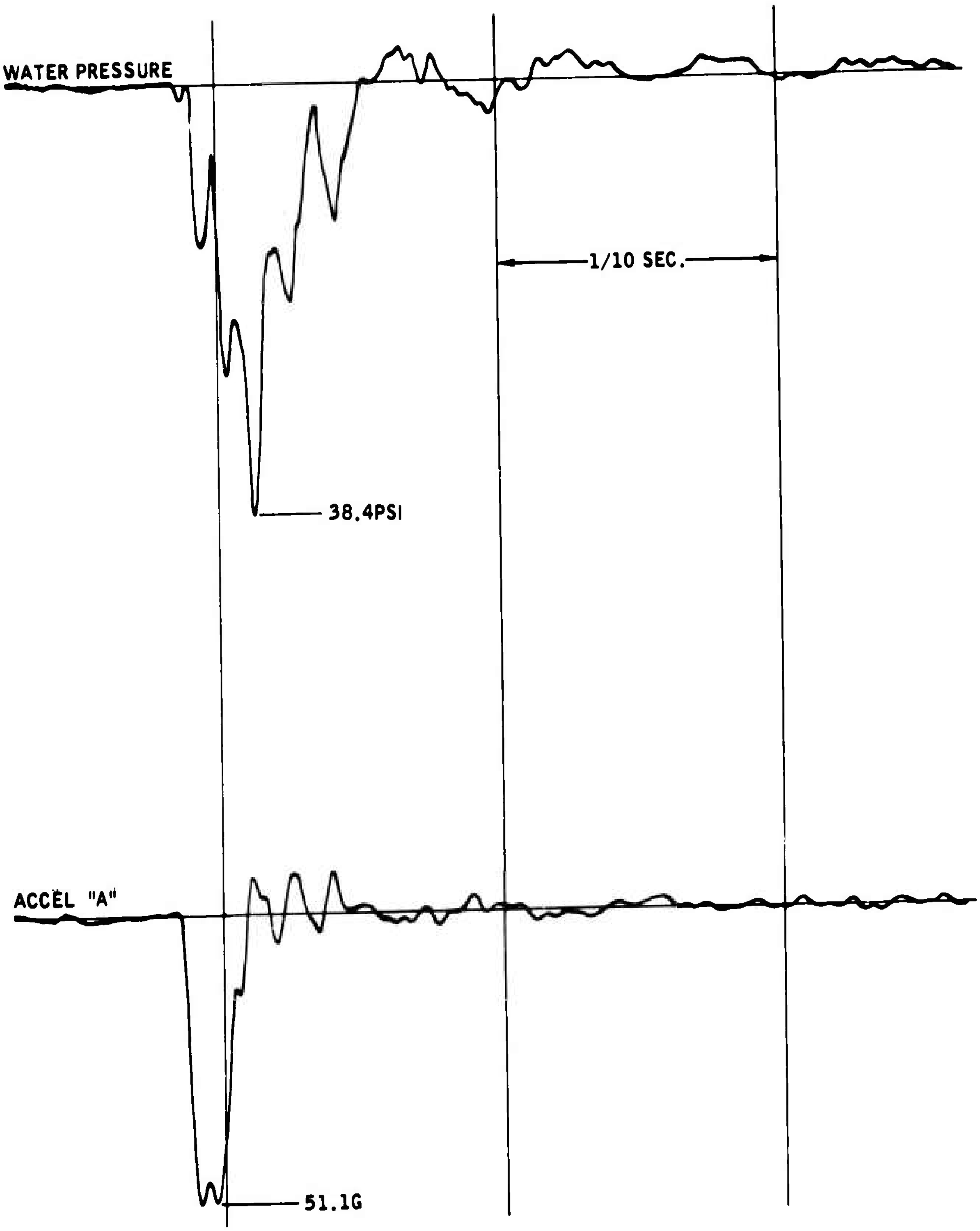
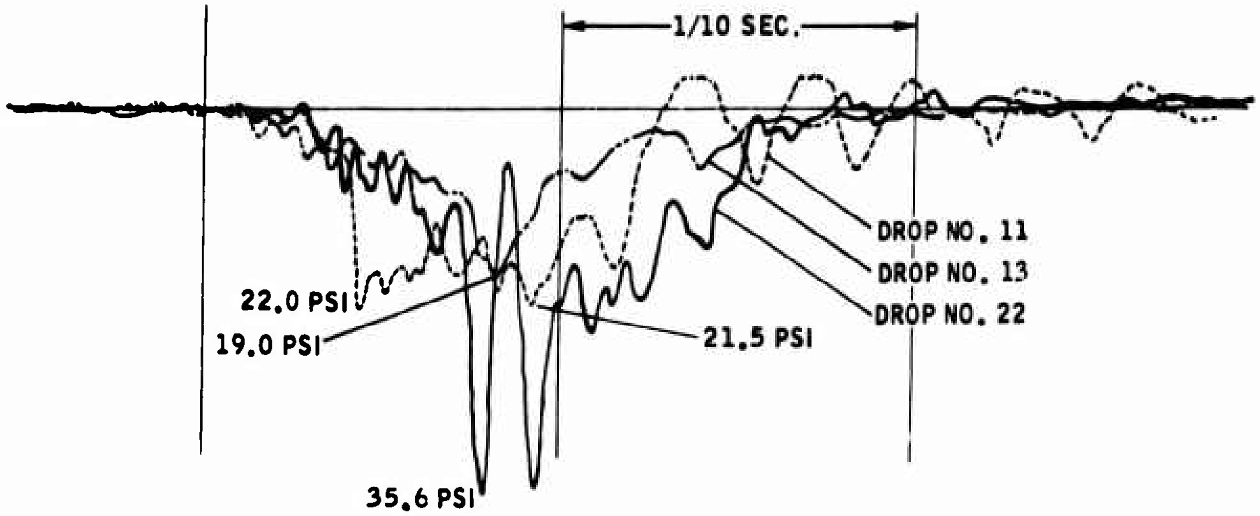
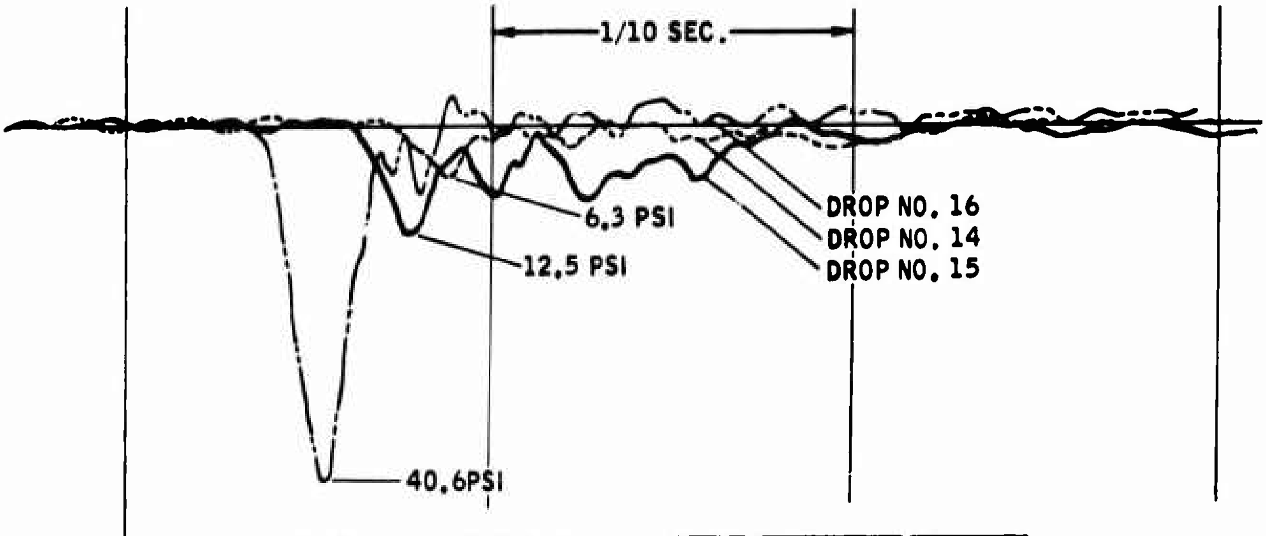


Figure B-48. Drop No. 50, 27-ft. Pole Impact, 16-in. Diameter, Tank Weight 2,830 lb.



DROP NO.	TANK FULLNESS	DROP HEIGHT	MAXIMUM VELOCITY	PEAK LOAD	PEAK RECORDED ACCELERATION
13	1/2 FULL	15 FT.	31.1 fps	13.8g	24.9
22	3/4 FULL	30 FT.	44.0 fps	15.4g	25.7
11	FULL	15 FT.	31.1 fps	15.2g	30.5

Figure B-49. Drop No. 11, 13 and 22 — Arrested Stop



DROP NO.	TANK FULLNESS	DROP HEIGHT	PEAK LOAD	PEAK RECORDED ACCELERATION
14	1/2	3 FT.	20.5	38.3
15	3/4	3 FT.	19.9	36.0
16	FULL	3 FT.	23.4	25.6

Figure B-50. Drop No. 14, 15 and 16 — Log Impact

Table B-I. Test Tank Description (16 x 48 x 72)
(Ref. Figures B-9, B-13, B-16 and B-28)

1	2	3	4	5	6	7	8	9	10	11 12
Tank No.	Upper Skin	Lower Skin	F. Spar Web	F. Spar Caps	Skin Doubler	Skin Stiffeners	Stringer	Ribs	Inter-costals	Remarks
1	0.080 2024-T3 Clad	0.080 2024-T3 Clad	0.063 2024-T3	0.125 2.0 x 2.0 Angle	None	None	None	Very light truss	None	
2	0.080 7075-T6 Clad	0.080 7075-T6 Clad	0.063 2024-T3	0.125 2.0 x 2.0 Angle	0.125 2024-T3 12-in. Chord	0.080 1.6 x 1.0 Tees	None	Very light truss	None	
3	0.090 7178-T6 Clad	0.100 2024-T3 Clad	0.071 7075-T6	0.250 4.0 x 2.4 Tee	None	0.080 1.6 x 0.8 Tees	0.125 J Sections at 8-in. spacing	Truss	0.080 1st Three & Last Bays	
4	0.090 7178-T6 Clad	0.100 2024-T3 Clad	0.071 7075-T6	0.250 4.0 x 2.4 Tee	0.125 9-in. Chord Same material as skins	0.080 1.6 x 0.8 Tees	0.125 J Sections at 8-in. spacing	Truss	0.080 1st Three & Last Bays	No. 3 Tank Rebuilt
5 & 6	0.090 7178-T6 Clad	0.100 2024-T3 Clad	0.071 7075-T6	0.250 4.0 x 2.4 Tee	0.125 9-in. Chord Same material as skins	0.080 1.6 x 0.8 Tees	0.125 J Sections at 8-in. spacing	0.050 7075-T6 Web	0.080 All Bays	Similar to No. 4 except for rib type & attachments

Table B-II. Swing Test Results

1	2	3	4	5	6	7	8	9	10	11	12
Drop No.	Tank No.	Type Test	Drop Height (ft.)	Drop Weight (lb.)	Impact Velocity (fps)	Peak Load (lb.)	Peak g			Peak Pressure (psi)	Damage
							Load	Accel. A End Plate	Accel. C R. Spar		
1	1	Arrested	5	2,784	17.9	24,220	8.7	--	--	7.4	No damage
2	1	Arrested	10	2,784	25.4	20,670	Arresting Straps Broke			8.1	Internal damage
3	1	Arrested	15	2,784	31.0	48,800	17.5	--	--	22.6	Internal damage
4	1	Log Impact	10	2,784	25.4	34,100	12.2	14.4	--	19.6	Tank ruptured
5	2	Arrested	10	2,802	25.4	30,820	11.0	19.6	--	13.1	No damage
6	2	Log Impact	2	2,580	11.3	35,410	13.7	22.0	--	20.1	Internal damage
7	2	Log Impact	3	2,575	13.9	40,450	15.7	33.1	--	30.5	Internal damage
8	2	Log Impact	4	2,570	16.0	48,080	18.7	32.7	--	29.1	Perm. set in F. Spar
9	2	Log Impact	5	2,565	17.9	52,440	20.4	30.6	--	28.7	Perm. set in F. Spar
10	2	Log Impact	6	2,560	19.6	52,710	20.6	30.0	--	26.8	Tank ruptured
11	3	Arrested	15	2,780	31.0	42,240	15.2	30.5	27.4	22.0	Internal damage
12	3	Log Impact	5	2,558	17.9	70,070	27.4	30.8	31.9	38.8	Upper skin cracks
13	4	Arrested	15	1,834 (1/2 full)	31.0	25.240	13.8	24.9	27.0	19.0	No damage
14	4	Log Impact	3	1,612 (1/2 full)	13.9	33,100	20.5	38.3	35.2	6.3	No damage

Table B-II. Swing Test Results (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
Drop No.	Tank No.	Type Test	Drop Height (ft.)	Drop Weight (lb.)	Impact Velocity (fps)	Peak Load (lb.)	Peak g			Peak Pressure (psi)	Damage
							Load	Accel. A End Plate	Accel. C R. Spar		
15	4	Log Impact	3	2,088 (3/4 full)	13.9	41,600	19.9	36.0	36.2	12.5	No damage
16	4	Log Impact	3	2,570	13.9	60,100	23.4	25.6	19.0	40.6	Internal damage
17	4	Arrested	26	2,790	40.9	74,300	26.6	35.2	33.6	34.7	Internal damage
18	4	Arrested	36.33	2,790	48.4	97,600	35.0	44.8	45.9	45.4	Note 1
19	4	Log Impact	5	2,590	17.9	70,200	27.1	40.9	40.9	28.3	Note 2
20	4	Log Impact	7	2,590	21.2	84,700	32.7	49.0	52.1	35.8	Note 2
21	4	Log Impact	9	2,570	24.0	94,100	36.6	53.8	51.4	41.0	Note 2
22	5	Arrested	30	2,316 (3/4 full)	44.0	35,740	15.4	25.7	27.8	35.6	No damage
23	5	Log Impact	10	2,316 (3/4 full)	25.4	89,680	38.7	56.4	68.8	25.6	No damage
24	5	Log Impact	12	2,316 (3/4 full)	27.8	97,500	42.1	58.5	70.4	33.6	Internal damage
25	5	Log Impact	12	2,786	27.8	97,000	34.8	42.4	48.3	59.5	Tank ruptured
26	6	Ground* Impact (Dry Sand)	5	2,880 (3/4 full)	17.9	--	--	5.7	6.0	5.1	No damage

* 30° Slope

Table B-II. Swing Test Results (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
Drop No.	Tank No.	Type Test	Drop Height (ft.)	Drop Weight (lb.)	Impact Velocity (fps)	Peak Load (lb.)	Peak g			Peak Pressure (psi)	Damage
							Load	Accel. A End Plate	Accel. C R. Spar		
27	6	Ground* Impact (Dry Sand)	7.5	2,875 (3/4 full)	22.0	--	--	6.8	7.3	15.2	No damage
28	6	Ground* Impact (Dry Sand)	10	2,870 (3/4 full)	25.4	--	--	7.5	8.0	12.9	No damage
29	6	Ground* Impact (Dry Sand)	12.5	2,860 (3/4 full)	28.4	--	--	11.2	10.7	16.2	No damage
30	6	Ground* Impact (Dry Sand)	15	2,810 (3/4 full)	31.0	--	--	11.2	12.0	18.0	No damage
31	6	Ground* Impact (Wet Sand)	15	2,795 (3/4 full)	31.0	--	--	13.7	14.0	21.7	No damage
32	6	Ground* Impact (Wet Sand)	17.5	2,785 (3/4 full)	33.6	--	--	13.7	14.7	23.6	No damage
33	6	Ground* Impact (Wet Sand)	20	2,775 (3/4 full)	36.9	--	--	15.6	17.3	22.2	No damage

* 30° Slope

Table B-II. Swing Test Results (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
Drop No.	Tank No.	Type Test	Drop Height (ft.)	Drop Weight (lb.)	Impact Velocity (fps)	Peak Load (lb.)	Peak g			Peak Pressure (psi)	Damage
							Load	Accel. A End Plate	Accel. C R. Spar		
34	6	Ground* Impact (Wet Sand)	25	2,765 (3/4 full)	40.1	--	--	16.2	19.4	24.0	No damage
35	6	Ground* Impact Sand & Rock	5	2,825 (3/4 full)	17.9	--	--	5.5	5.6	7.8	No damage
36	6	Ground* Impact Sand & Rock	10	2,825 (3/4 full)	25.4	--	--	9.8	11.3	20.1	No damage
37	6	Ground* Impact Sand & Rock	15	2,820 (3/4 full)	31.0	--	--	12.8	15.1	24.1	No damage
38	6	Ground* Impact Sand & Rock	20	2,795 (3/4 full)	36.9	--	--	22.0	19.7	28.9	No damage
39	6	Ground * Impact Sand & Rock	25	2,790 (3/4 full)	40.1	--	--	22.9	20.7	28.9	No damage

* 30° Slope

Table B-II. Swing Test Results (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
Drop No.	Tank No.	Type Test	Drop Height (ft.)	Drop Weight (lb.)	Impact Velocity (fps)	Pole Dia. (in.)	Wood Type	Peak g		Peak Pressure (psi)	Damage
								Accel. A End Plate	Accel. C R. Spar		
40	6	Pole Failure	5	2,820 (3/4 full)	17.9	6.6	Western Pine	6.8	4.6	2.0	No damage
41	6	Pole Failure	8	2,820 (3/4 full)	22.7	7.7	Western Pine	13.3	9.9	3.8	No damage
42	6	Pole Failure	12	2,820 (3/4 full)	27.8	10.1	Western Pine	20.1	13.5	6.4	No damage
43	6	Pole Failure	18	2,820 (3/4 full)	34.0	11.9	Western Pine	34.4	21.2	5.4	No damage
44	6	Pole Failure	18	2,820 (3/4 full)	34.0	12.5	Western Pine	28.9	22.2	5.0	No damage
45	6	Pole Failure	22	2,820 (3/4 full)	37.6	13.8	Western Pine	38.8	28.9	10.4	Note 3
46	6	Pole Failure	35	2,820 (3/4 full)	47.4	16.5	Red Cedar	--	--	28.5	Note 3
47	6	Pole Failure	18	2,820 (3/4 full)	34.0	13.2	Douglas Fir	36.1	--	12.3	Note 3
48	6	Pole Failure	20	2,820 (3/4 full)	36.9	14.0	Douglas Fir	42.4	--	20.5	Note 3
49	6	Pole Failure	24	2,820	39.3	14.8	Douglas Fir	53.0	--	20.8	Note 4

Table B-II. Swing Test Results (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
Drop No.	Tank No.	Type Test	Drop Height (ft.)	Drop Weight (lb.)	Impact Velocity (fps)	Pole Dia. (in.)	Wood Type	Peak g		Peak Pressure (psi)	Damage
								Accel. A End Plate	Accel. C R. Spar		
50	6	Pole Failure	27	2,820	41.6	16.0	Douglas Fir	51.1	--	38.4	Note 4
51	6	Pole Failure	31	2,820	44.6	17.2	Douglas Fir	54.6	--	35.6	Note 4
52	6	Pole Failure	35	2,820	47.4	17.4	Douglas Fir	--	--	35.8	Note 4
53	6	Stump Impact	35	2,820	47.4	14.8	Douglas Fir	--	--	21.7	Note 5

Note 1. Extensive internal damage (Figure B-23). Only external damage was six popped rivets (Figure B-20). Also refer to the high-speed sequence in Figure B-21.

Note 2. Figure B-24 shows progressive skin failure resulting from three successive drop tests. Drop No. 19 caused cracks approximately 2 in. long at the aft end of the intercostals supporting the third skin bay. Drop No. 20 extended the cracks somewhat and Drop No. 21 extended the cracks from tip to tip.

Note 3. Permanent set began to appear in the form of flange rolling in the legs of the front spar caps.

Note 4. The outstanding leg of the most forward intercostals began to crack during Drop No. 49. The cracks progressed slowly through Drop No. 52.

Note 5. A pole was set edgewise in the sand back stop. The lower front spar cap hit the center of one end of the pole. The log was split lengthwise, the lower half going under the tank and the upper half penetrating the tank back to the rear spar.

Table B-III. Fuel Slosh Test Data

	1	2	3	4	5	6	7	8	9	10	11	12
					Peak			Sustained Max. for 0.01 Sec.				
Drop No.	Type	G. W. (lb.)	Water	Height (ft.)	Load (g)	Accel. A (g)	Press. (psi)	Load (g)	Accel. C (g)	Press. (psi)		
14	Impact	1,612	1/2	3	20.5	38.3	6.3	15.4	31.1	3.6	No damage	
15	Impact	2,088	3/4	3	19.9	36.0	12.5	13.6	27.8	8.4	No damage	
16	Impact	2,570	Full	3	23.4	25.6	40.6	20.5	14.7	29.4	Internal damage	
24	Impact	2,316*	3/4	12	42.1	58.5	33.6	34.9	52.3	22.6	Internal damage	
25	Impact	2,786*	Full	12	34.8	42.4	59.5	34.4	33.9	46.7	Tank ruptured	
13	Arrested	1,834	1/2	15	13.8	24.9	19.0	12.6	15.9	15.7	No damage	
22	Arrested	2,316	3/4	30	15.4	25.7	35.6	14.1	17.0	17.9	No damage	
11	Arrested	2,780	Full	15	15.2	30.5	21.5	14.4	13.9	17.4	Internal damage	

* This was a tank with web ribs; all other had truss-type ribs.

FAA ADS-19
Federal Aviation Agency, National Aviation Facilities Experimental Center, Atlantic City, New Jersey

STRUCTURAL DESIGN FOR FUEL CONTAINMENT UNDER SURVIVABLE CRASH CONDITIONS, Final Report by P. M. Nissley and T. L. Heid, August 1964, 39 pp., including 2 illus., 37 ref. Two appendices, 86 pp., including 75 illus. (Contract No. FA-WA-4607)

Unclassified Report

This study is an investigation of crash-resistant design principles for integral fuel tanks. The objective was to improve fuel containment as a means of minimizing or eliminating post-crash fires during severe but survivable accidents. Aircraft types studied were multi-engine transports. Analytical studies indicate relative strengths, weights and costs for various tank configurations subjected to concentrated impact, distributed impact and fuel inertial loadings. Results of full-scale tank tests substantiate analytic results.

UNCLASSIFIED

I. P. M. Nissley and T. L. Heid
II. Contract No. FA-WA-4607
III. Report No. ADS-19
IV. Convair Report No. GDC-64-222

Descriptors

Aircraft Fires
Fire Safety
Aviation Safety

UNCLASSIFIED

FAA ADS-19
Federal Aviation Agency, National Aviation Facilities Experimental Center, Atlantic City, New Jersey

STRUCTURAL DESIGN FOR FUEL CONTAINMENT UNDER SURVIVABLE CRASH CONDITIONS, Final Report by P. M. Nissley and T. L. Heid, August 1964, 39 pp., including 2 illus. 37 ref. Two appendices, 86 pp., including 75 illus. (Contract No. FA-WA-4607)

Unclassified Report

This study is an investigation of crash-resistant design principles for integral fuel tanks. The objective was to improve fuel containment as a means of minimizing or eliminating post-crash fires during severe but survivable accidents. Aircraft types studied were multi-engine transports. Analytical studies indicate relative strengths, weights and costs for various tank configurations subjected to concentrated impact, distributed impact and fuel inertial loadings. Results of full-scale tank tests substantiate analytic results.

UNCLASSIFIED

I. P. M. Nissley and T. L. Heid
II. Contract No. FA-WA-4607
III. Report No. ADS-19
IV. Convair Report No. GDC-64-222

Descriptors

Aircraft Fires
Fire Safety
Aviation Safety

UNCLASSIFIED

FAA ADS-19
Federal Aviation Agency, National Aviation Facilities Experimental Center, Atlantic City, New Jersey

STRUCTURAL DESIGN FOR FUEL CONTAINMENT UNDER SURVIVABLE CRASH CONDITIONS, Final Report by P. M. Nissley and T. L. Heid, August 1964, 39 pp., including 2 illus. 37 ref. Two appendices, 86 pp., including 75 illus. (Contract No. FA-WA-4607)

Unclassified Report

This study is an investigation of crash-resistant design principles for integral fuel tanks. The objective was to improve fuel containment as a means of minimizing or eliminating post-crash fires during severe but survivable accidents. Aircraft types studied were multi-engine transports. Analytical studies indicate relative strengths, weights and costs for various tank configurations subjected to concentrated impact, distributed impact and fuel inertial loadings. Results of full-scale tank tests substantiate analytic results.

UNCLASSIFIED

I. P. M. Nissley and T. L. Heid
II. Contract No. FA-WA-4607
III. Report No. ADS-19
IV. Convair Report No. GDC-64-222

Descriptors

Aircraft Fires
Fire Safety
Aviation Safety

UNCLASSIFIED

FAA ADS-19
Federal Aviation Agency, National Aviation Facilities Experimental Center, Atlantic City, New Jersey

STRUCTURAL DESIGN FOR FUEL CONTAINMENT UNDER SURVIVABLE CRASH CONDITIONS, Final Report by P. M. Nissley and T. L. Heid, August 1964, 39 pp., including 2 illus. 37 ref. Two appendices, 86 pp., including 75 illus. (Contract No. FA-WA-4607)

Unclassified Report

This study is an investigation of crash-resistant design principles for integral fuel tanks. The objective was to improve fuel containment as a means of minimizing or eliminating post-crash fires during severe but survivable accidents. Aircraft types studied were multi-engine transports. Analytical studies indicate relative strengths, weights and costs for various tank configurations subjected to concentrated impact, distributed impact and fuel inertial loadings. Results of full-scale tank tests substantiate analytic results.

UNCLASSIFIED

I. P. M. Nissley and T. L. Heid
II. Contract No. FA-WA-4607
III. Report No. ADS-19
IV. Convair Report No. GDC-64-222

Descriptors

Aircraft Fires
Fire Safety
Aviation Safety

UNCLASSIFIED

FAA ADS-19
Federal Aviation Agency, National Aviation Facilities
Experimental Center, Atlantic City, New Jersey

STRUCTURAL DESIGN FOR FUEL CONTAINMENT UNDER SURVIVABLE CRASH CONDITIONS. Final Report by P. M. Nissley and T. L. Heid, August 1964, 39 pp., including 2 illus., 37 ref. Two appendices, 86 pp., including 75 illus. (Contract No. FA-WA-4607)

Unclassified Report

This study is an investigation of crash-resistant design principles for integral fuel tanks. The objective was to improve fuel containment as a means of minimizing or eliminating post-crash fires during severe but survivable accidents. Aircraft types studied were multi-engine transports. Analytical studies indicate relative strengths, weights and costs for various tank configurations subjected to concentrated impact, distributed impact and fuel inertial loadings. Results of full-scale tank tests substantiate analytic results.

UNCLASSIFIED

I. P. M. Nissley and
T. L. Heid
II. Contract No. FA-WA-4607
III. Report No. ADS-19
IV. Convair Report
No. GDC-64-222

Descriptors

Aircraft Fires
Fire Safety
Aviation Safety

UNCLASSIFIED

FAA ADS-19
Federal Aviation Agency, National Aviation Facilities
Experimental Center, Atlantic City, New Jersey

STRUCTURAL DESIGN FOR FUEL CONTAINMENT UNDER SURVIVABLE CRASH CONDITIONS. Final Report by P. M. Nissley and T. L. Heid, August 1964, 39 pp., including 2 illus. 37 ref. Two appendices, 86 pp., including 75 illus. (Contract No. FA-WA-4607)

Unclassified Report

This study is an investigation of crash-resistant design principles for integral fuel tanks. The objective was to improve fuel containment as a means of minimizing or eliminating post-crash fires during severe but survivable accidents. Aircraft types studied were multi-engine transports. Analytical studies indicate relative strengths, weights and costs for various tank configurations subjected to concentrated impact, distributed impact and fuel inertial loadings. Results of full-scale tank tests substantiate analytic results.

UNCLASSIFIED

I. P. M. Nissley and
T. L. Heid
II. Contract No. FA-WA-4607
III. Report No. ADS-19
IV. Convair Report
No. GDC-64-222

Descriptors

Aircraft Fires
Fire Safety
Aviation Safety

UNCLASSIFIED

FAA ADS-19
Federal Aviation Agency, National Aviation Facilities
Experimental Center, Atlantic City, New Jersey

STRUCTURAL DESIGN FOR FUEL CONTAINMENT UNDER SURVIVABLE CRASH CONDITIONS. Final Report by P. M. Nissley and T. L. Heid, August 1964, 39 pp., including 2 illus. 37 ref. Two appendices, 86 pp., including 75 illus. (Contract No. FA-WA-4607)

Unclassified Report

This study is an investigation of crash-resistant design principles for integral fuel tanks. The objective was to improve fuel containment as a means of minimizing or eliminating post-crash fires during severe but survivable accidents. Aircraft types studied were multi-engine transports. Analytical studies indicate relative strengths, weights and costs for various tank configurations subjected to concentrated impact, distributed impact and fuel inertial loadings. Results of full-scale tank tests substantiate analytic results.

UNCLASSIFIED

I. P. M. Nissley and
T. L. Heid
II. Contract No. FA-WA-4607
III. Report No. ADS-19
IV. Convair Report
No. GDC-64-222

Descriptors

Aircraft Fires
Fire Safety
Aviation Safety

UNCLASSIFIED

FAA ADS-19
Federal Aviation Agency, National Aviation Facilities
Experimental Center, Atlantic City, New Jersey

STRUCTURAL DESIGN FOR FUEL CONTAINMENT UNDER SURVIVABLE CRASH CONDITIONS. Final Report by P. M. Nissley and T. L. Heid, August 1964, 39 pp., including 2 illus. 37 ref. Two appendices, 86 pp., including 75 illus. (Contract No. FA-WA-4607)

Unclassified Report

This study is an investigation of crash-resistant design principles for integral fuel tanks. The objective was to improve fuel containment as a means of minimizing or eliminating post-crash fires during severe but survivable accidents. Aircraft types studied were multi-engine transports. Analytical studies indicate relative strengths, weights and costs for various tank configurations subjected to concentrated impact, distributed impact and fuel inertial loadings. Results of full-scale tank tests substantiate analytic results.

UNCLASSIFIED

I. P. M. Nissley and
T. L. Heid
II. Contract No. FA-WA-4607
III. Report No. ADS-19
IV. Convair Report
No. GDC-64-222

Descriptors

Aircraft Fires
Fire Safety
Aviation Safety

UNCLASSIFIED