Status of The Space Shuttle Solid Rocket Booster

William P. Horton
Solid Rocket Booster Engineering Office, George C. Marshall Space Flight Center,

Follow this and additional works at: http://commons.erau.edu/space-congress-proceedings

Scholarly Commons Citation
http://commons.erau.edu/space-congress-proceedings/proceedings-1980-17th/session-1/3

This Event is brought to you for free and open access by the Conferences at ERAU Scholarly Commons. It has been accepted for inclusion in The Space Congress® Proceedings by an authorized administrator of ERAU Scholarly Commons. For more information, please contact commons@erau.edu.
ABSTRACT

Two Solid Rocket Boosters provide the primary first stage thrust for the Space Shuttle. These Boosters, the largest and most powerful solid rocket vehicles to meet established man-rated design criteria, are unique in that they are also designed to be recovered, refurbished, and reused.

The first SRB's have been stacked on the Mobile Launch Platform at the Kennedy Space Center and are ready to be mated with the External Tank and Orbiter in preparation for the first Shuttle flight.

This readiness is built upon a design within the state-of-the-art and, to the maximum extent practicable, within the state-of-experience. Component qualification, subsystem verification, system checkout, and recovery tests are essentially complete and provide the basis for certifying the Solid Rocket Boosters for manned flight.

INTRODUCTION

The Space Shuttle Solid Rocket Booster (SRB) has essentially completed its Qualification Program for one mission use, and the two Boosters for the first launch have been "stacked" on the Mobile Launch Platform (MLP) at the Kennedy Space Center (KSC) and are ready for mating with the External Tank (ET) and then the Orbiter.

The development and qualification ground test programs have been highly successful and, with only minor problems, have demonstrated that the basic design and performance requirements have been met. This paper will summarize the certification program which establishes the basis for first flight readiness, will discuss retrieval and refurbishment plans for Booster reuse, and will address Booster status for multimission use.

BOOSTER CONFIGURATION

It is appropriate to review the Booster configuration before describing the mission profile. The Booster is 150 feet long and is 148 inches in diameter (Figure 1). The inert weight is 186,000 pounds and the propellant weight is approximately 1.1 million pounds for each Booster. The major elements consist of the structural assemblies (Aft Skirt, Forward Skirt, and Nose Assembly) and the four Solid Rocket Motor segments. The parachutes are mounted in the Nose Assembly, electronics in the Forward Skirt, and the Thrust Vector Control (TVC) System in the Aft Skirt. The structural assemblies are designed for 40 uses, the motor case for 20 uses, the electronics and TVC hardware for 20 uses and the parachutes for 10 uses.

Solid Rocket Motor

The Solid Rocket Motors (SRM's) are cast and delivered to the launch site in four segments. The case segments are roll formed D6ac steel with pinned clevis joints. Two O-ring seals in each joint provide redundancy for the maintenance of pressure integrity. The design and fabrication of the case are a scaled-up version of the Titan III motor cases. Structural design factor of safety of the case is 1.4, typical of man-rated vehicles.

The composite propellant is a proven PBAN propellant used in the Minuteman and Poseidon systems. More than 200 million pounds of this propellant have been produced. The propellant is vacuum cast and case bonded. The Design, Development, Test and Evaluation (DDT&E) Motors are all X-rayed for propellant
void screening. After finalization of the casting tooling, the casting operations have consistently produced void-free grains.

The SRM thrust-time curve is tailored to meet the flight requirements (Figure 2). The thrust reaches a peak at 20 seconds after ignition, then tapers off until 50 seconds into the flight. A progressive thrust follows until 3g acceleration is achieved at approximately 80 seconds into the flight. There is a gradual tapering of the thrust to preclude exceeding the 3g acceleration constraint. Motor tailoff initiates at approximately 113 seconds. A gradual tailoff has been designed into the motor to preclude high thrust imbalance during burnout of the two motors used on any flight. In addition to the design details, steps are taken in processing the motors to ensure that any thrust imbalance is kept within the allowable limits. These limits are 300,000 lbf ignition transient, 85,000 lbf steady state operation with maximum allowable imbalance of 710,000 lbf occurring 30 percent through tailoff. On the average, it requires approximately 48 separate propellant mixes to cast a segment. Matched flight motors are cast from a single lot of materials which are tightly controlled with quality control tests upon receipt and prior to use of the materials. Additionally, the propellant mix procedures are controlled and verified for every mix. Finally, the burn rate for each mix is verified before it is cast in a segment.

The SRM nozzle is a 20 percent submerged, omnidirectional movable nozzle. The throat diameter is 54 inches and the diameter at the end of the exit cone is 148 inches.

The nozzle has an aft pivoted, flexible bearing that provides an omniaxial TVC deflection capability of ±8 degrees. The bearing consists of a flexible core that is contained by two large steel end rings attached to the motor case on one end and the nozzle on the other (Figure 3). The flexible core consists of a laminated construction of 10 spherical steel shims and 11 natural rubber pads. All metal parts of the nozzle are designed for 20 uses. The nozzle uses ablative materials which are standard in the industry with demonstrated consistency of performance. These materials are principally carbon cloth and silica cloth phenolics. A safety factor of two has been used in determining the ablative thickness for the nozzle. This factor has been demonstrated in the ground test motors.

Forward Skirt

The Forward Skirt comprises all structure between the forward SRM segment and the Ordnance Ring. It includes an SRB/ET attach fitting which transfers the thrust loads to the ET and a forward bulkhead which seals the forward end of the skirt. The Forward Skirt provides the structure to react parachute loads during deployment and descent, and provides an attach point for towing the Booster during retrieval operations.

Secondary structure is provided for mounting components of the Electrical and Instrumentation (E&I) subsystem, and rate gyro assemblies, range safety components, and interconnecting cables. The skirt assembly is sealed to provide additional flotation capability.

The Forward Skirt is 146 inches in diameter and 125 inches in height. It consists of a 2219 aluminum welded cylinder assembly made from machined and brake-formed skin panels and a welded thrust post structure. The Forward Skirt weighs approximately 6400 pounds.

Ordnance Ring

The Ordnance Ring, 146 inches in diameter, provides a plane for pyrotechnically separating the Frustum from the Forward Skirt during the parachute deployment process. The ring is machined from a 2219 aluminum ring forging and provides mounting provisions for the linear-shaped charge used in the severance function.

Frustum

The Frustum houses the Main Parachutes, provides aerodynamic protection, thermal protection, and mounting provisions for the TVC subsystem and the aft mounted Separation Motors. The Aft Skirt provides sufficient clearance for the SRM nozzle at the full gimbal angles. The Aft Skirt kick ring provides the necessary structural capability to absorb and transfer induced prelaunch loads.

The Aft Skirt structure assembly is a welded and bolted conical shape, 146 inches in diameter at the top, 212 inches at the bottom, and is 90.5 inches in height. It is configured for left-hand and right-hand assemblies, is fabricated using 2219 aluminum with D6ac steel rings, and weighs approximately 12,000 pounds.

Aft Skirt

The Aft Skirt provides attach points to the launch support structure and provides support to the Space Shuttle on the MLP for all conditions prior to Booster ignition. The Aft Skirt provides aerodynamic protection, thermal protection, and mounting provisions for the TVC subsystem and the aft mounted Separation Motors. The Aft Skirt provides sufficient clearance for the SRM nozzle at the full gimbal angles. The Aft Skirt kick ring provides the necessary structural capability to absorb and transfer induced prelaunch loads.

The Aft Skirt structure assembly is a welded and bolted conical shape, 146 inches in diameter at the top, 212 inches at the bottom, and is 90.5 inches in height. It is configured for left-hand and right-hand assemblies, is fabricated using 2219 aluminum with D6ac steel rings, and weighs approximately 12,000 pounds.

Ordnance Ring

The Ordnance Ring, 146 inches in diameter, provides a plane for pyrotechnically separating the Frustum from the Forward Skirt during the parachute deployment process. The ring is machined from a 2219 aluminum ring forging and provides mounting provisions for the linear-shaped charge used in the severance function.

Frustum

The Frustum houses the Main Parachutes, provides aerodynamic protection, thermal protection, and mounting provisions for the TVC subsystem and the aft mounted Separation Motors. The Aft Skirt provides sufficient clearance for the SRM nozzle at the full gimbal angles. The Aft Skirt kick ring provides the necessary structural capability to absorb and transfer induced prelaunch loads.
beams, ring fittings, separation motor supports, Main Parachute Supports, and 7075 aluminum formed skins. The Frustum weighs approximately 3800 pounds.

Nose Cap

The Nose Cap houses both the Pilot and Drogue Parachutes and is separated from the Frustum by three pyrotechnic thrusters to initiate the parachute deployment sequence. The Nose Cap is basically an aluminum monocoque structure with a hemispherical section at the forward end. The base is 68 inches in diameter and the overall height is 35 inches. The structure is a riveted assembly of machined 2024 aluminum sheet skins, formed ring segments and cap, and a machined separation ring. Its weight is approximately 300 pounds.

Systems Tunnel

The Systems Tunnel is located outboard on each Booster and houses the electrical cables and linear-shaped charge of the Range Safety System. The Tunnel provides lightning, thermal, and aerodynamic protection and mechanical support for the cables and destruct charge. It is manufactured from 2219 aluminum and extends from the Forward Skirt along the motor case to the Aft Skirt. The Tunnel is approximately 10 inches wide and 5 inches high. Its floor plate is vulcanized and bonded to each motor segment by Thilokol, the SRM contractor. The overall weight of the Systems Tunnel is approximately 600 pounds.

Thrust Vector Control Subsystem

The Booster TVC Subsystem works in conjunction with the TVC system for the Orbiter Main Engines and provides the vast majority of gimbal authority for the Space Shuttle during first stage flight. Pitch, roll, and yaw commands are provided by the Orbiter flight control system.

Booster TVC Subsystems are mounted in each Aft Skirt and consist basically of two hydraulic power units and two electrohydraulic servoactuators per Booster (Figure 4). Each power unit is assigned to an actuator; however, automatic switching permits both servoactuators to be powered by a single hydraulic power unit to provide redundancy in this mission-critical function.

Each hydraulic power unit is independent and consists of an auxiliary power unit, reservoir, fuel supply module, hydraulic pump, and fluid manifold assembly (Figure 5). The auxiliary power unit is driven by liquid hydrazine stored and conditioned in the fuel supply module. Power is transmitted from the hydraulic pump to each servoactuator at the required flow rate to operate a 3200 psig, closed center, Type II hydraulic system (MIL-H-5450).

Should one hydraulic power unit fail to supply power to its assigned actuator, switching occurs within the actuator to take power from the remaining hydraulic power unit and operate at a degraded rate.

The electrohydraulic servoactuators are the linear double acting type. Four servovalves with mechanical feedback are used to provide redundancy. All critical seals within each servoactuator are redundant to assure that a single failure cannot deplete hydraulic fluid from both hydraulic power units.

The servoactuators have a stroke of ±6.4 inches which provides a gimbal angle of ±5 degrees in the plane of each servoactuator. They are oriented at 45 degrees to the Shuttle pitch and yaw axis to provide 7 degrees gimbal authority in the pitch and yaw planes.

Electrical and Instrumentation Subsystem

The E&I Subsystem is composed of two subgroups designated as the Operational Flight (OF) subgroup and the Development Flight (DF) subgroup. The OF subgroup is required on every flight and is powered from the Orbiter. The DF subgroup is required for development flights only, has an independent power source in the Booster Forward Skirt, and is designed to be removed for operational flights without impacting other subsystems.

The OF E&I subgroup simplified schematic is depicted in Figure 6. This subsystem functions during prelaunch, boost, and recovery of the Booster. Prelaunch functions include test and calibration of Booster components including the SRM ignition components. The E&I OF subgroup components and cabling provide the interface with the Orbiter for the Booster TVC subsystem, Rate Gyro System, SRB/ET Separation Subsystem, and Range Safety Subsystem during the boost phase of flight; and the recovery functions after separation. The OF subgroup also contains sensors; signal conditioning equipment; Pyrotechnic Initiator Controllers; switching and logic circuits; various buffer, interfacing, timer, and sequencing circuits; and controllers used to regulate the speed of the Auxiliary Power Units. These circuits provide a means of responding to commands from the Orbiter during boost, and also circuitry to sequence separation of the Boosters and the subsequent deployment of parachutes and location aids after splash-down. The OF subgroup components associated with the boost phase are active until separation and powered by the Orbiter. Components associated with the
Recovery sequence are turned on just prior to separation and are powered by the Recovery Battery on each Booster. Most E&I components are designed for reuse with appropriate inspections and refurbishments for a minimum of 20 flights.

The DF E&I subgroup monitors parameters that are used to verify Booster design during the DDT&E flights. Parameters include: current, voltage, structural strain, vibration, pressure, temperature, acoustic, acceleration, vehicle rates, and heat flux. DF components are not designed for reuse. Tape recorders provide information storage and data retrieval. Development flight hardware has a power source which is independent from other E&I subsystems. The Right Hand (RH) Booster is the primary DF subgroup carrier. The Left Hand (LH) Booster is utilized only if the desired function cannot be accomplished from the RH Booster. Measurements are duplicated on the LH Booster when necessary. No direct redundancy in system design is provided. The DF components, with the exception of sensors, are mounted in the forward sealed compartment and are not reused.

Separation Subsystem

Separation of the Booster from the ET is achieved by pyrotechnically releasing all attach points and simultaneously igniting four Booster Separation Motors forward and four aft (Figure 7). The Separation Motors are oriented so as to avoid plume and particle impingement on the Orbiter.

Double ended separation bolts are used at all attach points (one forward and three aft) to provide redundancy for this critical event. Similarly, the firing circuits to each of the Separation Motors are redundant. Each motor provides an average thrust of 22,500 pounds for 0.66 second. All sequencing and commands are issued by the Orbiter through hard-wired paths.

Recovery Subsystem

The Booster Recovery Subsystem provides the necessary hardware to control the Booster final descent velocity and attitude after separation. The recovery subsystem includes parachutes, methods of sequencing and deploying these parachutes, parachute separation components, and location aids that help in search and retrieval operations for the expended booster and the parachutes.

The Pilot and Drogue parachutes are housed in the Nose Cap and are deployed as the Nose Cap separates from the Frustum. The Nose Cap separation is initiated by a barometric switch at approximately 16,000 feet. The Nose Cap deploys the pilot parachute which in turn deploys the Drogue parachute. The pilot parachute bag and Nose Cap are released after deployment of the Drogue parachute and are not recovered. The Drogue parachute, nominally 54 feet in diameter, stabilizes and decelerates the Booster. It opens through one reefing stage to full open. A second barometric switch output initiates separation of the Frustum at approximately 6,600 feet. As the Drogue parachute pulls the Frustum away from the Booster, the main parachutes are deployed. The Drogue parachute decelerates the Frustum for recovery.

The main parachute assembly decelerates the Booster to an 85 feet per second nominal water impact velocity. The parachute cluster assembly consists of three parachutes each approximately 113 feet in diameter and is housed in the Frustum structural component. The parachutes are opened through two reefed stages to full open (Figure 8). At Booster impact, the main parachutes are disconnected and the Booster radio frequency beacons and lights are actuated. The main parachutes have flotation gear and location aids to help in recovery operations.

MISSION PROFILE

Figure 9 shows the mission profile for the SRB's. The two Boosters burn in parallel with the Orbiter main engines from liftoff through the first boost phase. Their ignition signals are interlocked with the Orbiter main engines. The Boosters are ignited when the third Orbiter engine reaches the 90 percent thrust level. The combined initial thrust of the two Boosters at launch is approximately 6 million pounds. During the first boost phase, the Shuttle vehicle reaches a velocity increment of approximately 4,400 feet per second at an altitude of 24 nautical miles. The Boosters provide the primary thrust and TVC during the initial boost phase. At the end of the first boost phase, the SRM chamber pressure is down to 50 psi with the thrust at tailoff approximately 100,000 pounds. After separation, the Boosters coast to an apogee of 220,000 feet where they begin the descent phase.

The Recovery Subsystem operational sequence is initiated at Booster separation by commands from the Orbiter Guidance Navigation Control Computers. The recovery sequence is programmed by combinations of solid state switches, two time delay devices, and an altitude switch assembly. When the altitude switch senses atmospheric pressure corresponding to 16,000 feet, pyrotechnic devices separate and eject the Nose Cap and the parachute system deployment commences with the deployment of a Pilot chute which, in turn, deploys
a Drogue chute which is 56 feet in diameter. With two reefing stages, the Boosters descend under the control of the Drogue to approximately 6600 feet. The second switch position of the altitude switch senses the appropriate pressure and initiates deployment of the three 113-foot diameter main chutes. The main chutes open through three programmed reefing stages to slow the Booster descent to 85 feet per second at water impact.

The water impact site for the Boosters is approximately 130 to 140 miles downrange and covers an area of 6 by 9 miles. Prior to launch, retrieval vessels will be dispatched to the predicted impact area. The vessels will be stationed at a safe location outside the Booster impact footprint. At splashdown, the vessels will proceed into the impact area and execute search strategies to locate the Boosters and parachutes. The Boosters are equipped with location aids to assist in location and retrieval. The Boosters will float, aft end down, in the vertical (or spar buoy) mode. At the impact site, the Boosters will be verified to be safe, and an underwater maneuverable dewatering device will be deployed and remotely controlled into the nozzle throat (Figure 10). With the throat sealed, air is pumped into the chamber and water is forced out until the Booster translates into the horizontal (or log) mode for towing back to shore. The parachutes are recovered and stowed on the retrieval vessel.

After return to shore, the Boosters are brought into a disassembly facility. They are thoroughly washed and dried. Residual thermal protection material is removed with high pressure water jets. The structural elements and motor case segments are separated for transfer to the refurbishment facilities. The motor cases are returned by rail to the Thiokol facility in northern Utah, and the remaining elements of the Booster to the refurbishment facility at the launch site.

**BOOSTER CERTIFICATION**

The Booster is designed for recovery, retrieval, refurbishment, and reuse. This provides a reduction in cost of approximately 50 percent from the fully expendable approach over 487 missions. In general, Booster components are targeted for 20-mission use. The major exceptions are the basic structure, which is planned for 40-mission use, and the parachutes, which are planned for 10-mission use. The feasibility of reuse was established through drop tests conducted in 1973 using Titan III motor cases and nozzles. These tests proved that Boosters could survive water impact at vertical velocities of approximately 100 feet per second. System trade studies indicated that the delta inert weight required to decelerate the vehicle during descent and withstand water entry loads is approximately 10 percent greater than inert weights required to survive ascent loads only. For the SRB, 16,000 pounds of a total inert weight of 186,000 pounds applies against the reuse capability with a water impact vertical velocity of 85 feet per second.

Certification of the Booster for first ascent flight is essentially complete and was accomplished along classical lines, e.g., expose the qualification components and subsystems to tests which simulate the predicted flight environments of vibration, loads, thermal, acoustics, shock, and reduced pressure for the predicted time durations.

Certification of the Booster for operational reuse is unique for manned space flight and is considerably more challenging. Reuse certification, extending throughout the development flight phase and into the operational flight phase, will be accomplished in sequence as follows:

1. Predict the environments to be encountered during ascent, descent, and ocean retrieval.

2. Expose test articles to these environments for a time duration representing a one mission cycle. Environments are to be applied in the order in which they occur, to the extent practicable, with water impact and ocean environments last. Assess components for proper performance and reuse capability. This qualifies the design for one mission.

3. Expose the same test articles to the environments for a time duration representing six missions. Assess for proper performance and reuse capability. Then expose the same articles for a 13 mission time duration and assess for proper performance.

4. Using data recorded during development flights, validate the predictions used during qualification testing.

5. Disassemble and closely inspect flight components retrieved during early flights and establish realistic refurbishment requirements and/or design changes required to assure confident reuse.

**Solid Rocket Motor Firings**

The SRM has completed seven successful static firing tests (Figure 11). The first four firings were classified as development tests whose objectives were to evolve the qualification and flight motor configuration. The development tests confirmed the basic design and very minor modifications were necessary to establish the flight configuration. The three qualification firings have confirmed that the SRM design meets or exceeds specification requirements and indicated excellent reproducibility.
between motors. Figure 12 shows a comparison of the thrust-time traces for the first and second qualification motor firings.

Static Structural Tests

Structural tests of the Booster under static load conditions have been underway since early 1979. Ascent flight load conditions have been successfully completed to a safety factor of 1.4 on ultimate. Descent load condition tests will complete next month to a safety factor of 1.25 on ultimate. All the testing to date has verified the design, and there have been no significant design changes resulting from the structural testing.

Thrust Vector Control

Components of the TVC Subsystem are being subjected to environmental and functional qualification tests. All components have successfully completed single mission qualification and are in the process of completing the 20 mission sequence which includes the full cycle of pre-launch, launch, descent, water impact, and retrieval tests. The subsystem test bed has accumulated approximately 100 equivalent missions of hot fire test time to date. Flight configured systems were used during five SRM static firings at Thiokol, and both flight systems currently stacked on the MLP at KSC have successfully passed full duration hot firings.

Electrical and Instrumentation

The E&I components, like other subsystem components, have been qualified at the component level for single mission and are in the process of qualifying for multimission use. Integrated subsystem verification has been accomplished at MSFC in Huntsville demonstrating adequacy of design and compatibility with automated checkout equipment. Verification with the Orbiter interface is in progress in the Shuttle Avionics Integration Laboratory at Johnson Space Center in Houston.

Booster Separation Motor (BSM)

Certification of the BSM's has been successfully accomplished through a series of 14 static firings at United Technologies, Chemical Systems Division, Sunnyvale, California. The test configuration of each firing is given in Figure 13, and the performance results are given in Figure 14.

Recovery Drop Tests

The Recovery Parachute system has completed its preflight verification program with a series of air drop tests in 1978 and 1979. The Recovery Subsystem parachutes were tested in a series of six drops in the period from June 1977 to September 1978. These tests successfully verified the subsystem sequence, performance characteristics, and structural design. Accomplishing these tests required very detailed analyses and innovative approaches. For instance, the spent Booster weighs over 186,000 pounds, but the test aircraft capability was limited to 50,000 pounds. This required a "fractional" objective test approach. That is, each test was carefully planned to simulate a particular step in the parachute deployment and inflation sequence. In this manner, the drogue parachute was tested in both its reeled configuration and full-open configuration, using separate tests.

The main parachutes were likewise tested and, by using a single main on certain tests instead of the cluster of three, the limited weight of the drop test vehicle was able to simulate full Booster-type loads on the parachute.

The drogue was tested to a load of 305,000 pounds and the main to 205,000 pounds. The design loads are 270,000 pounds and 173,700 pounds, respectively, which shows demonstrated margins of safety. These loads also show an advancement in the capability of heavy-duty parachutes. The successful recovery of the Booster will triple the world's current record parachute payload weight of 55,000 pounds.

RETRIEVAL

The Booster retrieval system has been developed to recover the Booster and its expended main parachutes, nose-cone Frustums, and drogue parachutes after descent to and landing in the ocean. Two offshore supply boats are utilized as platforms for the retrieval system components which are used to perform the various phases of the retrieval operation.

The retrieval vessels will depart the Booster disassembly facility fully loaded with retrieval equipment, personnel, and provisions required to complete all phases of the retrieval operation. The entire mission cycle, from onload of the system aboard the retrieval vessels through retrieval, return, and offload of the system, is estimated to require a maximum of nine days. The major evolutions during the retrieval include: (1) search and location of the Booster hardware, (2) main parachute retrieval, (3) Frustum/drogue parachute retrieval, (4) Booster dewatering, (5) ocean tow, (6) hip tow, and (7) dock transfer.
The retrieval vessels are basically offshore supply boats which have been leased for Booster retrieval. They have twin diesel engines and a minimum of 3,000 total shaft horsepower. Each vessel is capable of maintaining a service speed of 14 knots and a towing speed with Booster of 10 knots in a sea state of 3 or less. General characteristics include: overall length - 205 feet, beam length - 40 feet, draft - 10 feet, and endurance (food, water, fuel) - 30 days. Each vessel is equipped with a 400-horsepower bow thruster to provide maximum directional control when maneuvering during retrieval operations. Each vessel has the capability to berth and mess the normal ship’s crew of 12 plus a retrieval crew of 15 including technical representatives.

To aid in navigational search for the Booster hardware, a portable sonar system and a radio direction finder (RDF) system have been installed on each vessel to provide a search capability in addition to the ship’s installed radar system. The sonar system will be able to obtain bearing information from acoustic beacons (pingers) which have been installed on the main parachute risers and allow the vessel to home in on the floating hardware. In addition, RF location aids installed on the Frustum and forward dome of the Booster will transmit signals which can be picked up by the shipboard RDF locator system for assistance in location. Finally, an acoustic pinger has also been installed on the forward dome of each Booster to provide search capability in the event that the Booster becomes submerged after ocean impact. The general layout of retrieval system components and location on the vessel deck is shown in Figure 15.

Main Parachute Retrieval

The vessels initiate main parachute retrieval by approaching the floating parachutes, recovering the floats, and attaching a winch line for retrieval. The line is attached to one of four hydraulically powered parachute power-reel assemblies which are located in line, facing aft, on the starboard side of the ship. The reels are driven by a hydraulic power supply which is powered by vessel-supplied electrical power. The parachutes are retrieved, canopy apex first, from the stern of the vessel across a deck edge roller onto the four reels directly in line of the in-haul path of each reel. The parachute, streaming behind the vessel, is fair leaded over the roller as it leaves the water and is recovered on the reel. The roller is designed to be easily removed after parachute retrieval to permit subsequent recovery of the Frustum at this location.

Frustum Retrieval

Recovery of the drogue parachute, using similar techniques employed for the main parachutes, initiates Frustum recovery which utilizes the retrieval hoist, power block, and drogue parachute suspension lines (Figure 16).

The power block connects to the retrieval-hoist boom and is powered by the hoist hydraulic power supply. It is utilized to lift the Frustum from the water via parachute suspension lines. The power block has a powered V-wheel in which the suspension lines are held under pressure by a hydraulically operated grip wheel. Rotation of the V-wheel recovers or pays out the suspension lines, which remain attached to the Frustum, thereby raising or lowering the Frustum. The power block is pinned to the retrieval-hoist boom end and thereby permits hoisting and landing of the Frustum onto the retrieval vessel deck (Figure 17).

A rope fender system designed to protect the Frustum is mounted on the ship's stern at the waterline and provides protection during hoisting from the water and landing on board. Once on board, the Frustum is lowered onto a pallet secured to the vessel deck.

Booster Dewatering

The dewatering equipment consists of a nozzle-plug underwater-tethered vehicle (Figure 18), an umbilical, a control console, a remote-control unit, and air/electrical power supply components to support the equipment.

To initiate the dewatering operation, the retrieval vessel approaches the Booster and launches the nozzle plug. The retrieval hoist, in conjunction with the cable hoist and hook, is utilized to ease the plug from the deck to the water by riding the port stern fender. Once it is waterborne, the nozzle plug is controlled remotely by an operator at the control console and can be maneuvered on the surface or underwater in all axes of motion. An umbilical to the nozzle plug provides compressed air and electrical power for operation. The umbilical is payed out or taken in to meet the demands of nozzle-plug travel. This is accomplished manually or by using the retrieval hoist and power block to feed the umbilical to the nozzle plug. A remote-control unit is utilized by a nozzle-plug operator to control travel by visual contact. When the nozzle plug submerges, control is transferred to a console where the operator relies on instrumentation and a camera monitor to command and control the nozzle plug.

In performing its dewatering function, the nozzle plug transits to the floating Booster (spar mode), establishes camera contact, and begins
a descending underwater inspection of the Booster casing. When reaching the nozzle, it maneuvers directly underneath the nozzle opening and continues to inspect casing condition. Upon command, the nozzle plug drives up into the nozzle opening and docks. When locked in, it is commanded to transfer air into the casing, thus forcing out water. This gradually causes the Booster to transition from spar to log mode. The nozzle plug seals the nozzle opening to prevent back flow and continues to expel water until the desired draft is achieved. The Booster is then ready to be taken under tow for return to port.

REFURBISHMENT

After the Boosters are towed to shore, they are brought into a Disassembly Facility where the structural elements and the motor case segments are separated from each other. They are thoroughly washed to remove ocean environment residue, and residual thermal protection material is removed with high pressure water jets.

The motor cases are returned by rail to the Thiokol facility in northern Utah where the residual internal case insulation material and nozzle ablatives are removed with high pressure water spray. The motor cases are grit blasted internally and externally, inspected, and subjected to a hydrostatic proof test. They are then ready to recycle through propellant loading process for reuse.

The parachutes are transferred from the retrieval vessel to the Parachute Refurbishment Facility at the launch site where they are thoroughly washed and dried. Subsequently, they are carefully inspected for damage and repaired in the Parachute Refurbishment Facility. Expendable components, such as reefing lines, reefing line cutters, and attach hardware, are replaced. The parachutes are then repacked on-site and made available for reuse.

The structural components from the first retrieval will be returned to Marshall Space Flight Center for extraordinary inspection of critical welds and dimensions. This is part of the "look and learn" process of certifying for manned flight reuse.

Likewise, all electrical, electronic, and mechanical components from the early flights will be removed and returned to their manufacturer for detailed inspections and tests necessary to establish refurbishment procedures to be used in the field for routine reuse.
FIGURE 1  SOLID ROCKET BOOSTER - SRB
FIGURE 2  THRUST VERSUS TIME SUMMARY AT 60°F
FIGURE 4. THRUST VECTOR CONTROL SYSTEM IN AFT SKIRT
Figure 6
FIGURE 7 SEPARATION SUBSYSTEM SCHEMATIC
FIGURE 8. PARACHUTES FULL REEFED DURING DROP TESTS
1. Space Shuttle launch.
2. SRB separation from Orbiter ET.
3. Orbiter continues flight to earth orbit.
4. SRB's continuing through parabolic trajectory (290,300 feet apogee).
5. SRB nose cap deployment for retrorocket boosters initiation.
6. At approximately 18,000 feet.
7. First chute pack deployment.
10. Full inflation of drogue chutes.
11. Preston separation and main parachute pack extraction.
12. Drogue chutes with Preston deploying to sea.
13. First phase inflation of three main parachutes.
15. Full inflation of main parachutes.
16. SRB water impact, main parachute separation, and two pendant deployment.
17. Drogue chute and Preston water impact.
18. Retrieval and return for refurbishment.

FIGURE 9. SOLID ROCKET BOOSTER (SRB) MISSION SEQUENCE
FIGURE 10. BOOSTER NOZZLE PLUG / DEWATERING DEVICE
FIGURE 11. SRM STATIC FIRING
FIGURE 12. COMPARISON OF QM-1 AND QM-2 THRUST-TIME TRACES AT SITE CONDITIONS
<table>
<thead>
<tr>
<th>TEST CONFIGURATION</th>
<th>QUALIFICATION MOTOR NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF INITIATORS</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14</td>
</tr>
<tr>
<td>SINGLE</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>DOUBLE</td>
<td>X X X X X X X</td>
</tr>
<tr>
<td>SEAL</td>
<td></td>
</tr>
<tr>
<td>HEAT</td>
<td>X X</td>
</tr>
<tr>
<td>AEROTHERMAL HEATING</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>CLUSTER</td>
<td>X X</td>
</tr>
<tr>
<td>PREFIRE CONDITIONING</td>
<td></td>
</tr>
<tr>
<td>TEMPERATURE CYCLING</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>ALTITUDE CYCLING</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>45 DAYS AGING</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>+130F</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>RAIN</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>SALT FOG</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>AERODYNAMIC HEATING</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>STRUCTURAL VIBRATION</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>PREFIRE AT 30°</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>PREFIRE AT AMBIENT</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>PREFIRE AT 120°q</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>SHOCK</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>MOTOR FIRING CONDITION</td>
<td></td>
</tr>
<tr>
<td>TEST TEMPERATURE</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>30°F</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>120°F</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>ALTITUDE START</td>
<td>X X X X X X X X</td>
</tr>
<tr>
<td>POSTFIRE CONDITIONING</td>
<td></td>
</tr>
<tr>
<td>RE-ENTRY VIBRATION</td>
<td>X X X X X X X X</td>
</tr>
</tbody>
</table>

**Figure 13** Separation Motor Static Test Configurations
# BSM Propulsion Performance

## Requirement Verification Test Data

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification Test Data</th>
<th>Verification Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web action time total impulse (lb-sec), minimum -3 sigma</td>
<td>14,000</td>
<td>14,429 14,784 15,139</td>
</tr>
<tr>
<td>Action time total impulse (lb-sec), minimum -3 sigma</td>
<td>15,000</td>
<td>17,468 18,107 18,746</td>
</tr>
<tr>
<td>Maximum thrust (lbf), maximum +3 sigma</td>
<td>29,000</td>
<td>21,425 23,269 25,113</td>
</tr>
<tr>
<td>Web action time average thrust (lbf), minimum -3 sigma</td>
<td>18,500</td>
<td>18,179 19,522 20,865</td>
</tr>
<tr>
<td>Ignition time (sec), maximum +3 sigma</td>
<td>0.100</td>
<td>0.040 0.067 0.094</td>
</tr>
<tr>
<td>Web action time (sec), maximum +3 sigma</td>
<td>0.800</td>
<td>0.709 0.757 0.805</td>
</tr>
<tr>
<td>Total time (sec), maximum +3 sigma</td>
<td>1.050</td>
<td>0.896 0.956 1.016</td>
</tr>
<tr>
<td>Pressure at end of web action (psi), maximum +3 sigma</td>
<td>2,000</td>
<td>1,703 1,798 1,893</td>
</tr>
</tbody>
</table>

*Within Level II BSN cluster performance specification
*Level II approval per PRCD S27938

FIGURE 14 SUMMARY OF SEPARATION MOTOR STATIC FIRING PERFORMANCE
FIGURE 15. RETRIEVAL SHIP DECK ARRANGEMENT
FIGURE 16. DROGUE PARACHUTE FLOTATION
1. Power block engagement with parachute lines
2. Power block takes tension on and begins reeling in lines
3. Power block lifts frustum to the trailing position off the ship's stern

Figure 17: Power block/drogue parachute line engagement and frustum lifting
FIGURE 18. BOOSTER NOZZLE PLUG