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STRUCTURAL AND MECHANICAL DESIGN CHALLENGES OF SPACE SHUTTLE SOLID ROCKET BOOSTERS SEPARATION AND RECOVERY SUBSYSTEMS

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ABSTRACT

The design of the Space Shuttle Solid Rocket Booster (SRB) subsystems for reuse posed some unique and challenging design considerations for the engineers at Marshall Space Flight Center, Alabama. The separation of the SRBs from the Cluster (Orbiter and External Tank) at 150,000 ft when the Orbiter engines are running at full thrust meant the two SRBs had to have positive separation forces pushing them away. At the same instant, the large attachments that had reacted launch loads of 7.5 million pounds thrust had to be severed. These design considerations dictated the design requirements for the pyrotechnics and separation rocket motors. The recovery and reuse of the two SRBs meant they had to be safely lowered to the ocean, remain afloat, and be towed back to shore. To safely lower a 150-ft long, 85 ton, steel cylinder to the ocean from a 220,000-ft free fall was a design challenge in every sense. It meant the development and testing of the largest parachute recovery system in use in the free world. The parachutes are capable of withstanding loads of 300,000 lb and slowing the SRBs, that would impact at 500 to 600 ft/sec to 85 to 95 ft/sec.

INTRODUCTION

The Space Shuttle concept was based on the idea of reducing the launch costs associated with putting a payload into space. One means of reducing launch costs is to return as much of the launch vehicle as practical for a safe Earth landing to be recycled for another launch.

NASA has achieved this objective by having the Orbiter "fly" back to Earth from orbit, land like an airplane, and be refurbished for future launches. Further, NASA decreed, from the onset of the Space Shuttle Program, that the Solid Rocket Boosters would also be recovered and reused after each launch. Early cost trades showed that this approach would be cost effective over the old Saturn throwaway booster concept.

This SRB reuse concept and the "piggy back" Space Shuttle design posed many unique and challenging design considerations for the engineers at Marshall Space Flight Center. The SRB reuse concept meant that a recovery system had to be developed that would safely lower the free falling SRB to an ocean landing at an acceptable impact velocity. The "piggy back" Space Shuttle design imposed special design requirements on the pyrotechnic separation systems that were to be used on the Solid Rocket Boosters (SRBs).

This paper will discuss some of the structural and mechanical challenges posed by the design of the pyrotechnic and recovery subsystems of the SRBs to the engineers and designers at Marshall Space Flight Center, Alabama.

PYROTECHNIC SEPARATION SYSTEMS

The pyrotechnic separation systems and the recovery subsystems are closely interrelated in that most of the separation systems' functions are necessary in order for the recovery subsystem to perform its function. Figure 1 shows a typical launch and recovery sequence of the Space Shuttle SRBs. At approximately 150,000 ft altitude, the three struts, which fasten the aft end of the SRB to the ET/Orbiter combination, and the separation bolt, which fastens the forward end of the SRB to the External Tank (ET)/Orbiter combination, are separated (by pyrotechnics). At the same time, four Booster Separation Motors (BSMs) in the frustum and four BSMs in the aft skirt of each SRB fire to push the SRBs away from the accelerating ET/Orbiter. Figure 2 shows the relative location of these separation systems on the SRB.

After the SRBs have coasted up to an apogee of 220,000 to 250,000 ft, they free fall back to Earth. At approximately 16,000 ft altitude, a high-altitude baroswitch closes which fires three nose cap thrusters which push the nose cap off the frustum. This event initiates the parachute sequence which will be discussed later. At approximately 9,000 ft altitude, a low-altitude baroswitch closes which fires a linear shaped charge that cuts the frustum free of the SRB. This action allows deployment of the main parachutes out of the frustum.

At approximately 1,000 ft altitude, a timer in the forward Integrated Electronics Assembly (IEA) fires an LSC which separates the aft 60 in. of the nozzle (nozzle extension) from the nozzle. At water impact, a "G" switch in the forward IEA senses 7.5 to 8.5 "g's" and fires six separation nuts which release the three main parachutes from the SRB.

SEPARATION BOLT

The forward SRB separation bolt is shown in Figures 3 and 4. The bolt is fabricated of 4340 steel heat treated to 180 to 200 ksi ultimate tensile strength and nickel plated. It is approximately 3 in. in diameter and 2 ft long. Launch and flight loads dictate that the bolt withstand 189,000 limit tension loads a bending end moment of 55,344 in.-lb. The bolt is torqued to 900 to 1,100 ft-lb of torque. The bolt has redundant pressure cartridges. At SRB burnout, redundant separation signals are sent to each of the two pressure cartridges. The pressure generated by each cartridge acts against a primary piston. This force is amplified through compression of a soft lead coupling and is transmitted to the secondary piston. The force generated by the secondary piston reacts against the secondary piston of the redundant side. This force causes the bolt housing to fail in tension at a pre-machined fracture groove. The sudden release of tension plus the extra margin of force/piston overstroke accelerates both ends of the bolt to approximately 100 ft/sec. The bolt ends are contained by crushable honeycomb installed in the SRB thrust fitting and the ET bolt catcher.

SRB/ET STRUTS

The aft SRB/ET attachment/separation system posed a unique design challenge in several areas. The strut design had to accommodate 5 to 6 in. of relative longitudinal motion between the SRB and ET, be able to transmit axial loads of 393,000 lb, transmit commands from the Orbiter/ET to the SRB, and be able to separate in a maximum of 0.010 sec. The struts had to be able to accomplish these tasks in severe flight environments. Figure 5 shows the orientation of the three strut assemblies on the SRB. All three terminate in the ET attach ring of the SRB. The lower strut and the diagonal strut are virtually the same design and could be interchangeable while the upper strut is considerably more complex because it carries the command and instrumentation signals across the ET/SRB interface.

During the stacking operation at KSC, the ET is lowered between the two vertical SRBs. The two diagonal struts (two SRBs) are pre-adjusted in length (although all three struts have adjustment capability) and are the first to be fastened to the ET when it is resting on the forward thrust posts of the two SRBs. The upper struts are the next system to be attached to the ET. At KSC, the diagonal and upper struts are premated to the SRB and swung back out of the way in low bay. The lower struts are the third and final SRB aft attach system to be mated to the ET in the high bay. They are brought into the high bay as a separate piece of hardware and mated to the "stack" at both ends — the SRB on one end and the ET on the other end.

During the initial mate, all three strut systems must rotate aft (or down) 9.5 deg. to support the ET and Orbiter (Orbiter and ET weight is supported by the forward thrust post). However, when the ET is loaded, the cryogenic temperatures of the fuel and oxidizer shrink the ET to 5.5 to 6 in. and all three strut systems swing up to a near or slightly above horizontal position. The upper strut, in addition to accommodating these initial "stacking operation" motions, must be able to rotate 18 to 20 deg (11 to 12 in.) further forward. This additional movement allows the seven electrical connectors to be separated by a more axial tensile force than sheared off by the wiping motion of the ET passing by the SRB (the strut separation planes are normal to the relative motion of the SRB/ET). All three strut systems have covers which protect the NSI cables that connect to the pressure cartridges. Figure 6 shows the cover configuration for the lower and diagonal struts. This cover is oriented on the aft side of the struts and protects the NSI cable from aerodynamic forces and heating during Space Shuttle ascent. The NSI cables cross the separation plane and are physically pulled apart by the motion of the SRB leaving the ET. It requires approximately 140 lb of pull to break the NSI cables on the lower and diagonal struts. The upper strut NSI cable crosses the separation plane through one of the seven electrical connectors (mentioned earlier) (Fig. 7).

Because of the need to protect all the electrical cables passing over the upper strut, the upper strut cover completely encapsulates the strut (Fig. 7) and is more complex than the small covers on the lower and diagonal struts. The large motion requirements of the struts, especially the upper strut, caused considerable difficulty in designing a Thermal Protection System (TPS) for the Orbiter command wiring and NSI cables. The TPS had to accommodate the motion and still prevent hot gas from reaching the cables. No mechanical transition sections from the strut to the ET ring could be designed that was rigid enough to withstand aerodynamic forces and yet flexible enough to accommodate the large angular excursions of the strut. The TPS system, finally derived for this area, is basically a "bandade" approach. The wires are wrapped with blast tape, then PR 855 foam is used to fill in between the wires. To protect the foam, it is covered with a silicon rubber and finally with three to five layers of EPDM rubber. It is desirable to accomplish the TPS closeout with the struts in the launch position (relative to the ET ring). However, this is not possible because this only occurs after ET fueling at the launch pad. Therefore, as much of the PR 855 foam and silicon rubber are pushed into the cavity as possible in an effort to allow the foam to expand and fill the gap left by the upward motion of the struts during ET filling. The whole TPS closeout process on the struts is extremely time consuming and cumbersome and will undoubtedly become an assembly "tent pole" as Shuttle launch rates increase.

SEPARATION MOTORS

Each SRB has eight Booster Separation Motors (BSMs) which fire, simultaneously, with the thrust post bolt and the strut separation initiators. These separation motors (four aft and four forward) fire for a nominal 0.7 sec and produce 20,000 lb thrust each (Fig. 8). The four forward BSMs are mounted in the frustum and canted inward toward the Orbiter and have their nozzle pointed forward (upward when sitting on the launch platform), their thermal shield design is rather complex. The thermal shield is required to insure that, during ascent, no hot gaseous flow funnels down the nozzle and impinges on the propellant. If this were to happen, the motor could be auto-ignited by this phenomena. Also, because of the possible Orbiter debris problem, the forward BSM thermal shield design had to insure that no debris would be generated at the time of BSM firing. This problem does not exist with the aft BSMs because they are aft of the Orbiter and pointed away from the Orbiter wings/tiles. The thermal shield design for the forward BSMs looks and functions like a hinged cover or door. The hinge pin is actually yielded in torsion by the opening of the door. In this way, the kinetic energy of the door is changed into heat energy by the yielding of the hinge pin (Fig. 9). Thus, the door is retained (i.e., no debris). Further, a ratchet latching mechanism insures that the door will not inadvertently swing closed after opening. The aft BSM thermal shields (covers) are not nearly as complex and are blown off at BSM ignition (Fig. 10). Because of the location of one of the skirt support posts, it was necessary to place one of the four aft BSMs by itself on the opposite side of the post structure (Fig. 11). The separation motor system and the structural separation system are initiated simultaneously. Redundant separation signals to the forward and aft separation motor systems initiate redundant NSI detonators. The detonation shock from the NSI detonators propagates through two CDF manifold and eight CDF assemblies to eight CDF initiators mounted in the separation motors (Fig. 12).

NOSE CAP THRUSTERS

The nose cap separation system is activated by the high baroswitch at approximately 16,000 ft. Because the nose cap encapsulates the drogue parachute/pilot parachute packs, the nose cap must be pushed off with a minimum of 80 ft/sec to clear the parachutes during nose cap deployment. The thruster (Fig. 13) consists of a small piston inside a cylinder that, using the gaseous pressure produced by the pressure cartridge, produces a 30,000-lb thrust over a 6-in. stroke. At the end of the 6-in. stroke, the piston rod separates from the piston and is ejected with the nose cap. Since the nose cap separation system is not man rated (i.e., is not required to function during ascent for mission success), it is a simplex system (Fig. 14). The thruster serves a dual purpose in that a 0.5-in.-diameter bolt screws into the piston body to fasten the nose cap structure to the frustum. To achieve this purpose, the thruster has a shear flange that will withstand a static tension load of 10,000 lb applied through the 0.5-in. nose cap holddown bolt's longitudinal axis prior to actuation. The thruster will also withstand a torque of 1,000 in-lb applied to the 0.5-in. holddown bolt. The shear flange is sheared by the upward movement of the piston during actuation. The majority of the thruster components (body, piston, piston rod, etc.) is 4340 steel.

SRB/FRUSTUM SEPARATION RING

The frustum separation system consists of one NSI detonator, one CDF assembly, and one frustum separation assembly (Fig. 15). During descent, as the SRB passes through approximately 6,000 ft, the low altitude barometric switch sends a fire command to the frustum separation pic. The pic initiates an NSI detonator located in the top ring of the forward skirt. The output of the detonator is propagated through the CDF assembly which detonates the Linear Shaped Charge (LSC) in the detonator block assembly. The detonator block assembly LSC detonates the LSC in the frustum separation assembly. The 30 grains/ft HMX Jetcord detonates at 7,000 m/sec and severs the 0.215 thick 2219 aluminum separation ring and releases the frustum from the forward skirt/SRB.

MAIN PARACHUTE SEPARATION NUT

The main parachute separation system consists of six separation nuts (Fig. 16) which are mounted to the underside of the forward skirt 401 ring. A 1.25-in.-diameter bolt fastens the main parachute attach fitting to the upper side of the 401 ring, passes through the ring, and threads into the separation nut.

At splashdown, a "G" switch located in the forward IEA of the SRB closes which issues a fire command through the recovery logic to the main parachute disconnect pic. The pic ignites an NSI detonator (Fig. 17) whose detonation is propagated through a CDF manifold, and six CDF assemblies to six CDF initiators installed in each of the six separation nuts attaching the three main parachutes to the SRB (there are two separation nuts per main parachute). When fired, these initiators pressurize the separation nut causing the case/collet ring to slide back opening the collet and releasing the main parachute attach bolt (Fig. 18). The attach bolt is ejected from the separation nut by the ejector piston and the tension in the main parachute links. The separation nuts are presently designed for a parachute bolt tension of 135,000 lb and a bolt torque of 750 to 800 ft-lb.

RECOVERY SUBSYSTEM

Each SRB contains a Recovery Subsystem which consists of five parachutes and associated support/attachment and deployment hardware (Fig. 19). All of the parachutes are ribbon construction made of nylon webbing, are 20 deg conical geometry, and have 16% geometric porosity. All five of the parachutes are contained in the SRB nose cone. The nose cone consists of a 75-in. tall nose cap forward section and a 120-in. tall frustum aft section. The nose cap houses the pilot and drogue parachutes while the frustum contains the three main parachutes. The frustum also contains the high and low altitude baroswitches described earlier. As might be expected of a Recovery (parachute) system that is designed to decelerate an 85-ton 150-ft-long cylinder, that is falling at about 600 ft/sec, all of the parachutes are of heavy duty construction. The pilot parachute is 11.5 ft in diameter and has a design limit load of 14,500 lb. It has a 50-ft trailing distance. It is deployed by the nose cap which has been ejected from the SRB by three piston thrusters at 80 to 90 ft/sec. The pilot parachute has 16 gores (i.e., 16 suspension lines), weighs 42 lb packed, and is attached to the top of the drogue parachute pack.

The drogue parachute is 54 ft in diameter and has 60 gores. It has two reefing stages (i.e., reefing lines) with two reefing cutters placed 180 deg apart on each reefing line. The design limit load of the drogue is 270,000 lb and its construction is massive. A few design details will illustrate this as follows: The radials are made of 4 plies of 4,000-lb strength nylon webbing, the 60 suspension lines are each made of 1 ply of 150,000-lb webbing, the reefing lines are made of 3 plies of 12,000-lb webbing, the horizontal ribbons are 1,000-, 1,500-, and 2,000-lb webbing, etc. The drogue parachute pack weighs 1,270 lb. The function of the drogue parachute is to rotate the descending SRB into a tail first orientation so that the cluster of three main parachutes can be deployed and the risks of their entanglement are minimal. The drogue parachute slows the SRB, and, when the low altitude baroswitch closes, provides the necessary force for main parachute deployment. The drogue parachute canopy trails the SRB by 105 ft and, when the frustum is released from the SRB, extracts the main parachutes (lines first) out of their deployment bags.

Each main parachute is 115-ft in diameter and has 96 gores. Like the drogue, they have two reefing stages (i.e., reefing lines) with two reefing cutters placed 180 deg apart on each reefing line. The design limit load of each main is about 174,000 lb. The radials on each canopy are made of two plies of 3,000-lb webbing, the 96 suspension lines are made of 6,000-lb webbing, each reefing line is made of two plies of 9,000-lb webbing, and the risers and dispersion bridles consist of 6 plies of 15,000-lb webbing. Each main parachute pack weighs about 1,700 lb. The function of the three main parachutes is to decelerate the SRB to an acceptable water impact terminal velocity (about 85 to 90 ft/sec) and then release from the SRB and be retrieved from the ocean by retrieval vessels.

PARACHUTE DEPLOYMENT SEQUENCE

The typical deployment sequence is shown in Figures 20 and 21. At approximately 16,000 ft the sequence is initiated by the high baroswitch as discussed earlier. The nose cap deploys the pilot chute whose function it is to deploy the drogue parachute. Early studies concluded that the nose cap did not have sufficient energy to deploy the drogue under all deployment conditions. After the pilot bag has moved about 8 ft, zero time delay cutters (100 msec) are initiated to release the drogue pack restraint straps. The pilot parachute inflates and pulls the drogue bag from the SRB. The drogue parachute is then deployed lines first. The pilot parachute and drogue bag are one-use items and are not recovered.

At drogue deployment, the angle of attack of the SRB is between 8υ and 140 deg. The function of the drogue is to rotate the falling SRB into a tail first orientation and reduce its velocity so that the cluster of three main parachutes can be deployed with minimum risk of deployment damage, entanglement or excessive loads. The drogue also provides the force required to deploy the main parachutes liner first from the frustum. After the main parachutes are stripped from their deployment bags, the drogue parachute, frustum and main parachute deployment bags continue to water impact and are retrieved for reuse.

The function of the three main parachutes is to decelerate the SRB to an acceptable water impact velocity of 85 to 90 ft/sec. In the initial concept, the main parachutes were released from the SRB at water impact to facilitate retrieval of both the SRB and the main parachutes.

The large recovery weight (160,000 to 170,000 lb) and the ocean landing of the SRBs posed some interesting design challenges for the Recovery Subsystem designers. A list of a few of these design challenges is as follows:

Pilot/drogue deployment.

Drogue loads measurement.

Main parachute flotation/energy absorbers.

Main loads measurement.

Each of these "design challenges" will be briefly addressed in this paper.

PILOT/DROGUE DEPLOYMENT

As stated earlier, because of the need of deployment condition flexibility (deployment dynamic pressure of 127 to 340 lbs/ft^2, SRB pitch attitudes of 70 to 140 deg, and SRB roll rates of 0 to 135 deg/sec), the decision was made to use a pilot parachute to insure a repeatable, orderly, drogue parachute deployment.

Figure 20 shows the deployment sequence of the nose cap pilot/drogue. The pilot bag is connected to the base of the nose cap by a three-legged bridle system. In order to limit the loads into the nose cap interface attach point and the pilot parachute bag, a method of absorbing the shock caused by the relative velocity between the nose cap and pilot parachute had to be devised.

Rip stitch type energy absorbers (Fig. 22) were developed by which shock loads could be controlled by varying the number of piles and the stroke of the energy absorbers could be controlled by varying the number of bight elements. After many static and dynamic development tests using various parent material fabrics, stitch patterns, thread strength and material, the selected configurations consist of 6,500 lb strength nylon MIL-W-4088 TY XIII with a modified six-point stitch using eight cord thread. Initially, we experienced problems of the parent material failing rather than the stitches failing. We noted that if the first stitch failed, the remainder failed in an orderly fashion with minimal damage to the parent material, the desired result. Initial test success was achieved by simply cutting the first stitch in each point of each bight. Later it was determined that the same results could be obtained by lifting the needle on the sewing machine at the end of each point stitch pattern and moving it laterally a small amount before returning back along the bight. The selected configuration produces 730 ± 230 lb per ply and 1 ft of stroke per bight. A three-ply, 10-bight configuration is used to connect the nose cap to the pilot parachute bag (Fig. 23). A 12-ply, 8-bight configuration of the same basic design is used to connect the main parachute floats to the apex of the main parachutes (discussed later). The momentum/aero drag of the nose cap provides the force necessary to break the cotton ties that fasten the pilot bag to the top of the drogue bag. As the pilot bag leaves the drogue pack, cotton ties break allowing the pilot to deploy lines first out of the bag. A drogue bag restraint loop passes through loops in the end of six drogue bag restraint straps and through two redundant reefing cutters. The other end of the six restraint straps attach to ratchet fittings on the frustum top deck to hold the drogue pack onto the frustum (i.e., SRB) until the restraint loop is cut by either of the two cutters. The two cutters are zero time cutters, i.e., they fire within 100 msec after their firing pin is pulled. The first 8 ft of motion of the pilot bag provides this pulling motion. A lanyard from the pilot bag is fastened to the firing pin of the cutters. As the pilot bag leaves, the lanyard becomes taut and pulls the cutter firing pins. We recognized a potential problem: after the two cutters had performed their function (i.e., they had cut the restraint loop), they would be unrestrained and flying freely. Because of their size and mass (2 lb), they would be potential "bullets" and could pass through the drogue canopy. If they severed a major structural member (vent line, radial, or suspension line), total loss of the SRB could result. This potential problem was averted by providing another lanyard to assure that the cutters would remain attached to the drogue deployment bag.

DROGUE DECK FITTING/LOAD PINS

At the time of drogue deployment, the SRB may at any angle of attack from 80 to 140 deg with pitch and yaw rates of 15 deg/sec and a roll rate up to 135 deg/sec. The deck fittings therefore must accommodate loads in any direction and allow changes in direction as the SRB is stabilized in a nozzle-first attitude. A double clevis arrangement shown in Figure 24 shows the selected configuration. Twelve of these fittings (each holding five suspension lines) react the drogue loads into the frustum.

At the high roll rates possible at drogue deployment, the possibility of the suspension lines twisting into a node and causing them to rub against each other as the SRB swings back and forth (pitch and yaw) was of some initial concern. A swivel attachment between the drogue and SRB was considered. However, the physical size required to react 270,000 lb, plus the tendency of bearings to lock up due to rapid load onset and the large increase in loads to individual fittings resulting from a confluence point in the drogue suspension lines caused the swivel concept to be discarded. Also, analysis showed that the rubbing force of the suspension lines, the relative velocity between suspension lines and the small number of cycles were all low enough to present a low risk. To date, after six drop tests and six Shuttle flights (12 SRBs), no suspension line damage due to twisting has been observed. The first development air drop test gave an indication of significant galling at the point contact of the 4340 steel clevises. An application of dry film lube on the rubbing surfaces has eliminated this problem.

The requirement to measure drogue loads during both development air drop tests and the first six Space Shuttle flights presented a unique challenge. Because of the symmetry of the twelve drogue attach points and the limitation of data channels, six of the fittings were instrumented. The concept of standard load cells placed in the suspension line was discarded because of the difficulty of assuring that they would not "bang" into each other during deployment and possible twisting of the lines and the expected problems of protecting the wires leading from the load cells to the frustum deck. The severe rotation and chafing environment of the clevises precluded putting strain gages on the fittings and there were not enough data channels available to instrument the four bolts on each fitting. The obvious choice remaining was the pin that fastens the drogue suspension line spool to the deck fitting shackle. Several instrumentation personnel advised against instrumenting a pin in bending because of lack of repeatability due to pin clocking and fulcrum shift during loading. The final load pin design is shown in Figure 25. Strain gages are applied to the machined "neck" of the pin. Collars are then pressed on to each end with a tolerance of ± 0.0002 in. The spacing between the ends of the upper shackle is controlled by placing a spreader tube between the clevis legs. Clocking accuracy (and pin retention) was accomplished by drilling the flange at one end of the pin and fastening it to the shackle by a screw. Once the unit is calibrated to a load of 35,000 lb, the shackle, pin and spreader tube remain as a unit until flight, so that the configuration flown is identical to the one calibrated. These drogue pins have proven very reliable and accurate. Only three drogue load measurements out of 72 pins have been lost on the first six Shuttle flights (no measurements were available from STS-4 due to SRB loss, but the retrieved drogue load cells were intact). Load accuracy of ±3% with 1% repeatability have been achieved.

MAIN PARACHUTE FLOTATION/ENERGY ABSORBERS

The expense of the large heavy duty parachutes dictated that they be retrieved for reuse. The original End Item Specification stated that access to the parachute apex be provided because riser-first retrieval causes the parachute to inflate under water and act as a sea anchor. The drogue parachute remains attached to the frustum. Access to the apex is provided by a long (175 ft) retrieval line supported by a small peanut float for easy location and retrieval.

The initial recovery concept called for the main parachutes to separate from the SRB at water impact and therefore had to be self supporting. Floats (Figs. 26 and 27) were attached to the apex of the main parachutes through 12-ply 8-bight energy absorbers (discussed earlier). The load from the floats acquired limiting for two reasons: (1) to avoid structural damage to the float bags and main parachute vent lines and (2) to limit the acceleration of parachute location aid (PLA) that was originally to be housed in the float. The PLA was never developed. The development air drop program confirmed our concern that retaining the flotation/PLA system in the dynamic environment of main parachute deployment would be difficult. During the first three drops, the PLA mass simulator nor the flotation foam could be retained. After redesigning the float and float bridle, the floats on drop tests 4, 5, and 6, with various degrees of float bag damage, were retained. Due to the uncertainty of PLA requirements and the limitation of funds for the drop test program, only one parachute on drop No. 5 tested the actual configuration used on the Shuttle flights. On the first Shuttle flight, two parachutes sank because of loss of flotation foam. On the second Shuttle flight, no parachutes were lost even though no design change was made. Examination of the float bag revealed the marginal nature of the bag design. Before flight three (STS-3) the float bag was strengthened. During STS-3, the floats of two chutes became entangled causing the failure of one chute. A program decision was then made to leave the parachutes attached to the SRB. On STS-4, the separation nut on one of two main chute attach fitting was deactivated. Due to premature activation of the active separation nuts, both SRBs were lost. On STS-5 and STS-6 and for the forseeable future, the main parachutes will remain attached to the SRB until the retrieval crew detaches them. If an improved separation nut design and software is developed, a deck-mounted flotation system will be developed to again allow separation of the main parachutes at impact.

MAIN PARACHUTE LOAD MEASUREMENT

Each of the three main parachutes are attached to the SRB at two attach points. The total of six attach points are equally spaced around the circumference of the forward skirt. Load measurement for the main parachute attach fitting presented a different challenge. These fittings were designed for a load of 125,000 lb. Since the SRBs might still be rolling and swinging at main chute deployment, and to accommodate changes in pull angle resulting from the different inflated stages of the main parachutes, the fittings were required to articulate in two planes to assure pure tension measurements (Fig. 28). Radial articulation was provided by means of a yoke attached to the fixed portion of the fittings bolted to the SRB. Tangential articulation was provided by pinning to the upper portion of yoke, the two plates that carried the loads from the four bolts through the risers to the yoke of the deck fittings. Since these plates are the only component reacting pure parachute riser tension loads, this was the logical place to locate the load cells. In order to control the attitude and restrict the motion of the articulated attach fittings, shear bolts were placed through the yoke and fixed deck fittings and tangs on the plates were forced against the fixed fittings. This approach held the total assembly rigid until the bolts were sheared at main parachute line stretch. In order to avoid bending stresses in the instrumented plates, the four bolts that pass through the spreader plates and spools were carefully torqued and a feeler gage measurement was made between the plate and spools. Also, once the unit was calibrated, all components remain together. A standard load cell was considered for this application, but 125,000 lb capacity load cells are quite large and supporting any hardware from the SRB forward skirt dome was not allowed. Therefore, the problem of cantilevering such large load cells from the deck fittings was avoided by using the selected configuration.

The main parachute attach fittings, the drogue load pins and the drogue deck fittings were all initially intended for single usage. The drogue deck fittings have been tempered from a maximum tensile strength of 180,000 lb to 160,000 lb and are certified for multiple reuse providing they pass proof test and magnetic particle inspections. The main chute deck fittings and drogue load pins have been refurnished and certified for a second use.

CONCLUSION

This paper has discussed some of the more significant design challenges raised by the initial specification requirements. Now that the developmental flights (STS-1 through STS-6) have flown, how well these challenges have been met can be assessed.

In general, both the pyrotechnic and recovery subsystems have met or exceeded design requirements. In twelve vehicles, there has only been one instance where the pyrotechnic system has failed to function properly. That was on STS-4 when a 7.5 g "G" switch sensed the design 7.5 g's from the pyrotechnic shock propagated by the frustum/SRB linear shaped charge and fired the main parachute separation nuts and released the parachutes before they could function. Since STS-4, the parachutes have been attached to the SRB's by structural nuts.

The recovery subsystem has had some anomalies occur because of the requirement for the parachutes to be separated from the SRB at water impact and be self floating. This buoyancy requirement requires flotation be added to the parachutes. This flotation has caused the following anomalies: On STS-1, two parachutes "drowned" because the flotation was torn off during parachute deployment and the parachutes sank. On STS-3, the floats of two parachutes became entangled and caused the failure of one of the parachutes. Since STS-4, the decision was made to leave the parachutes attached to the SRBs, and we have had no parachute failures since. The drogue parachute has always been subjected to loads above design limit on each Space Shuttle flight, and no major structural damage has been noted. One of the two remaining STS-3 main parachutes saw loading 34% above design limit and again no major structural damage was noted.

Presently, larger main parachutes (136-ft-diameter) are under development to slow the SRBs to 75 ft/sec to lessen water impact damage. We expect no major problems with this development based on our experience with the existing design.

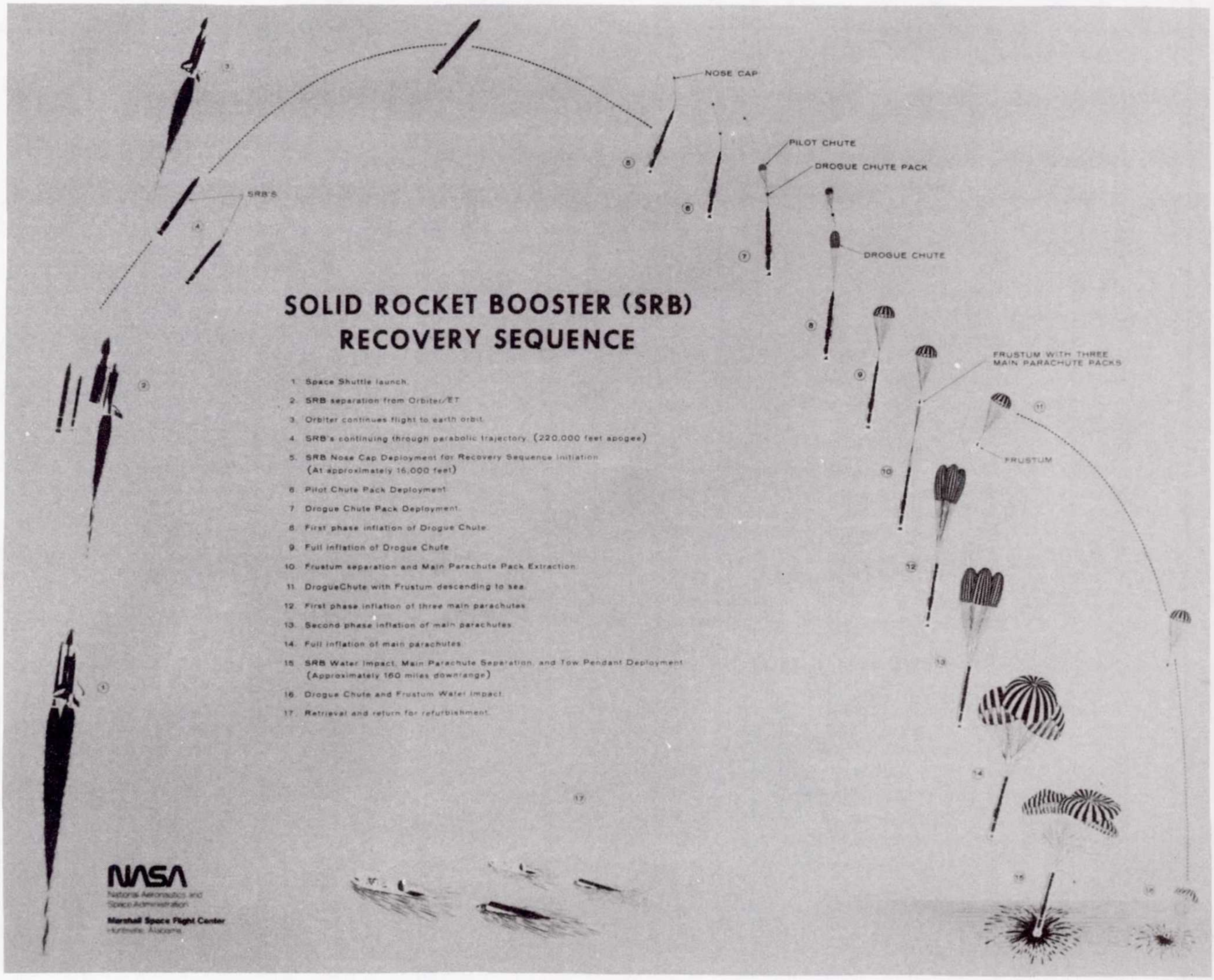

Figure 1. Solid Rocket Booster Recovery Sequence

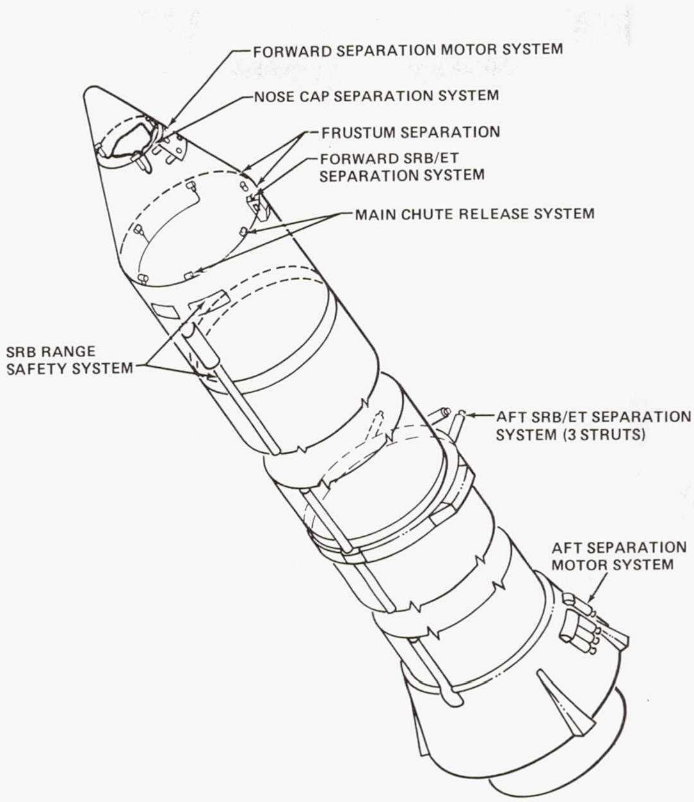

Figure 2. SRB/ET Separation and Recovery Systems.

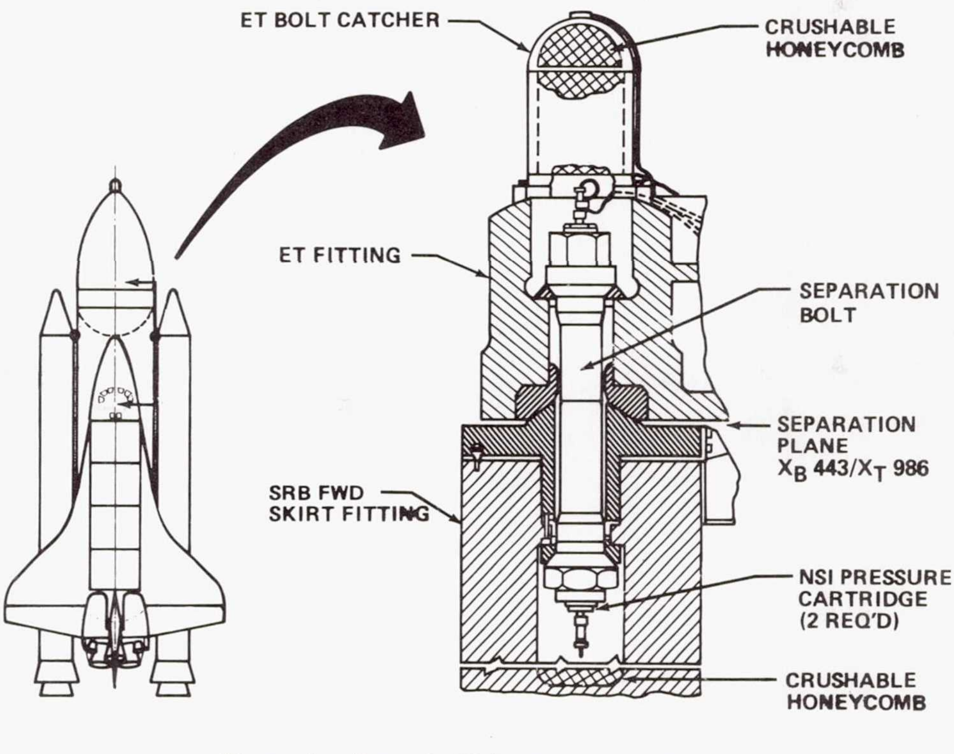

Figure 3. Forward SRB/ET Separation System.

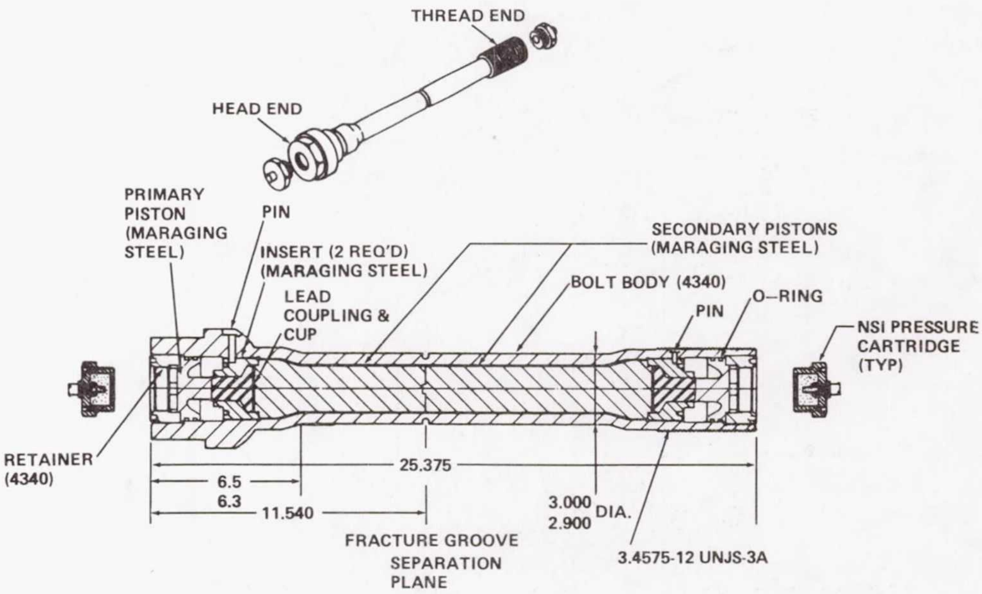

Figure 4. Forward SRB/ET Separation Bolt.

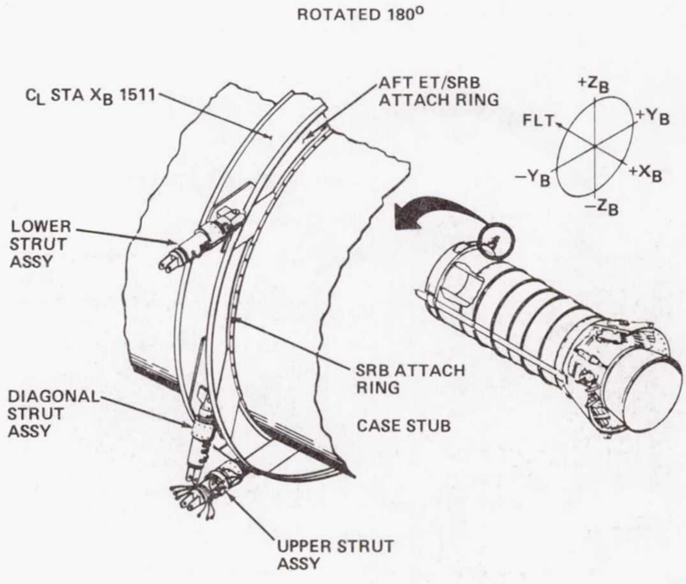

Figure 5. Aft Separation Strut Assemblies.

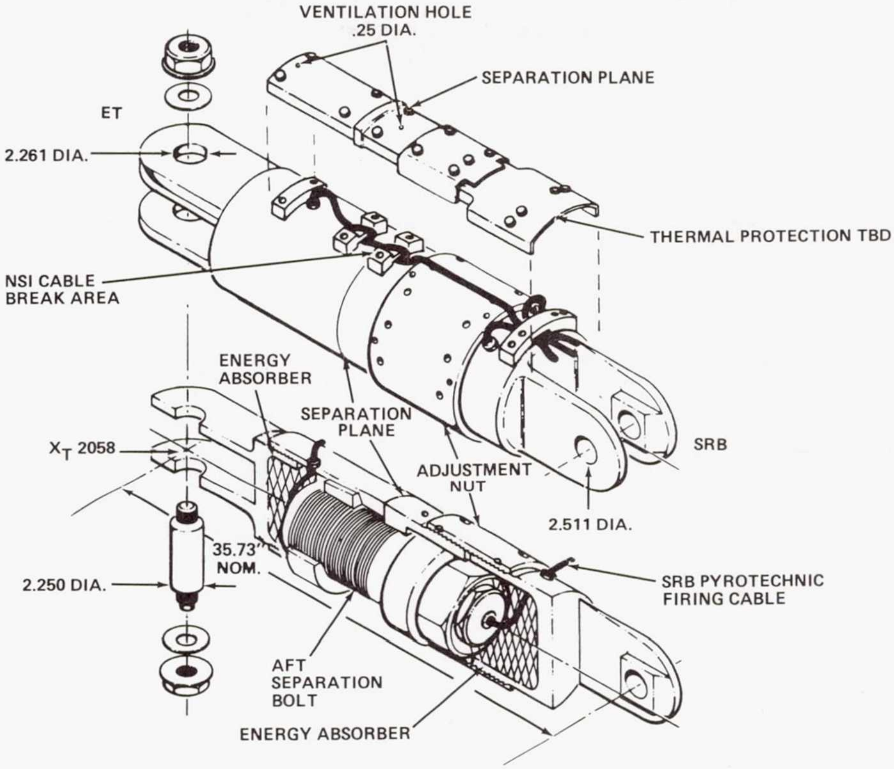

Figure 6. SRB/ET Aft Separation System, Lower and Diagonal Struts.

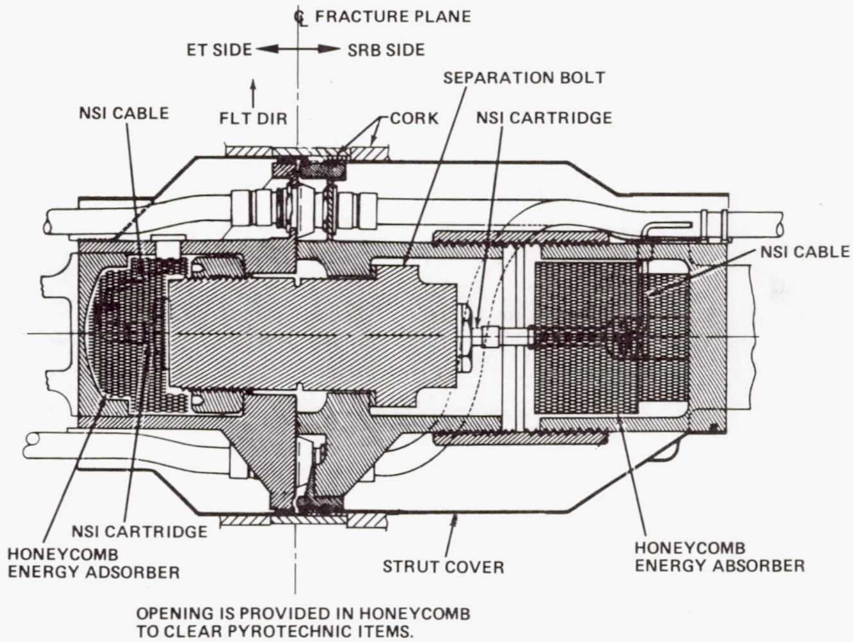

Figure 7. SRB/ET Aft Separation System (Upper Strut).

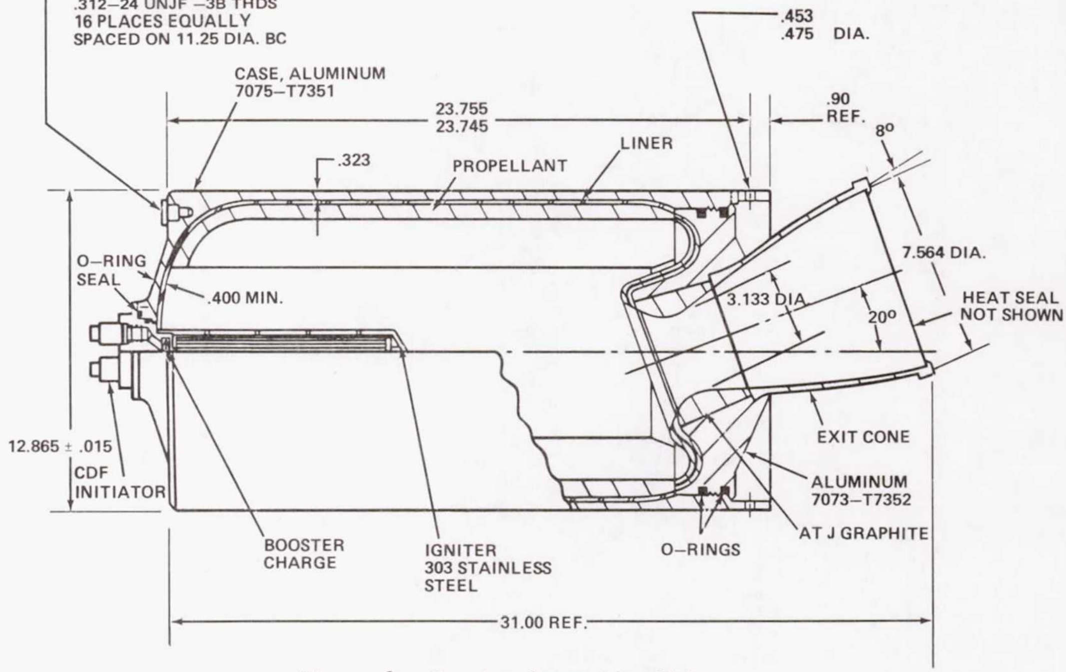

Figure 8. Booster Separation Motor.

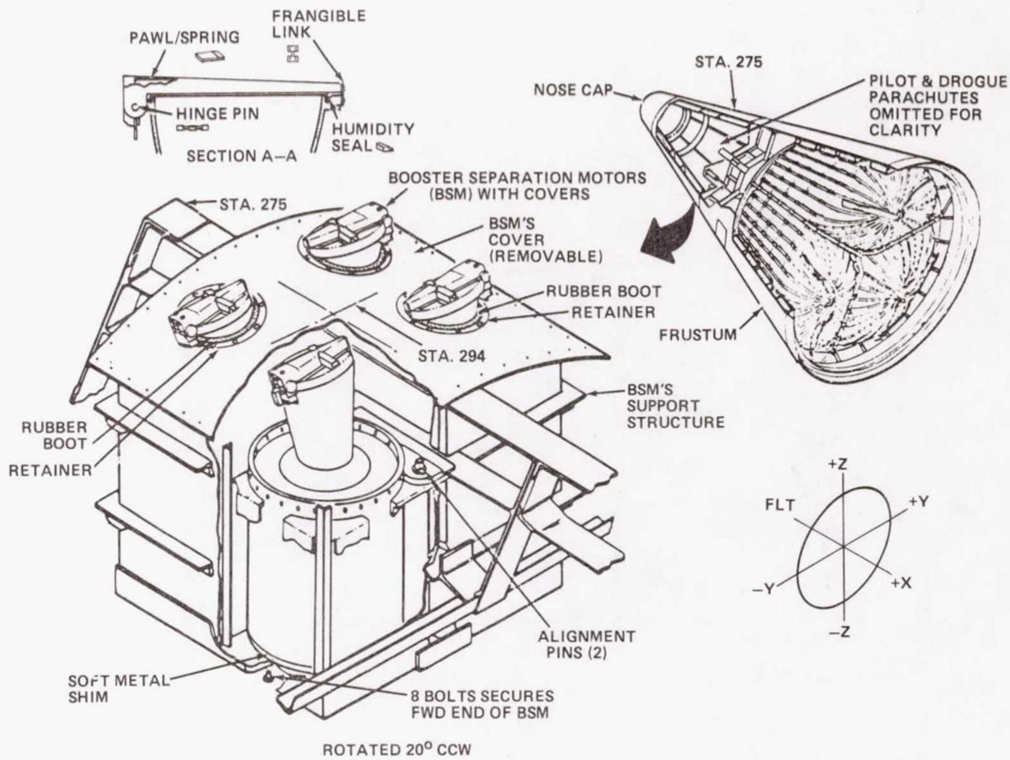

Figure 9. SRB Forward Booster Separation Motors.

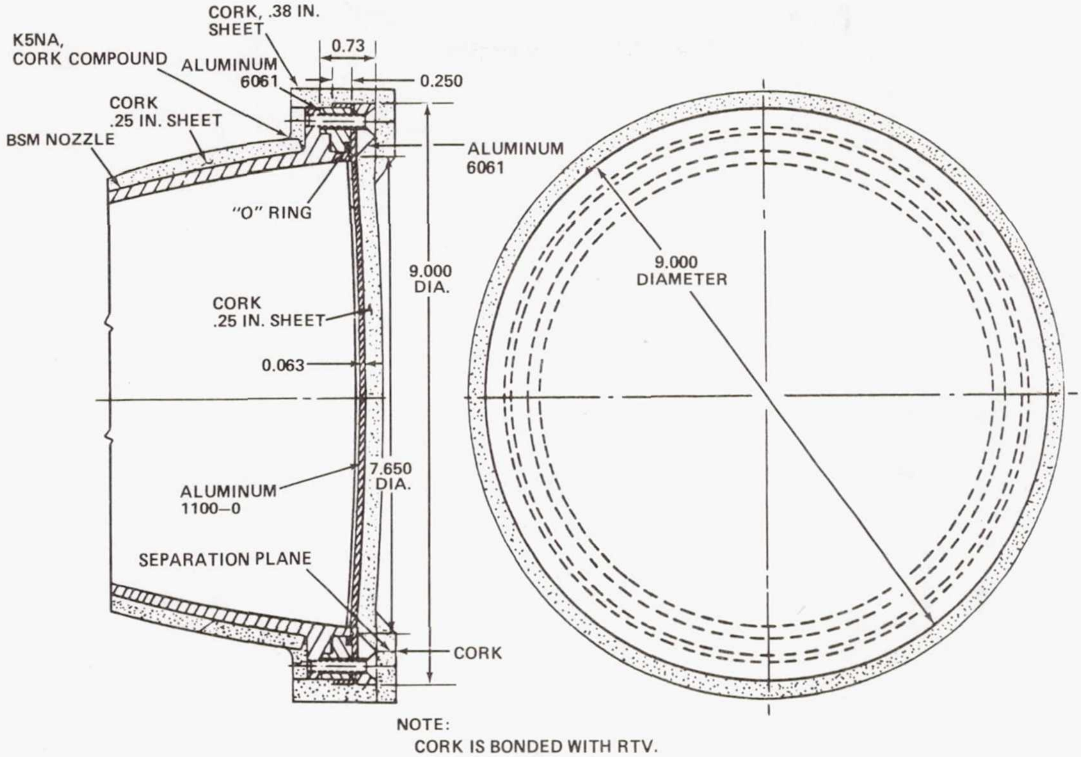

Figure 10. SRB Aft BSM Heat Seal.

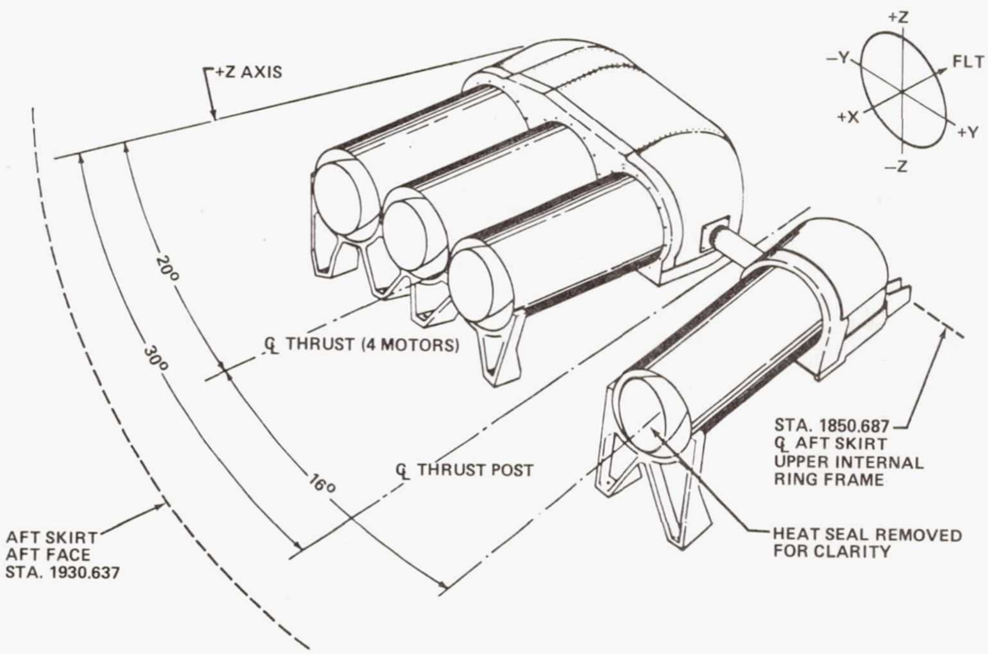

Figure 11. SRB Aft Booster Separation Motors.

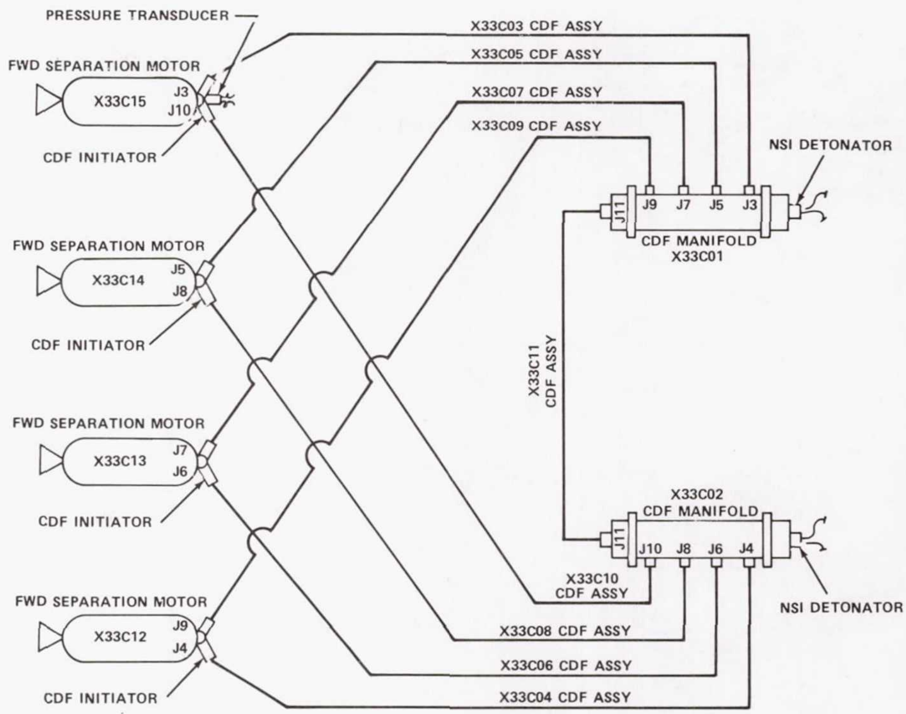

Figure 12. SRB Forward Booster Separation Motor (BSM) Ignition.

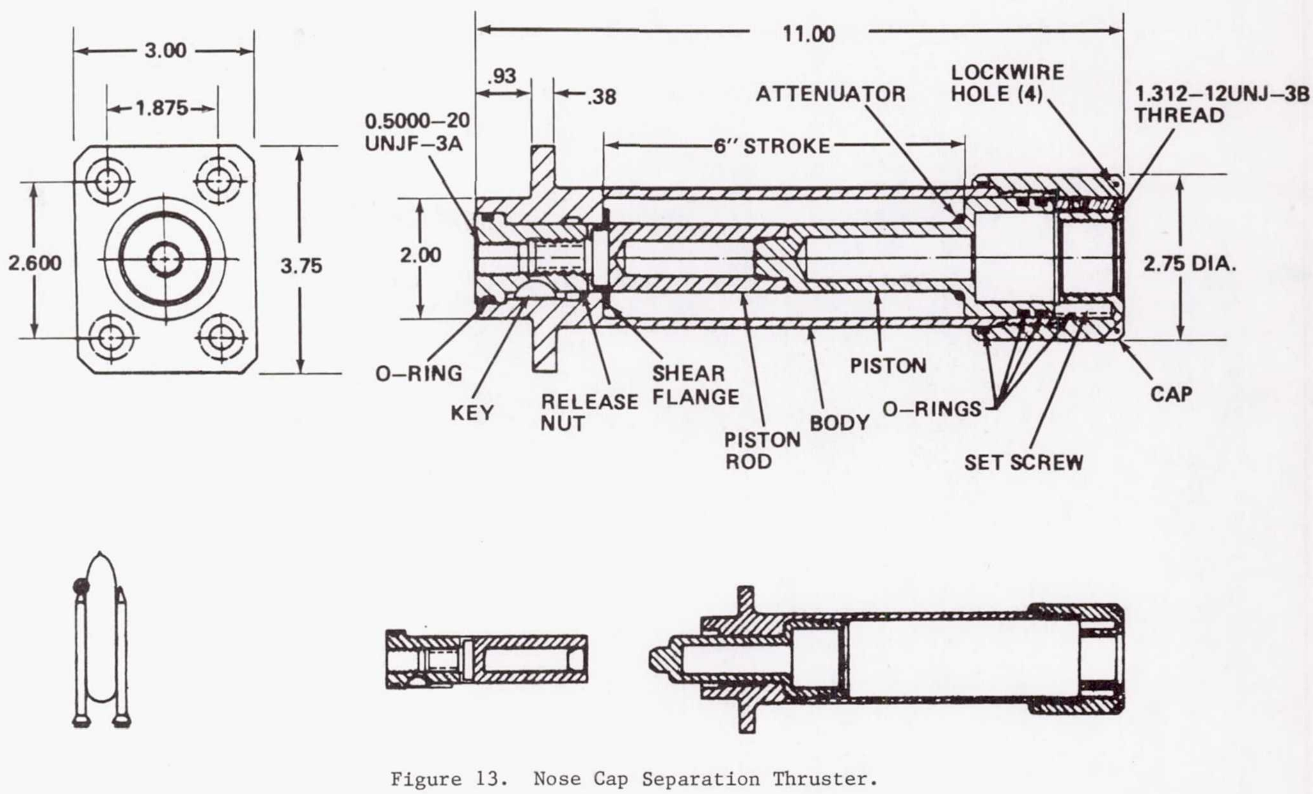

Figure 13. Nose Cap Separation Thruster.

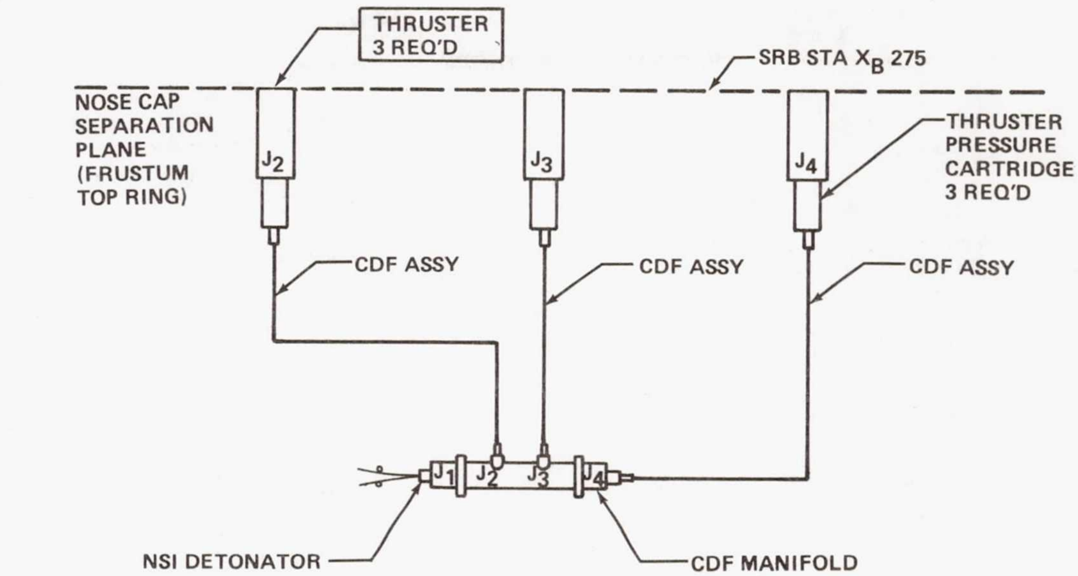

Figure 14. SRB Nose Cap Separation.

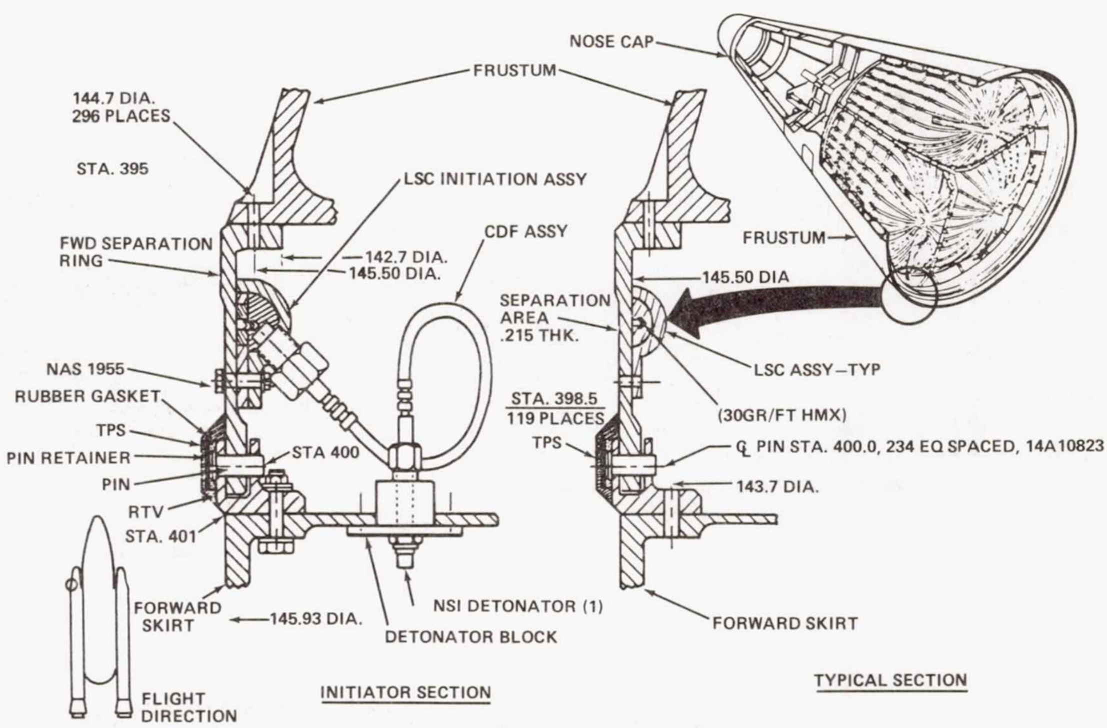

Figure 15. SRB Forward Separation Ring Cross Section.

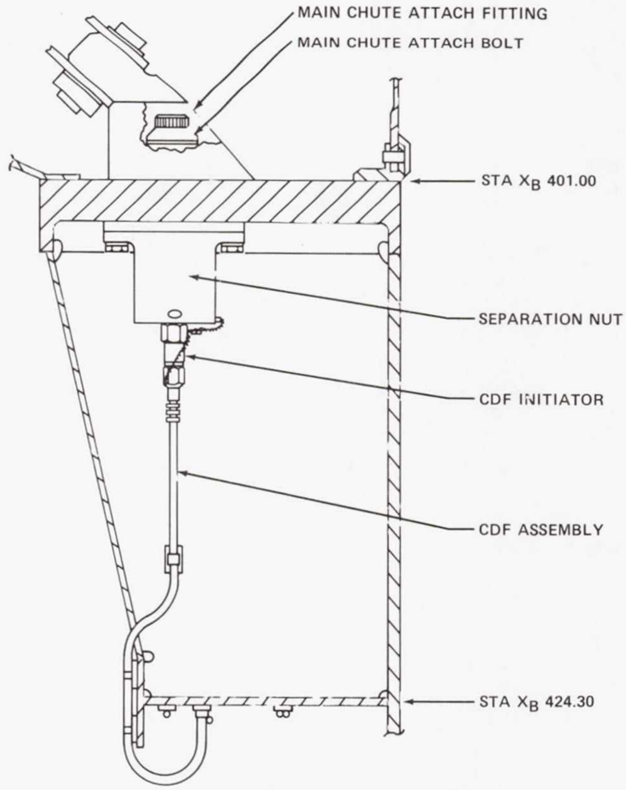

Figure 16. Main Parachute Release System.

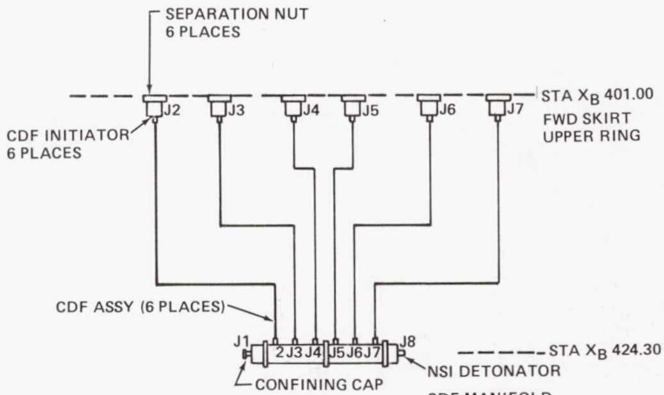

Figure 17. Main Parachute Release System

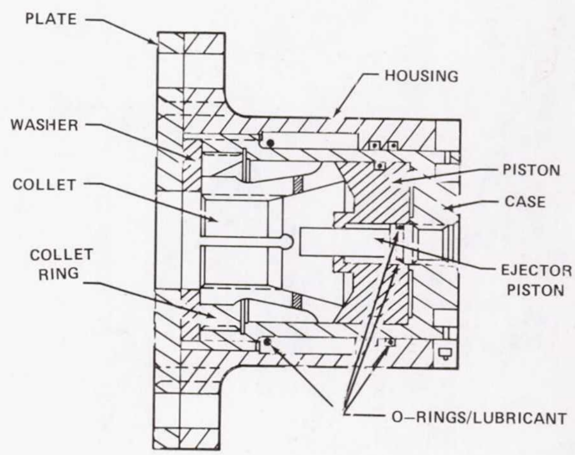

Figure 18. Separation Nut, Main Parachute Release.

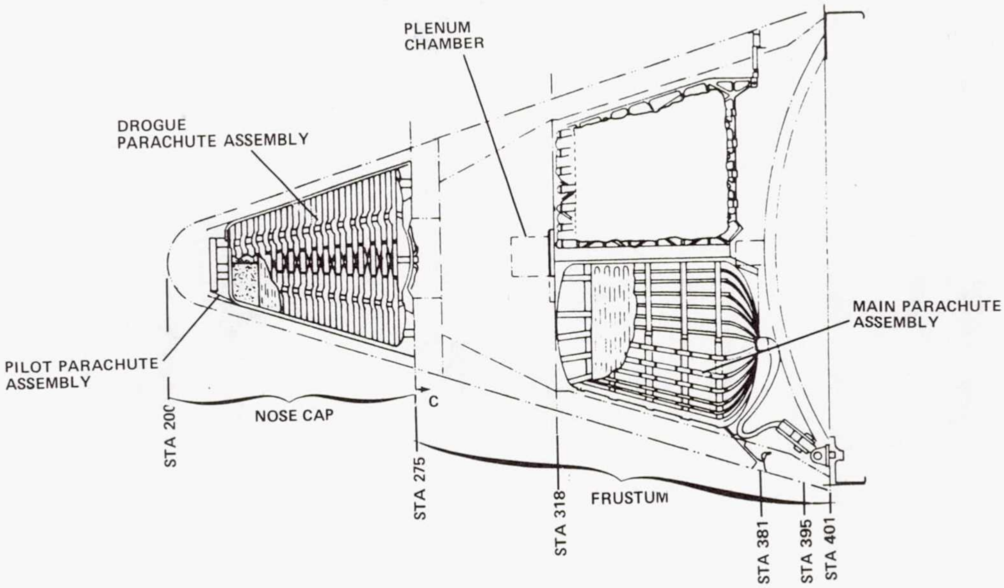

Figure 19. SRB Decelerator Subsystem Installed.

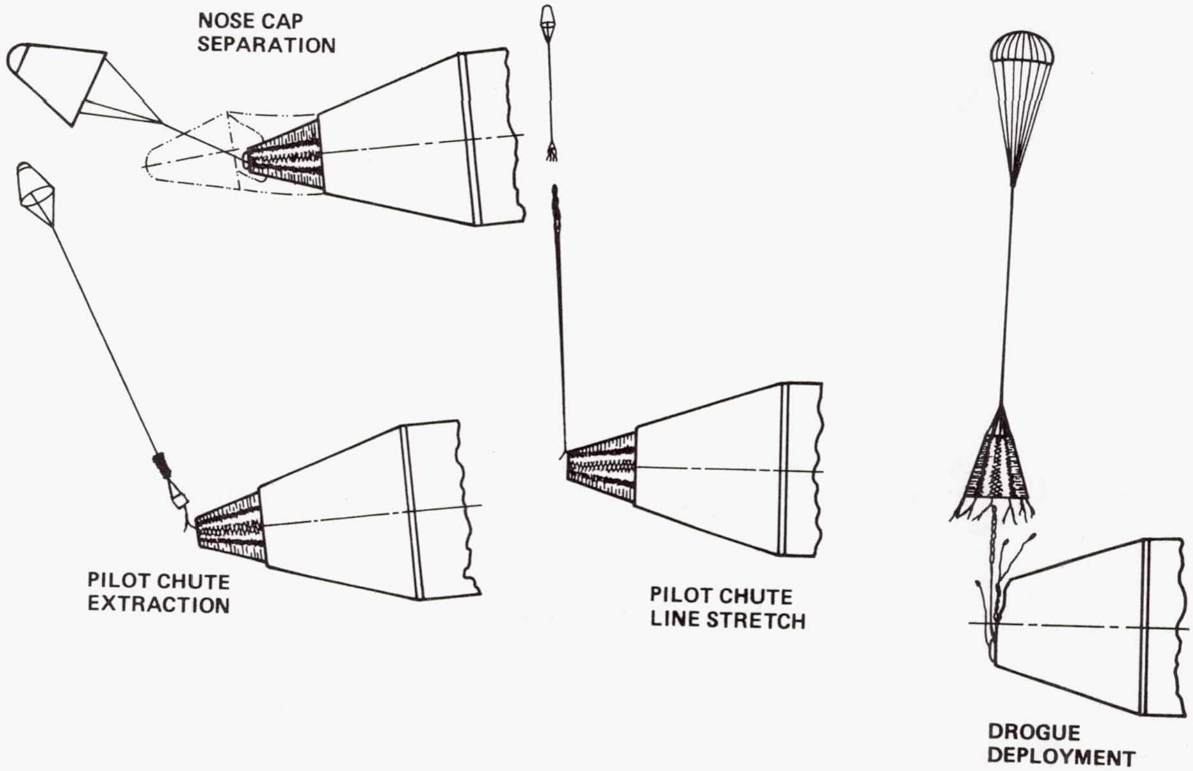

Figure 20. Deployment Sequence, Pilot Chute.

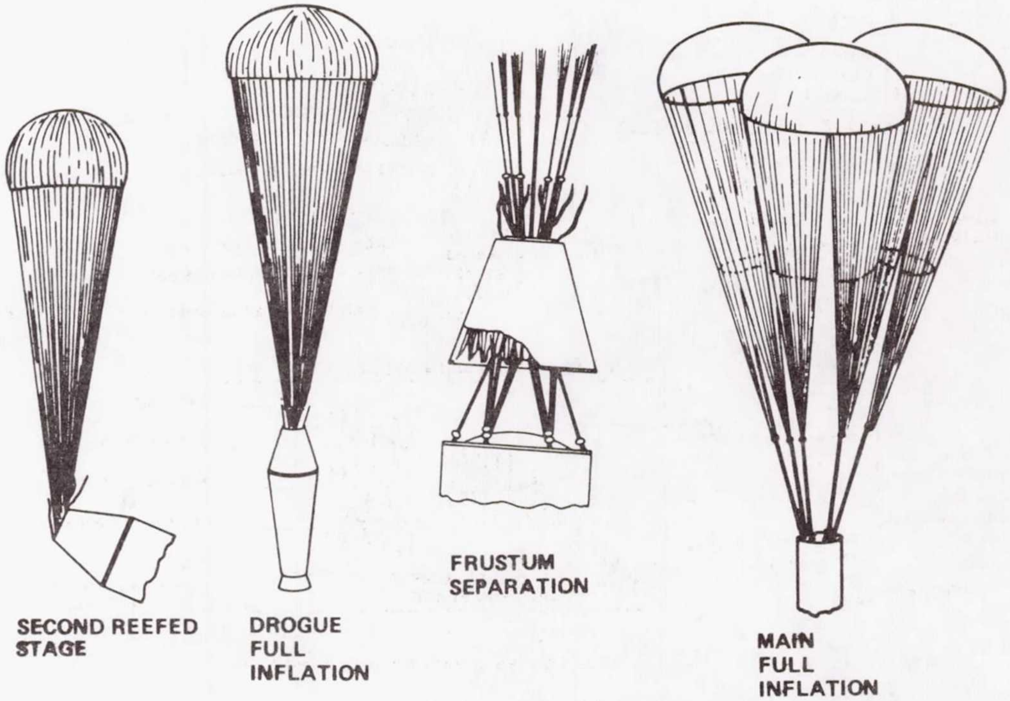

Figure 21. Deployment Sequence, Drogue/Main Chute.

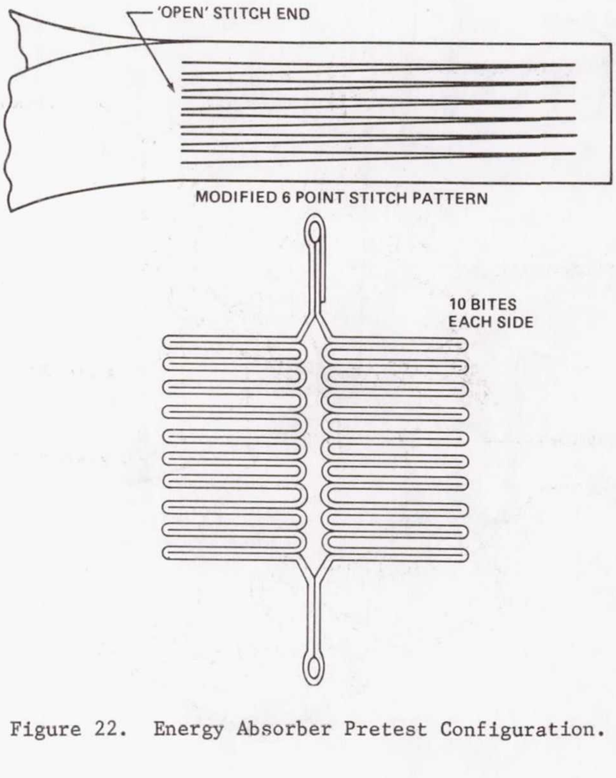

Figure 22. Energy Absorber Pretest Configuration.

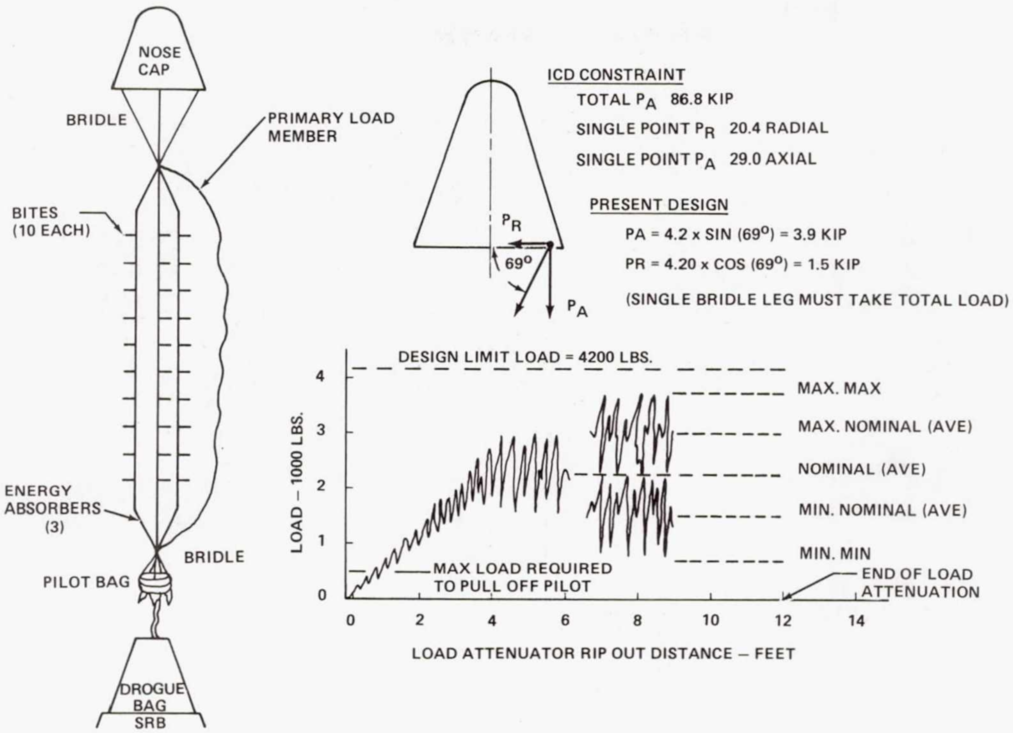

Figure 23. Nose Cap/Pilot Chute Load Attenuator.

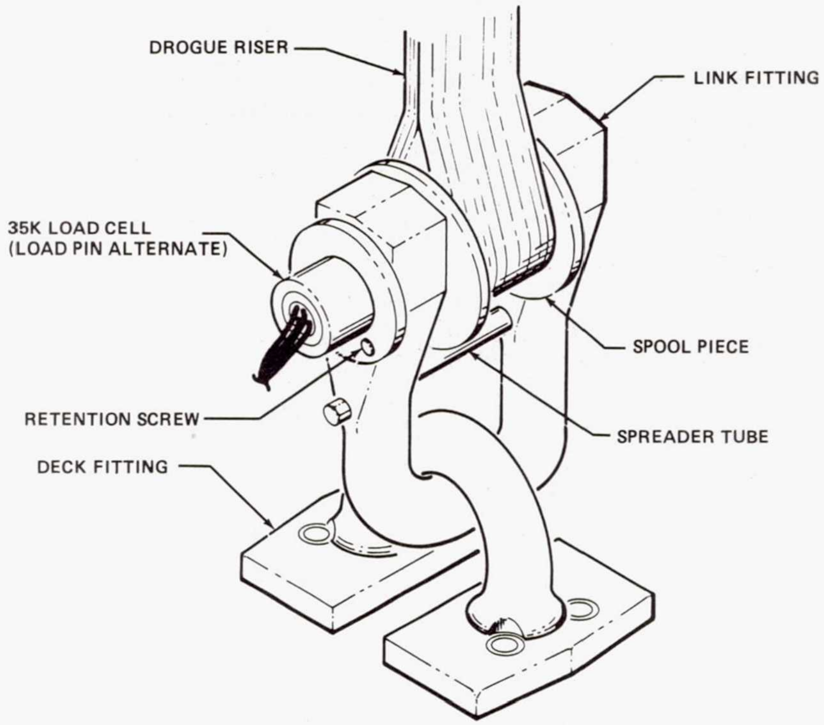

Figure 24. Drogue Riser Attach Fittings.

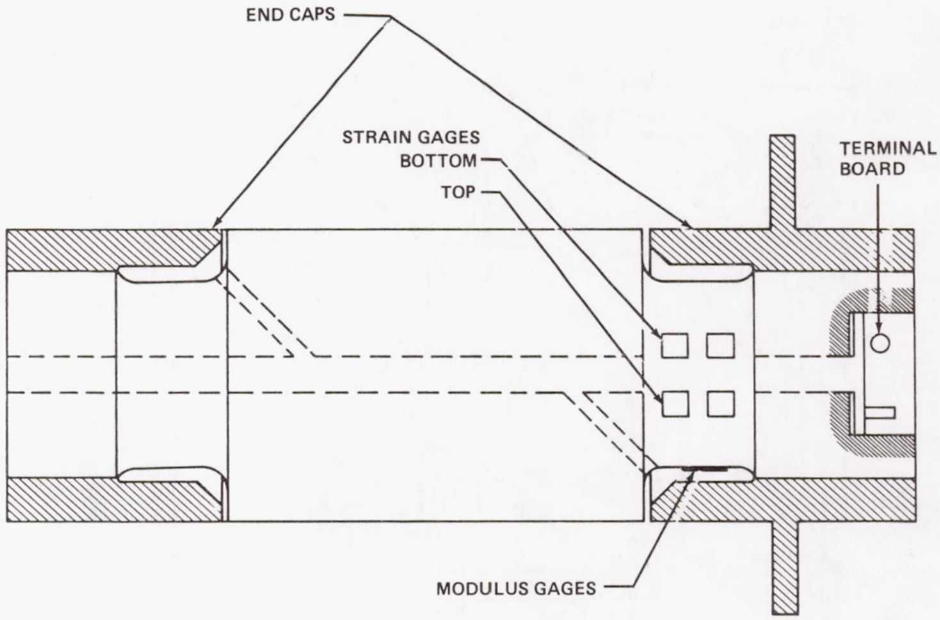

Figure 25. Drogue Load Cell.

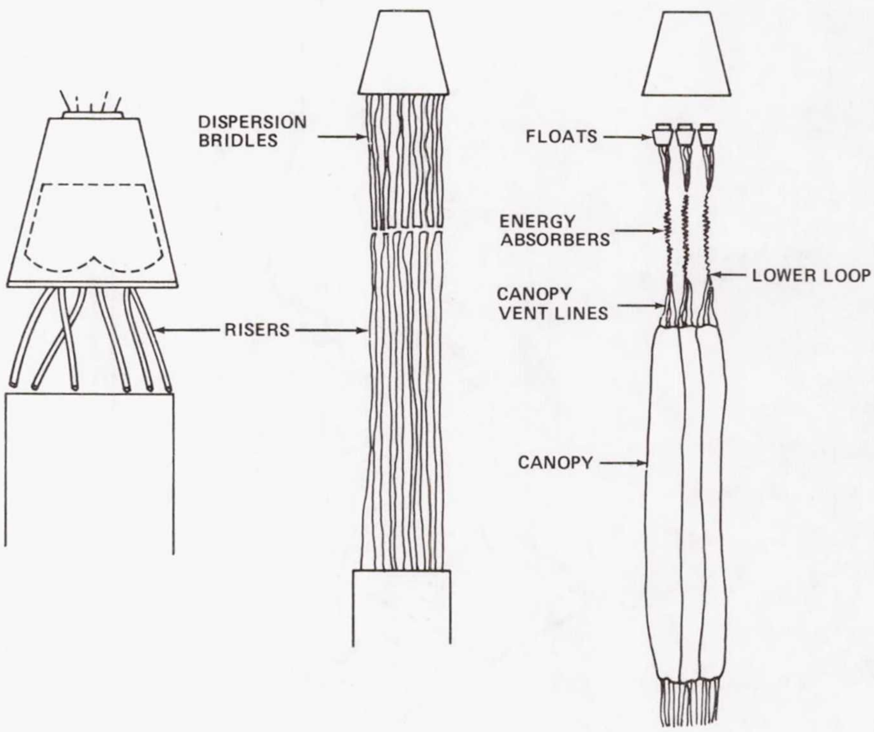

Figure 26. SRB-DBS Main Chute Deployment Sequence.

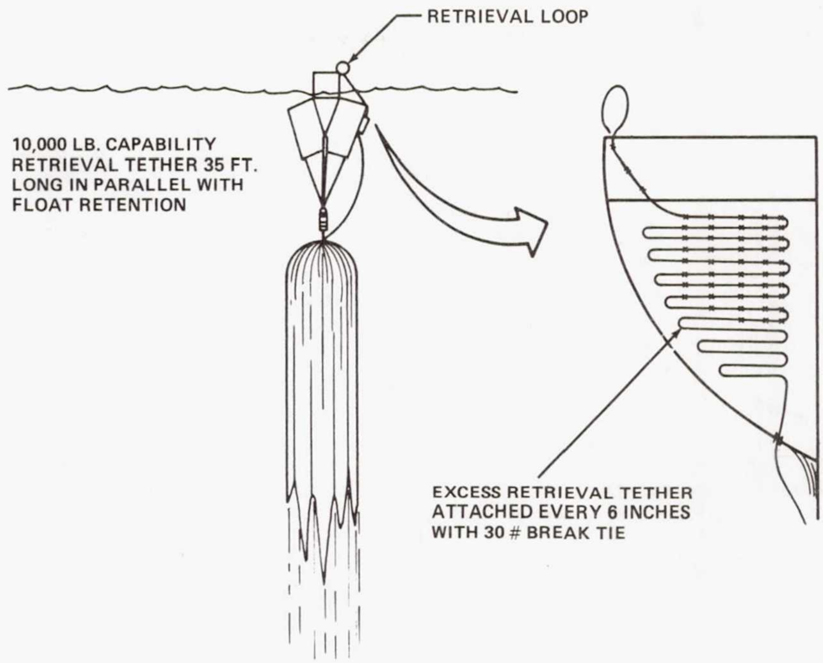

Figure 27. Main Parachute Float and Retrieval Provisions.

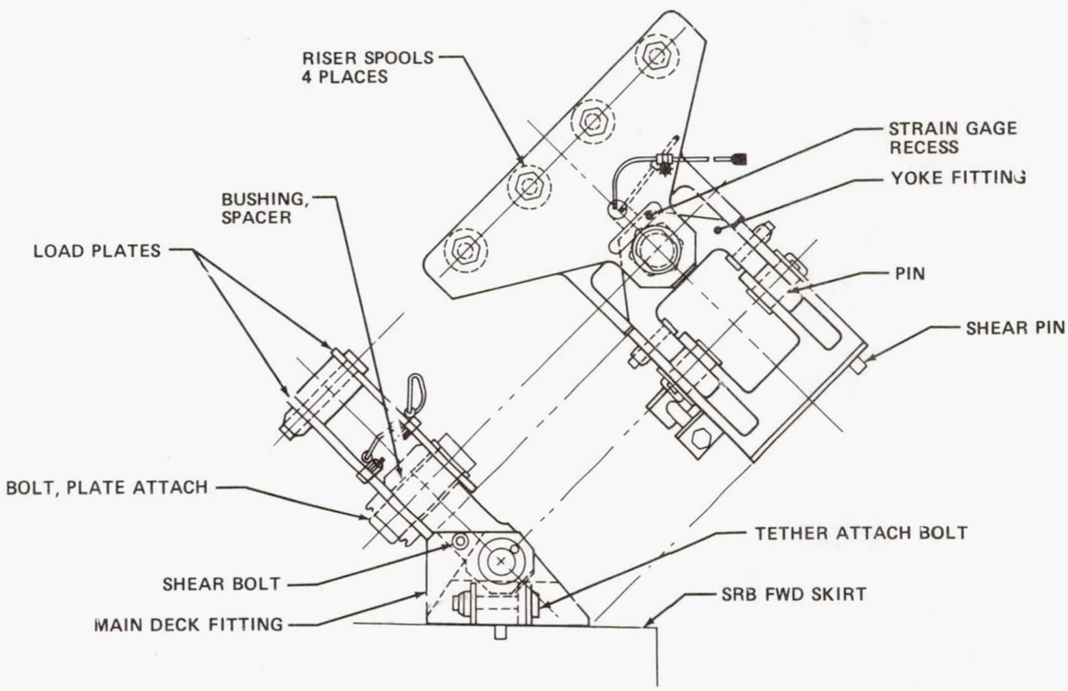

Figure 28. Main Riser Attach Fitting.