Nonlinear Transient Analysis of a Shock Isolated Mechanical Fuse

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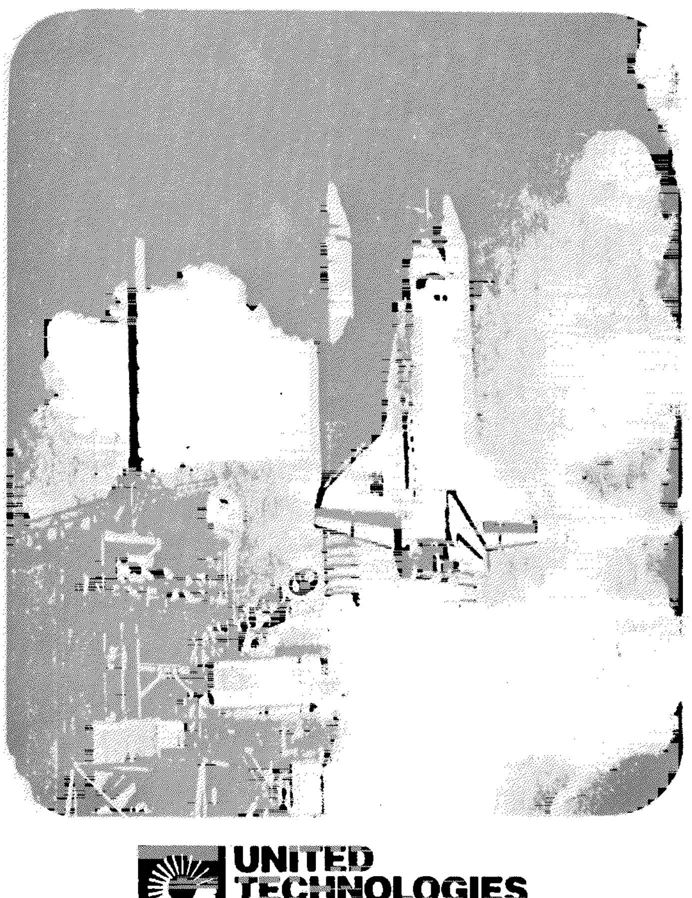
ABSTRACT:

MSC/NASTRAN Solution 99 was used to simulate a mechanical fuse in a severe dynamic load environment. The analysis model demonstrates the application of compression and tension GAP elements with a nonlinear strain hardening shock isolator. Results of the analysis were applied to redesign the mechanical fuse. The mechanical fuse is critical to the proper function of a debris retention system on the Solid Rocket Boosters (SRB). Space Transportation System (STS) 28 incorporated the redesigned mechanical fuse which performed exactly as predicted by the analysis.



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INTRODUCTION

The Shuttle Assembly connects to the Mobile Launch Platform (MLP) at eight SRB aft skirt HoldDown Post (HDP) locations. Figure 1.0 is a system view of the HDP connection. The connection consists of a pretensioned stud and two nuts. Figure 2.0 is a closeup section view of the connection. Upon SRB ignition, the frangible nut is split with a pyrotechnic charge. Destruction of the frangible nut releases the pretensioned HDP stud. A Blast Container (BC) contains the pyrotechnic blast and associated debris. After the HDP stud ejects, a Debris Containment Device (DCD) on the BC seals the open aft skirt HDP forging hole. Sealing the forging hole prevents frangible nut and pyrotechnic debris escape. Loose debris on the MLP can become dangerous projectiles if mixed with the SRB or SSME exhaust plume. Figure 3.0 displays three phases of the DCD operation at launch. Figure 4.0 is a section view of the BC/DCD showing the major components.

The requirement of a mechanical fuse evolved from DCD physical development testing. Early tests noted that the plunger did not track the HDP stud as it ejected from the BC. When the plunger lags the HDP stud during ejection, a space exists between the plunger tip and HDP stud top. Debris can enter this space and escape through the HDP forging hole. A mechanical fuse known as the attach stud was added to connect the plunger tip and HDP stud. The attach stud connection eliminates the lag space between the plunger plug tip and HDP stud during ejection. When the DCD seals the aft skirt forging hole, the attach stud fractures and the HDP stud ejection continues. Figure 5.0 is a detailed view of the frangible attach stud in the prelaunch configuration.

Performance of the DCD has been erratic and inadequate. Post flight assessment found nut and ordnance debris on the MLP after launch. Discussion and speculation lasted several months in an attempt to identify the failure mechanism of the DCD. A final consensus agreed upon by USBI and NASA pointed to premature failure of the attach stud.

USBI was directed to determine the corrective actions required for proper DCD operation. All redesign work required adherence to several constraints. Analysis, design and construction could not exceed a 2 month timeframe to support installation on STS-28. A maximum of two months were available to complete the task. Hardware changes were also to be minimized and the DCD needed to function properly without further engineering or mechanical changes. NASA does not approve of the shuttle assembly used as a development test bed for hardware modifications.

ATTACH STUD LOADS

The attach stud is a mechanical fuse. Failure occurs when the plunger plug tip seats in the aft skirt forging hole. Kinetic energy of the ejecting HDP stud provides the failure mechanism. Prior to plunger seating, the attach stud must survive all dynamic and static ejection loads.

Initial impact of the attach stud/plug tip interface defined the original design load. Figure 5.0 shows the detail of the interface. The interface gap is used in the original design to control the magnitude of the impact load. A simple analysis determined the gap which would minimize the impact load. The impact load then defined the minimum strength of the frangible neck of the attach stud.

USBI engineers agreed that the original analysis ignored several factors which influence the attach stud interface. One important factor is the sensitivity of the impact force to gap tolerances. A second factor is the possible existence of secondary impact forces during ejection. Neither factor could be adequately addressed with the original analysis. Before proceeding with construction of the analytical model, the ejection motion was studied.

EJECTION MOTION

Preload in the HDP stud produces potential energy. Fracturing the frangible nut starts a process of transforming potential energy into kinetic energy. HDP stud ejection results from this energy transformation. Attach stud analysis required a model to simulate the energy transformation process and resulting ejection motion of the HDP stud.

Deflections for HDP stud boundary conditions are expressed by the simple equation:

$\delta = \sigma l/E$ where:

δ = Holddown stud deflection
σ = Holddown stud axial stress
l = Tensioned length of holddown stud
E = Youngs modulus

Sudden release of the preload causes elastic excitation of longitudinal vibration modes in the HDP stud. Modes and displacements are represented by the partial differential equation:

$$\partial^2 u/\partial x^2 = \partial^2 u/c^2 \partial t^2 \quad \text{where} \quad c = \sqrt{E/\rho}$$

c = velocity of stress wave propagation

Solution to this equation subject to a fixed-free boundary condition describes the axial vibration state of the HDP stud. This solution will apply only during the initial contraction of the HDP stud. The lower nut provides a reaction force only for tension in the HDP stud.

When the lower nut reaction force becomes zero, the HDP stud fixed-free boundary condition becomes a free-free boundary condition. Rigid body motion of the HDP stud results from the boundary condition transition. Ejection is the rigid body motion of the HDP stud. Elastic vibration modes which are still present gradually convert to rigid body modes of motion.

During the ejection process, the frangible attach stud is experiencing elastic and rigid body motions of the HDP stud. These motions are transmitted to the plunger assembly through the frangible neck of the attach stud. Solutions from the above equations did not provide a detailed dynamic load environment needed to redesign the attach stud. Describing this changing dynamic environment could not be accomplished with equations. At this point only a nonlinear transient analysis would provide the information desired.

ANALYSIS MODEL

MSC/NASTRAN is the primary finite element program used in dynamic analysis at USBI. The decision to construct a nonlinear transient analysis model was based on the capabilities present is MSC/NASTRAN. The history of the model evolution is traced in this section.

The analysis model began with a simple one dimensional multiple element representation of the HDP stud. MSC/NASTRAN performed all of the finite element analysis. Original impact forces between the plug tip and attach stud were based on the first fixed-free frequency of the HDP stud. Initial modal analysis indicated elastic axial vibration modes that were higher than originally calculated. The correct fixed-free frequency was at least 100 Hz higher. Elastic acceleration increased accordingly as did the impact force. At this point in the analysis the decision was made to add interfaces to the model in increments.

The next model iteration added the motion of the HDP stud during the ejection process. Simulation of the MLP/lower nut interface required the use of a compressive GAP element. Nonlinear analysis activates the nonlinear properties of the GAP element. Initial displacements specified the loading at the HDP element gridpoints. Static analysis of a HDP stud with a 834 Kip preload generated the TIC card initial conditions. This preload produces the maximum attach stud deflection and acceleration environment.

The next iteration added the frangible neck of the attach stud (CBAR) and the plunger stiffness/mass properties (CONROD). A GAP element represented the frangible attach stud washer head to plunger tip interface. A NOLIN1 forcing function with TABLED1 entries provide the plunger spring force. These modifications produced some interesting results which aided in understanding the DCD/HDP stud interactions.

Initial impact forces in the transient analysis were greater than the fracture design limit of the frangible neck. Strains in the frangible neck exceeded the attach stud material ultimate strain limit. These strains confirmed premature failure of the attach stud prior to plunger seating. Analysis also generated a phenomena previously considered unimportant. After the GAP element closed the attach stud/ plug tip interface, the plunger assembly would pass the ejecting HDP stud. This meant the plunger analytically sealed the forging hole before complete ejection of the HDP stud. Another GAP element was required to represent the plug tip/HDP stud top surface interface. The additional GAP would prevent the physically impossible motion of the plunger assembly.

The final attach stud/plunger/HDP stud model is sketched in Figure 6.0. A finite element plot will not provide the conceptual detail of the model components and interfaces. This is due to the one dimensional nature of the model and GAP elements not having a visual geometric shape. GAP element ID 23 transmits only tension forces through the attach stud frangible neck. Reversing the geometry of the GAP element allows the representation of a tension interface. The CONROD element with ID 1011 represents the shock isolator stiffness. TABLES1 cards represented the strain hardening characteristics of the isolator. During the attach stud gap sensitivity analysis this spring was not present in the model.

A series of SOL 99 transient solutions provided an impact load sensitivity analysis with respect to gap settings. Figure 7.0 is a plot of the forces seen in the frangible neck during HDP stud ejection for a gap value of 0.07 inches and no shock isolator. The initial and secondary force spikes result from closure of the attach stud/plug tip gap. Secondary gap closures result from strike and rebound motions between the plunger plug tip and top of the HDP stud. Since the plunger assembly cannot physically move past the top of the HDP stud, a GAP element enforces this constraint. Striking the HDP stud top results in loss of momentum and rebound in the plunger assembly. Momentum loss and rebound retards the plunger motion with respect to the HDP stud motion. When the HDP stud begins to pull away from the plunger assembly, the attach stud/plug tip gap closes causing the secondary shock force peak.

Figure 8.0 is a summary plot for the attach stud gap sensitivity analysis for a HDP stud preload of 834 Kip. Impact force generated from the stress wave in the attach stud neck is defined along the ordinate. The abscissa has two related scale definitions. One scale defines the initial attach stud/plug tip interface gap. The second scale defines the difference between the preload deflection and initial attach stud/plug tip interface gap. The lower curve represents the initial impact force in the attach stud neck immediately after HDP stud release. Initial impact force is the first spike in Figure 7.0. The upper curve represents the maximum secondary impact force in the attach stud neck. In Figure 7.0, this would be the maximum value for all secondary force spikes.

ANALYSIS LIMITATIONS

Timeframe constraints imposed limitations on the degree of refinement that could be incorporated into the model. The NONLIN1 forcing function has an inherent time delay in the computational algorithm. Forces are calculated at the last time step causing a delay in force application for the next time step. The analysis was primarily concerned with the initial impact forces between the attach stud and plug tip. The plunger spring force plays a very minor role in the analysis at this point in the ejection cycle. We judged that the error was negligible and acceptable. Future analysis will incorporate a correction.

A second limitation is the time step interval with respect to the stress wave velocity in the frangible neck. Time step interval was selected by executing the model several times with increasing smaller time steps. When the amplitude of the shock forces in the attach stud stabilized refinement stopped. The point of the analysis was to determine the shock force magnitudes. Deflection amplitudes are to be addressed in a future analysis.

REDESIGN

The results of Figure 8.0 showed that the attach stud would never be able to withstand the impact loads regardless of the gap value. The original attach stud failure load was roughly 7500 lbf. In order to withstand the highest impact load, the redesigned attach would require a diameter of .75 inch. An attach stud with this strength would not fail on plunger seating. Should the attach stud not fail, HDP stud hang-ups will occur. HDP stud hang-ups are not a desirable situation with NASA.

The stud consumes a portion of the HDP stud kinetic energy to fail. Minimizing the energy use is a constraint to prevent HDP stud hang-up. The solution required two modifications to the attach stud interface. First the attach stud geometry and material was revised to increase the dynamic toughness. Fracture strength of the attach stud slightly increased, under USBI protest, to satisfy a few individuals. The second modification was to add a shock isolation material in the attach stud/plug tip interface. Shock isolation provided the key change in reducing the load environment without negative impact to HDP stud ejection. The new design is shown in Figure 9.0.

Strain hardening characteristics of the isolator were found with physical testing. The spring in the model was simulated by a NOLIN1 forcing function and TABLES1 cards. The results of the analysis can be found in Figure 10.0. The impact forces were below the breaking strength of the attach stud. At this point in the analysis the hardware was already built and sent to KSC for installation.

CONCLUSION

The final analysis indicated that the attach stud would survive the ejection loads of the HDP stud. We were able to complete the analysis in time to approve the new design components and install them on flight STS-28. After recovery of the SRB's, the Blast Containers were opened and the retained debris examined. Debris surveys involving reassembly of the frangible nut and weight analysis indicated +99 percent debris containment inside the BC. NASA was extremely satisfied with the results as were USBI management.

Figure 1.0

Holddown Post System Description

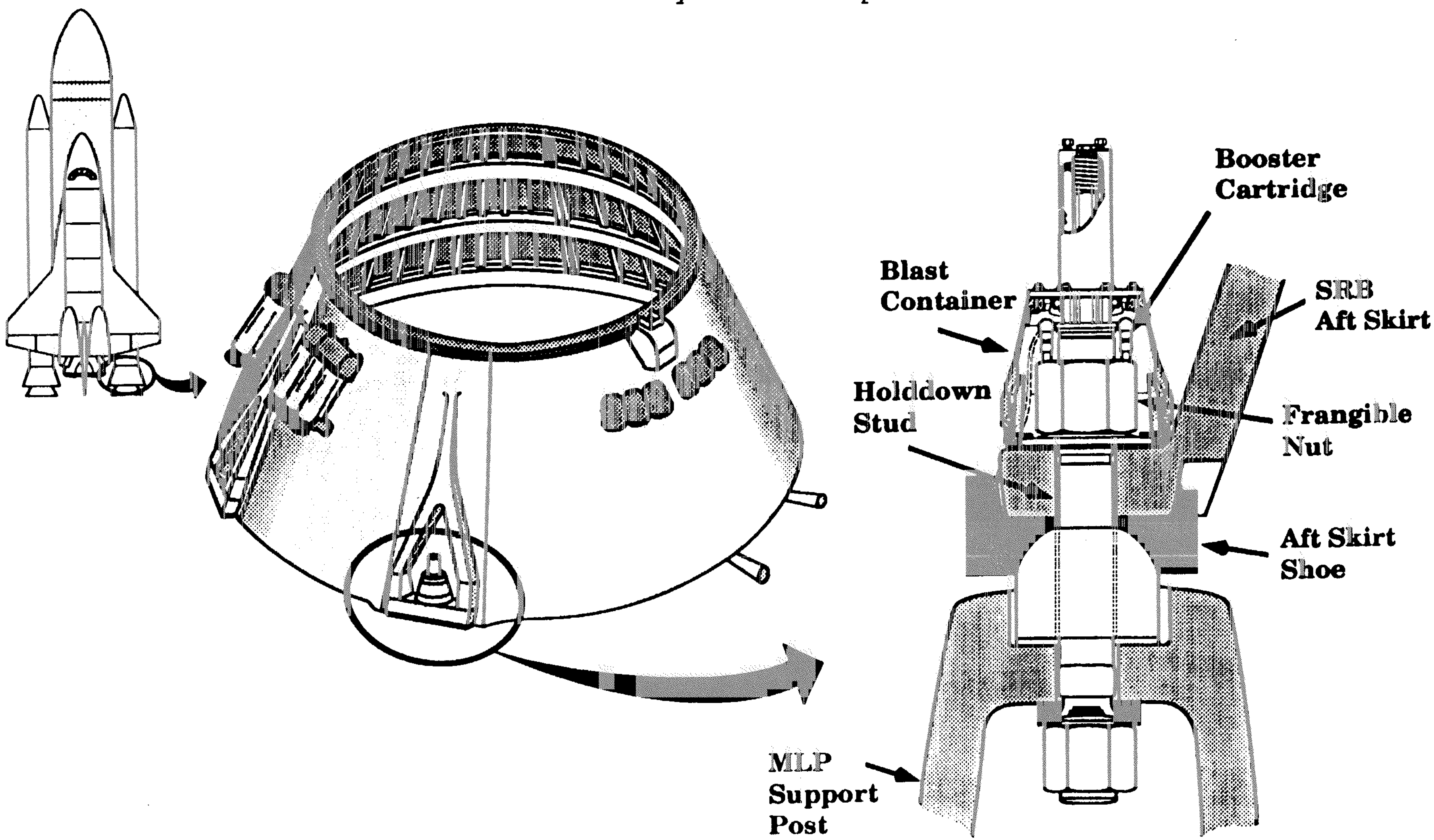


Figure 2.0

Section View for a Typical Holddown Post
and
BC/DCD Assembly

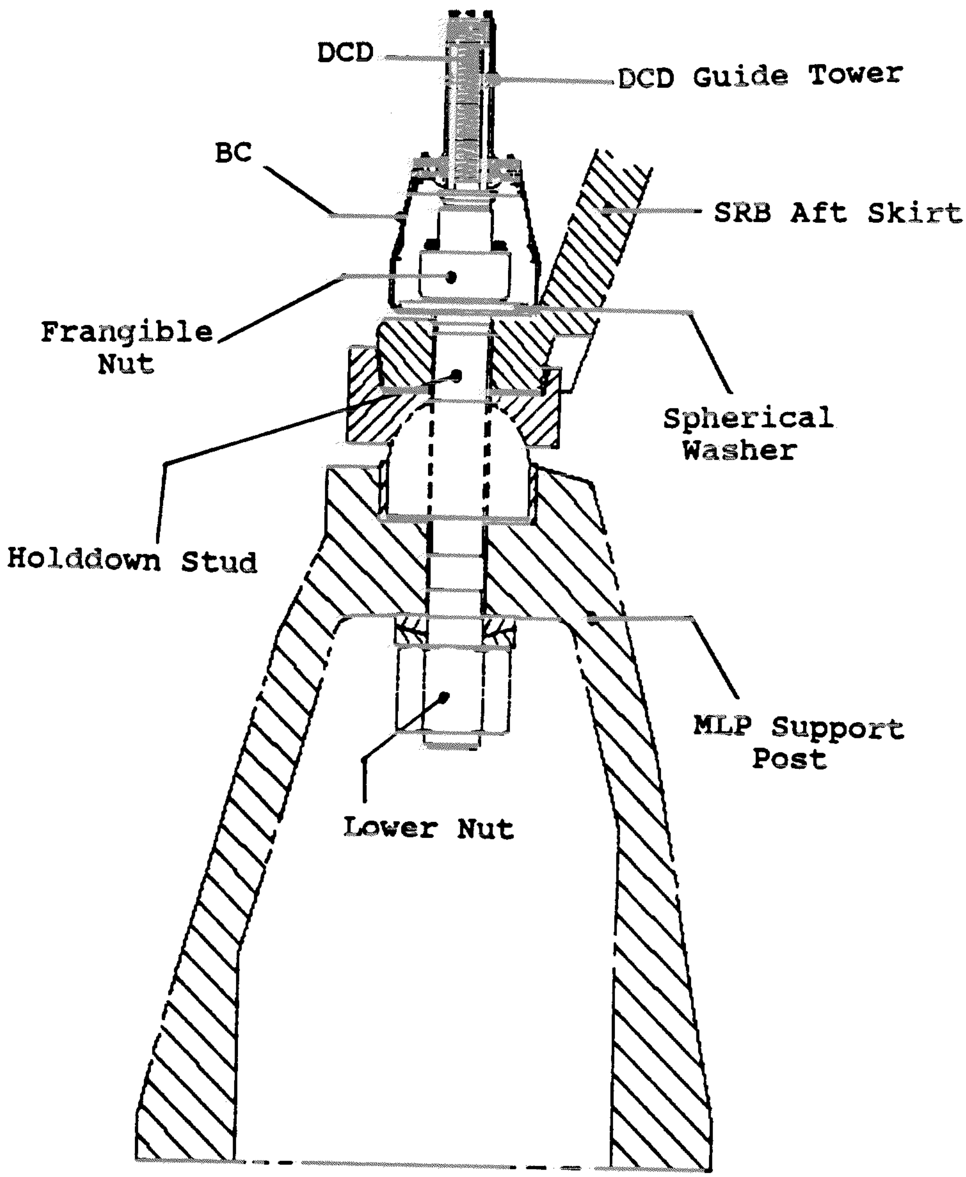
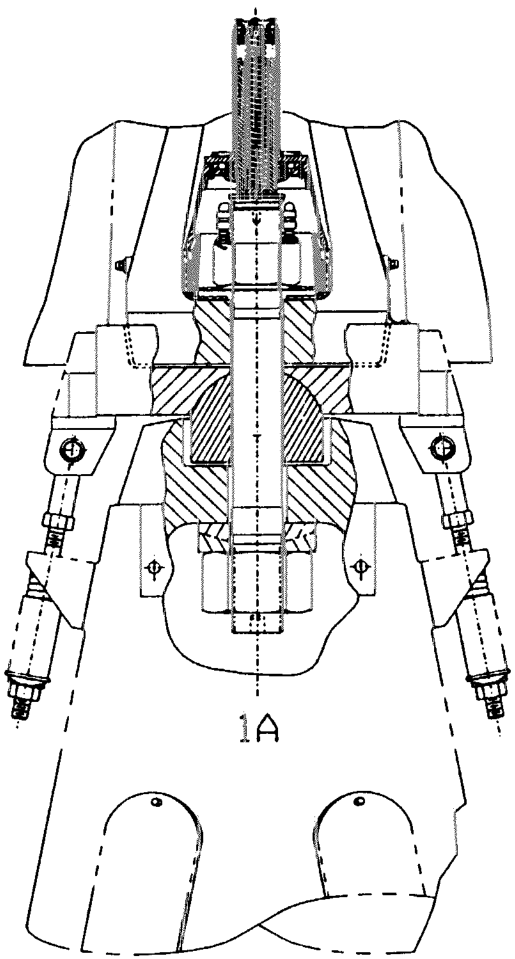
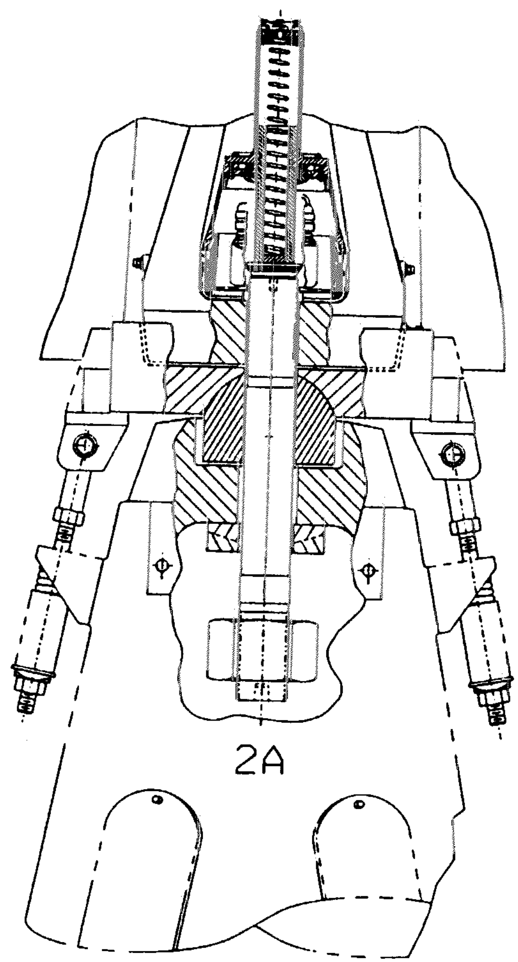


Figure 3.0

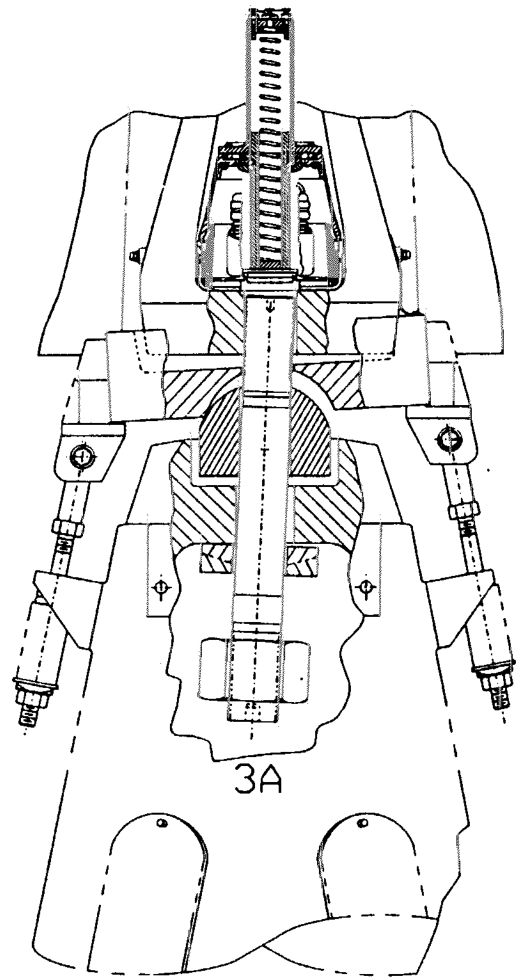
Ejection Phases of BC/DCD



Prelaunch
Configuration



HDP Stud Ejection



DCD Seal of Aft Skirt
Forging Hole

Figure 4.0

Section View of BC/DCD

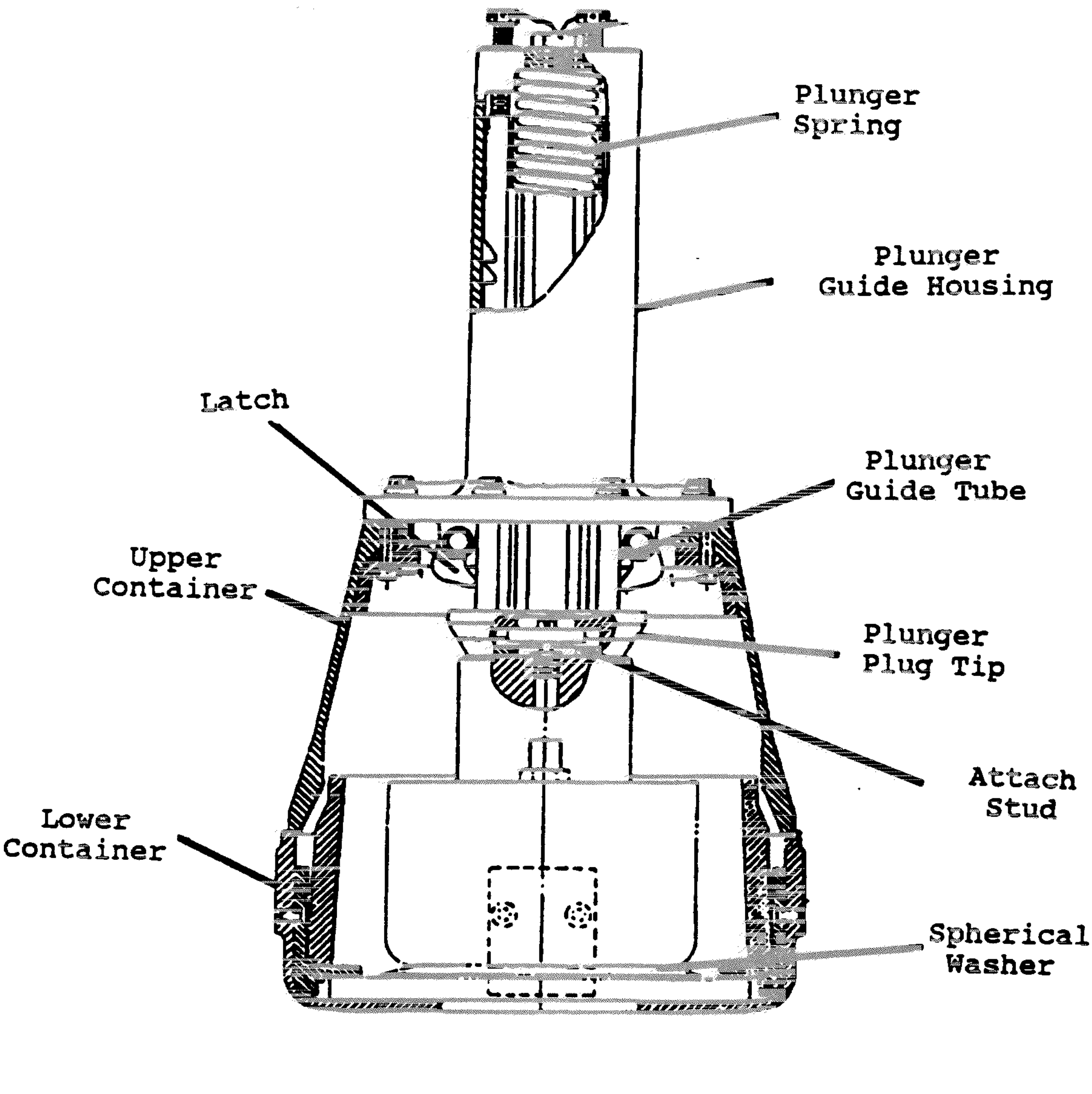


Figure 5.0

Original Frangible Attach Stud Assembly

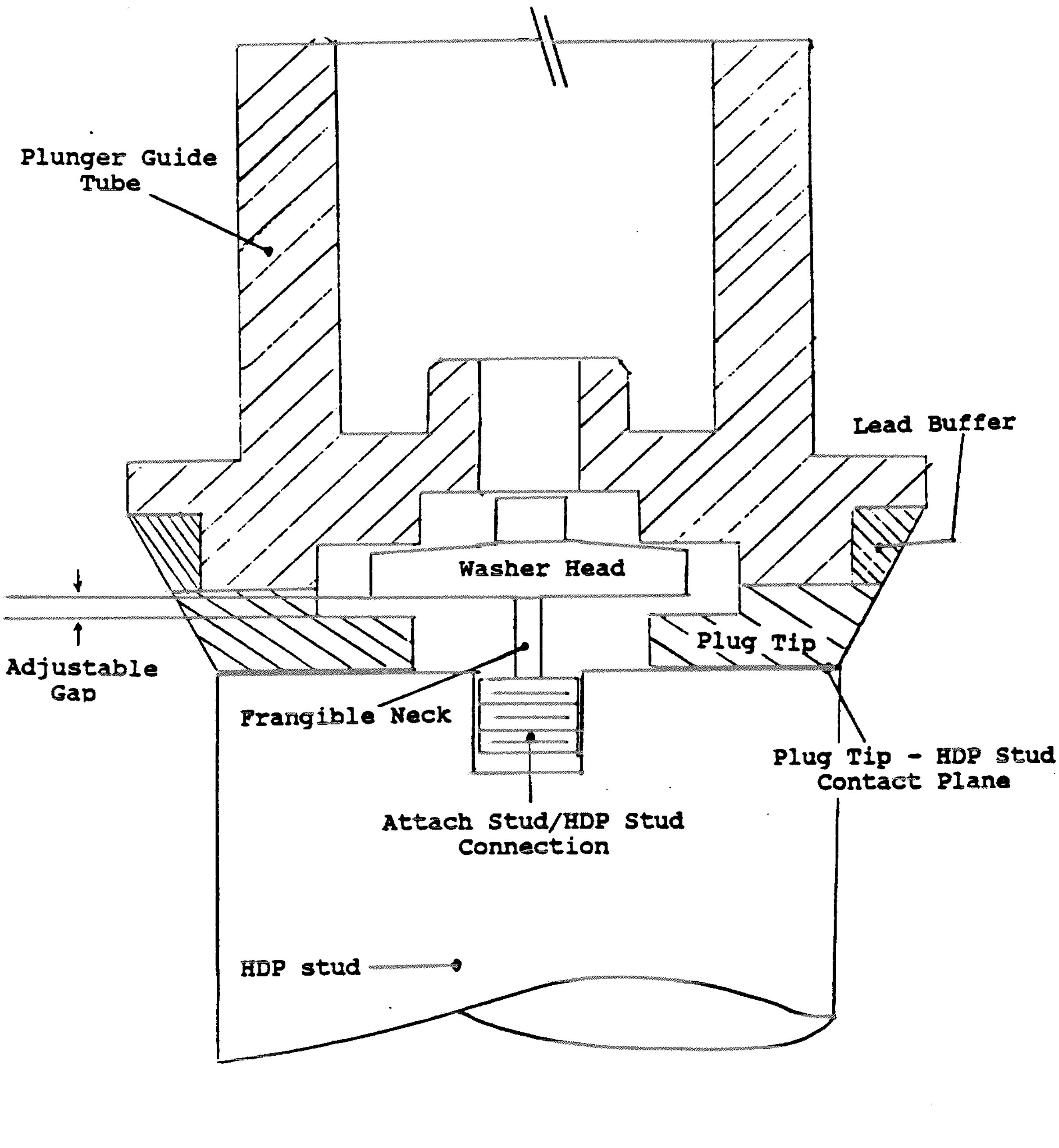
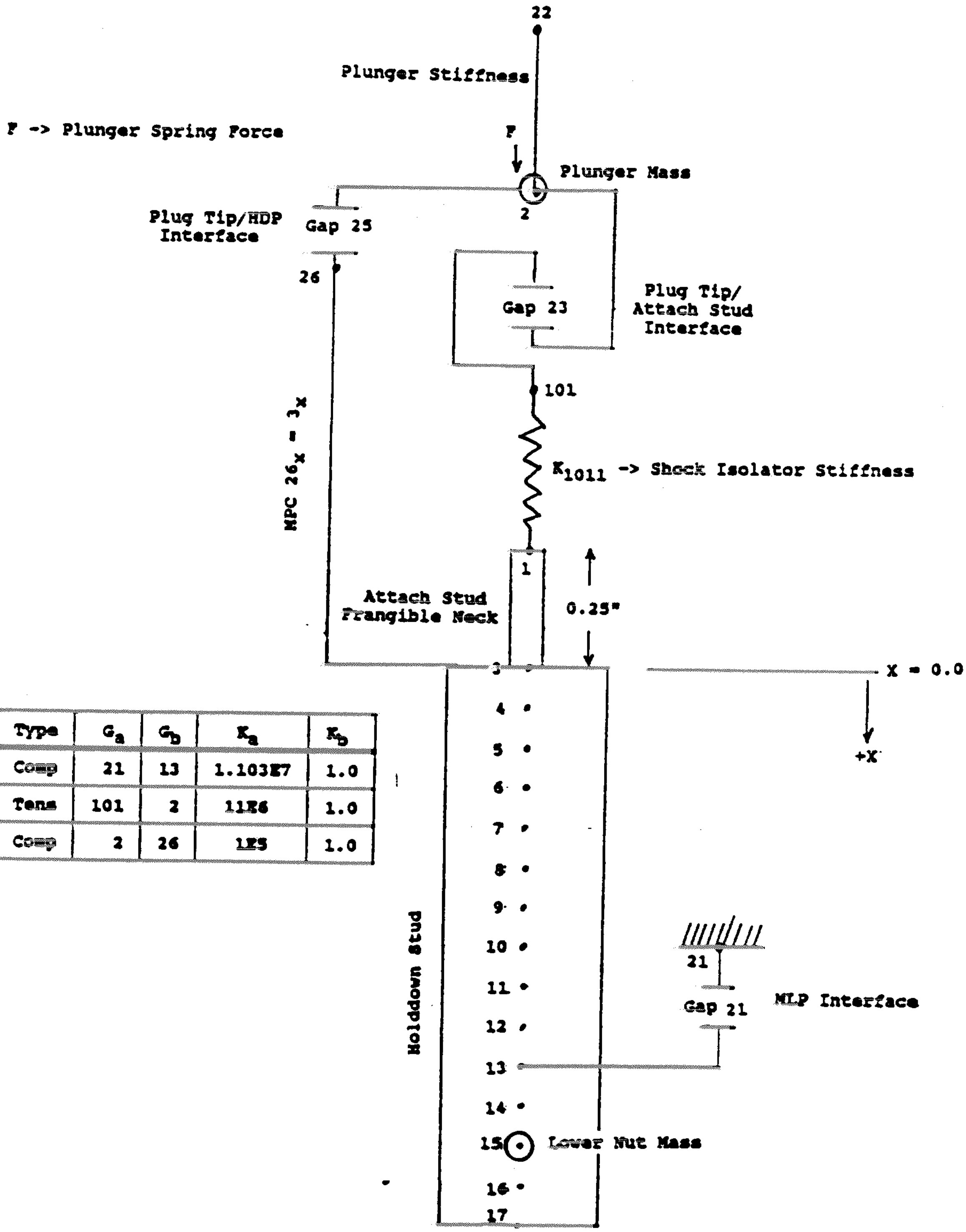


Figure 6.0

Attach Stud/HDP Finite Element Model



Gap	Type	G_a	G_b	K_a	K_b
21	Comp	21	13	1.103E7	1.0
23	Tens	101	2	1E6	1.0
25	Comp	2	26	1E5	1.0

Figure 7.0

Time Dependent Frangible Attach Stud Impact Force Summary
Attach Stud/Plug Tip Interface Gap = 0.070 Inches

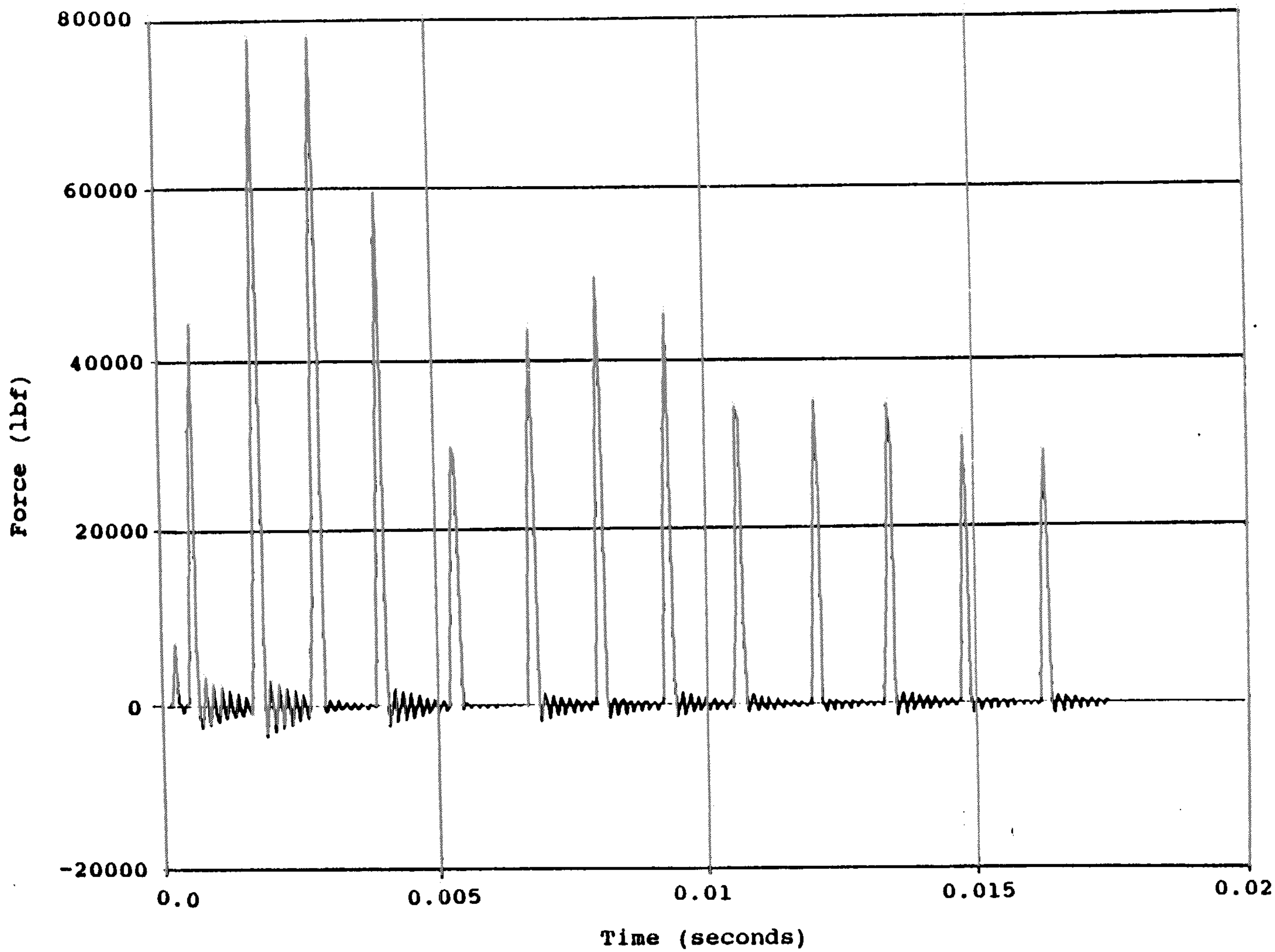


Figure 8.0

Summary of Peak Impact Forces
for the
Frangible Attach Stud

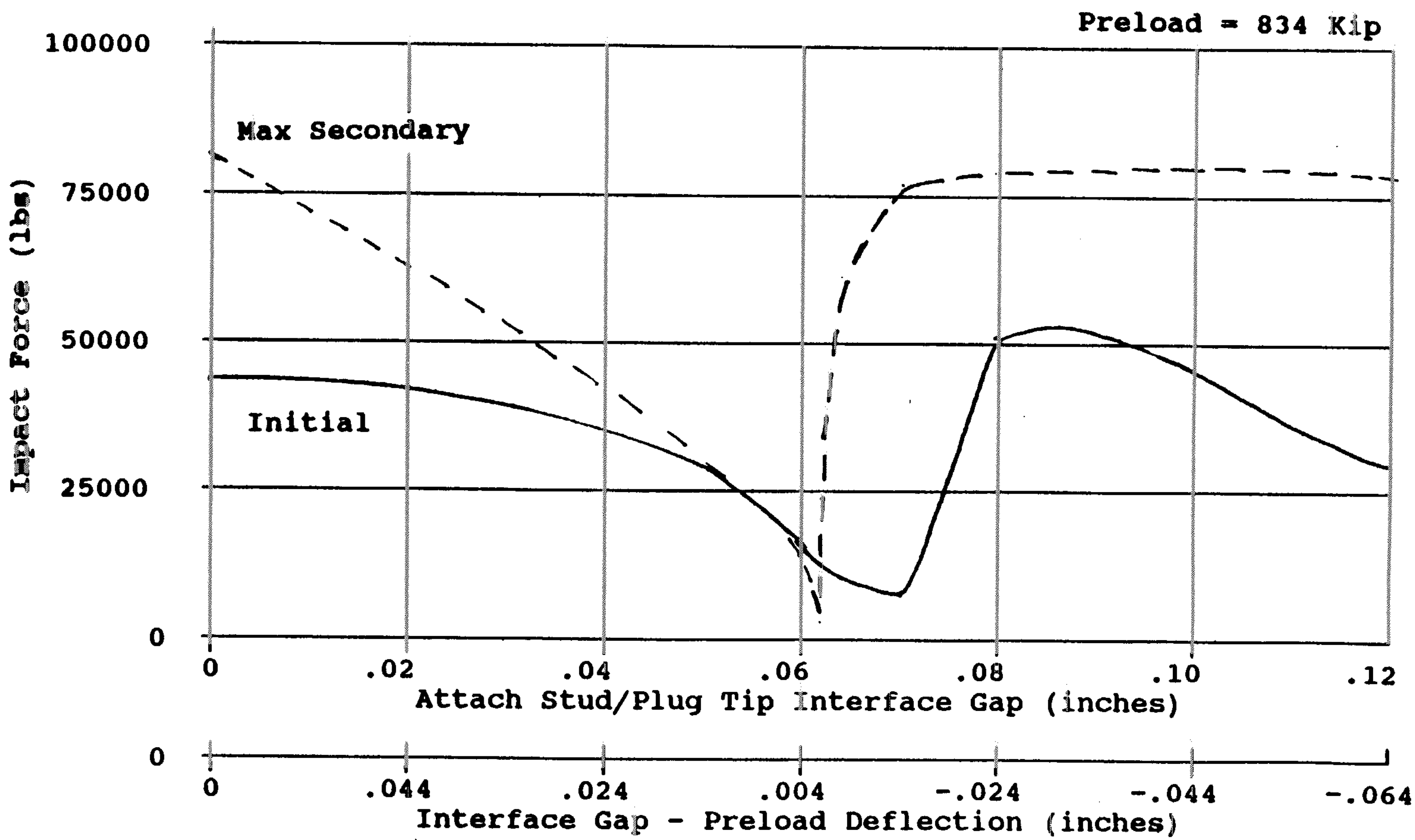


Figure 9.0

Shock Isolator in the Plunger Plug Tip Assembly

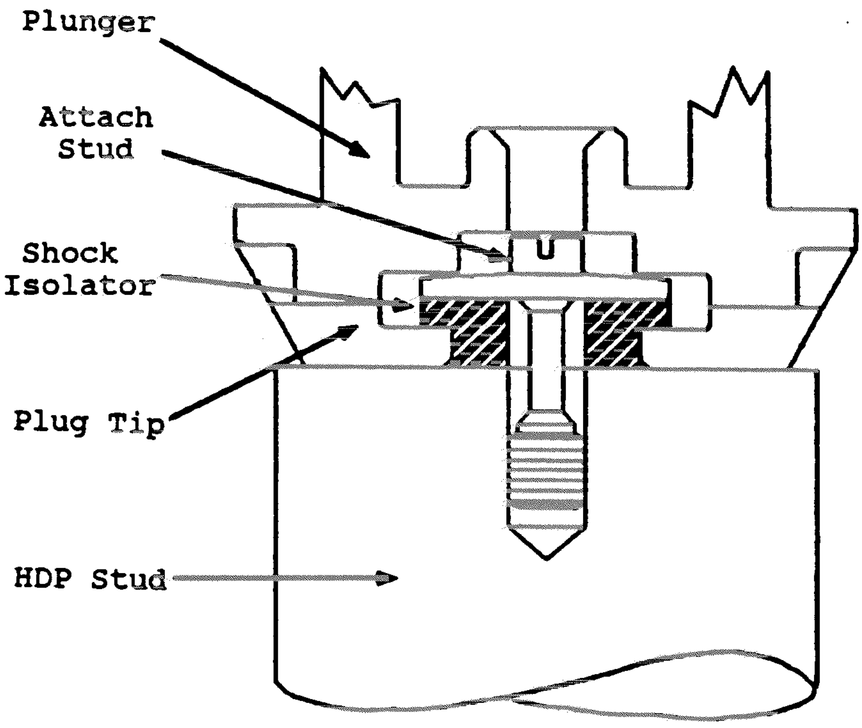


Figure 10.0

Isolated Frangible Attach Stud Impact Force Summary
Attach Stud/Plug Tip Interface Gap = 0.00 Inches