

SOLID ROCKET BOOSTER (SRB) FLIGHT SYSTEM INTEGRATION AT ITS BEST

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ABSTRACT

The Solid Rocket Booster (SRB) element integrates all the subsystems needed for ascent flight, entry, and recovery of the combined Booster and Motor system. These include the structures, avionics, thrust vector control, pyrotechnic, range safety, deceleration, thermal protection, and retrieval systems. This represents the only human-rated, recoverable and refurbishable solid rocket ever developed and flown.

Challenges included subsystem integration, thermal environments and severe loads (including water impact), sometimes resulting in hardware attrition. Several of the subsystems evolved during the program through design changes. These included the thermal protection system, range safety system, parachute/recovery system, and others. Because the system was recovered, the SRB was ideal for data and imagery acquisition, which proved essential for understanding loads, environments and system response.

The three main parachutes that lower the SRBs to the ocean are the largest parachutes ever designed, and the SRBs are the largest structures ever to be lowered by parachutes. SRB recovery from the ocean was a unique process and represented a significant operational challenge; requiring personnel, facilities, transportation, and ground support equipment.

The SRB element achieved reliability via extensive system testing and checkout, redundancy management, and a thorough postflight assessment process. However, the in-flight data and postflight assessment process revealed the hardware was affected much more strongly than originally anticipated. Assembly and integration of the booster subsystems required acceptance testing of reused hardware components for each build. Extensive testing was done to assure hardware functionality at each level of stage integration. Because the booster element is recoverable, subsystems were available for inspection and testing postflight, unique to the Shuttle launch vehicle. Problems were noted and corrective actions were implemented as needed. The postflight assessment process was quite detailed and a significant portion of flight operations.

The SRBs provided fully redundant critical systems including thrust vector control, mission critical pyrotechnics, avionics, and parachute recovery system. The design intent was to lift off with full redundancy. On occasion, the redundancy management scheme was needed during flight operations. This paper describes some of the design challenges and technical issues, how the design evolved with time, and key areas where hardware reusability contributed to improved system level understanding.

INTRODUCTION

Nomenclature

<i>APU</i>	= <i>Auxiliary Power Unit</i>	<i>MSFC</i>	= <i>Marshall Space Flight Center</i>
<i>BSM</i>	= <i>Booster Separation Motor</i>	<i>NASA</i>	= <i>National Aeronautics and Space Administration</i>
<i>DAS</i>	= <i>Data Acquisition System</i>	<i>APU</i>	= <i>Auxiliary Power Unit</i>
<i>DFI</i>	= <i>Developmental Flight Instrumentation</i>	<i>NDE</i>	= <i>Non-Destructive Evaluation</i>
<i>EDAS</i>	= <i>Enhanced Data Acquisition System</i>	<i>NSI</i>	= <i>NASA Standard Initiator</i>
<i>ET</i>	= <i>External Tank</i>	<i>OEM</i>	= <i>Original Equipment Manufacturer</i>
<i>KSC</i>	= <i>Kennedy Space Center</i>	<i>STS</i>	= <i>Space Transportation System</i>
<i>MLP</i>	= <i>Mobile Launch Platform</i>	<i>TPS</i>	= <i>Thermal Protection System</i>
<i>MMT</i>	= <i>Mission Management Team</i>	<i>TVC</i>	= <i>Thrust Vector Control</i>
<i>MRB</i>	= <i>Material Review Board</i>		

SRB-101

The SRBs are the largest solid propellant rocket motors ever flown, and the first designed for Treuse. The two SRBs provide the main thrust to lift the Space Shuttle off the launch pad to an altitude of ~150,000 feet (28 miles) and burn for 123 seconds during ascent. Each SRB is 149.16 feet long, 12.17 feet in diameter and weighs ~1,300,000 pounds at launch. During flight, each SRB burns ~1,100,000 pounds of propellant, with a final weight of ~192,000 pounds. The flight sequence for the SRBs can be seen in Figure 1, from lift-off through retrieval.

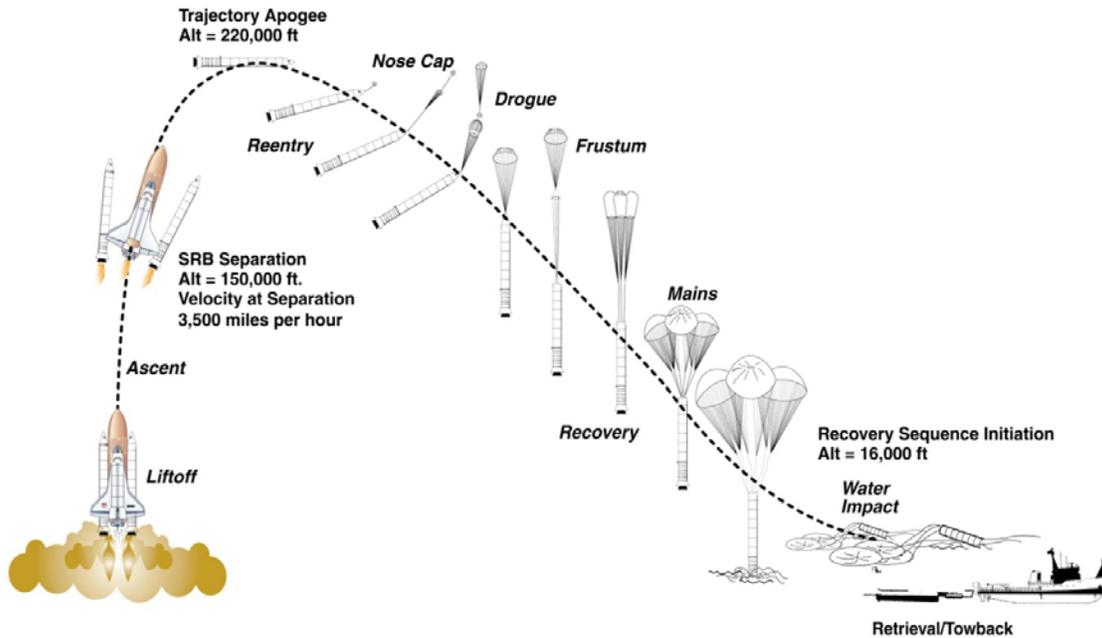


Figure 1. SRB Flight Sequence

The primary elements/systems of the SRBs include the solid rocket motor (motor case, propellant, igniter and nozzle), forward and aft structures, separation systems, operational flight instrumentation, recovery avionics, pyrotechnics, deceleration system, thrust vector control system and range safety destruct system. Each booster is attached to the External Tank (ET) at the SRBs aft frame by two lateral sway braces and a diagonal attachment (struts). The forward end of each SRB is attached to the ET on a ball fitting on the SRBs forward skirt. On the launch

pad, each booster is secured to the Mobile Launcher Platform (MLP) at the aft skirt by four bolts and frangible nuts which are severed by small explosives at lift-off. In fact, the entire Space Shuttle system is attached to the MLP with these eight bolts! The two SRBs carry the entire weight of the ET and Orbiter, and transmit the weight load (4,500,000 pounds) through their structure to the MLP.

Each booster has a sea level thrust of ~2,800,000 pounds at launch (peaking to 3,300,000 pounds). The two SRBs provide ~83% of the lift-off thrust. At 123 seconds/150,000 feet (technically when the propellant is consumed), a series of pyrotechnic events occur to disconnect the SRBs from the ET at the struts and forward attach point, followed by eight Booster Separation Motors per SRB igniting for a 0.8 second burn, providing 20,000 pounds of thrust each, and pushing the SRBs safely away from the ET and Orbiter.

Seventy-five seconds after SRB separation, the SRBs reach apogee at an altitude of ~220,000 feet (41 miles). During decent through the Earth's atmosphere, the SRBs aerodynamically bleed energy, slowing down sufficiently until the deceleration system initiates. The SRB deceleration sequence provides attitude and terminal velocity control of the SRB for water impact. This system is located in the forward assembly of each SRB and is comprised of the drogue pilot assembly, main parachute cluster assembly and altitude switch assembly. SRB water impact occurs in the ocean ~141 miles downrange. The SRBs and parachutes are retrieved and towed back to Kennedy Space Center (KSC) for reuse via recovery ships. The retrieval process begins once splash down occurs (T+6.5 minutes) in the ocean and the ships approach each SRB for recovery operations. At KSC, the SRBs are inspected, disassembled, refurbished, re-assembled, stacked and integrated with an ET and Orbiter, and the process begins anew (Figure 2).

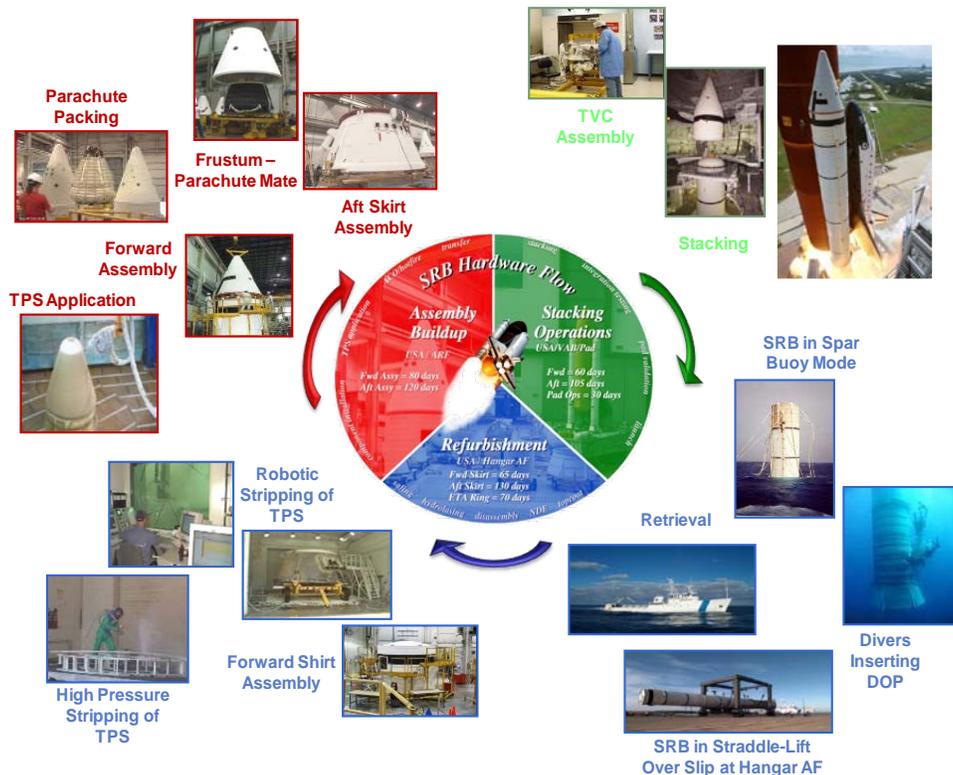


Figure 2. SRB Circle of Life.

RESULTS AND DISCUSSION

KEY SRB POSTFLIGHT/REFURBISHMENT FINDINGS AND CORRESPONDING LESSONS LEARNED

Over the next few sections, this paper will provide insight into several of the significant design and/or process changes that were a direct result of SRB postflight/refurbishment findings. These examples cover a wide array of deficiencies (manufacturing, workmanship, and design) that were unknown prior to flight and in many of the cases would not have been realized without inspection of the flown hardware. In each case the program was able to take action to mitigate the risk of these issues adversely affecting the next launch vehicle. This corrective action response would not have been possible if the SRBs were not recovered and assessed.

POSTFLIGHT ASSESSMENT PROCESS

Following each mission, the recovered boosters were brought back to Kennedy Space Center for a thorough inspection of how the environments affected the hardware. The combination of flight environments (aeroheating, accelerations, vibration, etc.) with the recovery environments (water impact, sea-water immersion, etc.) left the hardware needing more processing than the anticipated "Wash, Dry and Fly" program goal.

As a result of the postflight condition observed early on in the Shuttle program, a reuse standard (SRB Refurbishment Specification, 10SPC-0131) was developed to define the inspection, testing and refurbishment criteria for each reusable part before such a part could be placed back into serviceable stock.

The other consequences of the postflight assessment was improvements to design, processes, workmanship and in-flight data acquisition systems, all of which are detailed further in this paper.

SRB CAMERA AND DATA ACQUISITION SYSTEM DEVELOPMENT

The Space Shuttle Solid Rocket Boosters were the first of their kind to be recovered and reused. In order to support that design requirement, flight environments, performance and imagery data were acquired heavily during the onset of the program, and the flight hardware was refined and improved throughout the program. Data systems were located on chase planes, boats and on-board the flight hardware. They all played a key role for assessing the vehicle performance as well as providing a better understanding of the flight environments.

For the first six Space Shuttle flights, a full set of Developmental Flight Instrumentation (DFI) data was acquired, measuring in-flight parameters such as temperatures, pressures, accelerations, strains and heating rates. Thereafter, a limited set of data was acquired on several flights, until Return to Flight from the Challenger Accident, where we had three more flights of DFI. Starting STS-72 (January 1996), an on-board Data Acquisition System (DAS) was installed which recorded accelerometer data within the forward skirt to assess splashdown loads at water impact. An "enhanced" system (EDAS) was also used periodically from STS-91 (June 1998) to gather specific data for an area of interest (i.e. thermocouples to assess Thermal Protection System removal, strain gages, accelerometers and/or force gages to validate analytical models, and most recently pressure and strain gages to assess SRB thrust oscillations). With this data, the booster design could be continually examined, allowing analysis models to be further developed and refined to predict the hardware performance.

In addition to data acquisition systems, in-flight imagery was acquired, starting with video from tracking ships as well as Air Force Starcast and Navy Castglance aircraft. STS-41G (October 1984) incorporated a 16mm camera to capture parachute deployment, and it was used periodically on subsequent flights. Camcorders were implemented into the DAS system starting on STS-77 (May 1996). A second flight camera was installed on STS-95 (October 1998), and utilized for five flights to observe External Tank (ET) foam performance on the Intertank (the region between the liquid oxygen and liquid hydrogen tanks), and was permanently implemented on STS-114 (July 2005). On STS-121 (July 2006), two more in-flight video cameras were added to the SRBs to evaluate ascent debris concerns, with one camera on the forward skirt of the SRBs looking aft, and another on the ET Attach Ring looking forward (Figure 3). All of these



Figure 3. STS-114 (July 26, 2005) Views from SRB Forward and Aft Pointing Cameras.

cameras, in addition to the ground-based imagery, ET Feedline Camera and Orbiter imagery, were tools that provided the Mission Management Team (MMT) valuable data to assist in evaluating the on-orbit condition of the Orbiter. In addition, the cameras provided details of in-flight anomalies, such as parachute failures (Figure 4) and material liberation that could strike the Orbiter (Figure 5).

From chase planes and boats, to on-board digital systems, data acquisition has been a key tool for supporting assessment of vehicle performance and in-flight debris imagery. Such data supports flight assessments, expands upon the understanding of flight environments (and their variability from flight-to-flight) and provides



Figure 4. STS-122 Parachute Failure Observed With Parachute Forward Skirt Dome Camera.



Figure 5. STS-116 In-Flight Anomaly of TPS Striking the Orbiter during SRB Separation.

records of historical performance, which has led to improved hardware designs and processing. The systems used on the flight vehicle were classified as low criticality hardware, but they provided invaluable data throughout the program.

LOSS OF TURBINE WHEEL BLADE PORTIONS DURING OPERATION

During disassembly of the SRB Auxiliary Power Unit (APU) balance assembly that flew on STS 61 (1994), portions of the turbine wheel blade tips were noted to be missing on 62, 2nd-stage blades. (Figure 6) The missing blade tips exited the turbine wheel area through the exhaust housing, fortunately causing no significant damage to any other parts. Due to the low mass of the missing blade tips, the turbine wheel balance was negligibly affected. The turbine wheel blade damage was attributed to a machining feature which accelerated the known crack growth. A review of all manufacturing paper for this unit indicated that a groove had been machined into each second stage blade of the turbine wheel. These grooves were accepted by the Original Equipment Manufacturer (OEM) on a Material Review Board (MRB) disposition in 1985. A material analysis has determined that the turbine blade damage was precipitated by this machining feature. This feature introduced a stress riser which accelerated known crack growth. This anomaly required that all of the OEM's

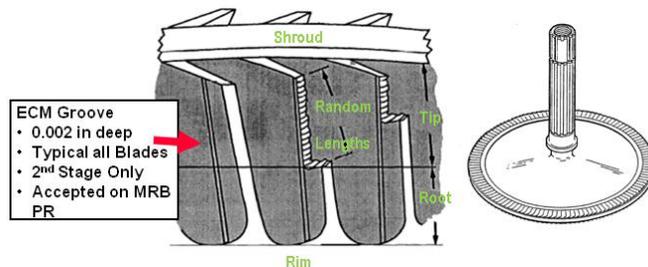


Figure 6. Auxiliary Power Unit S/N 171 Turbine Wheel

MRB activity be reviewed by representatives of NASA and the SRB Contractor to gain confidence in supplier dispositions in addition to insuring that no other manufacturing defects existed on flight hardware which could result in turbine wheel blade damage. All turbine wheels NDE (dye penetrant) mapping was reverified in order to restore hardware integrity. If this APU had not been recovered and assessed after flight this anomaly would not have been known and other units with similar defects could have potentially flown.

UNBURNED BOOSTER SEPARATION MOTOR PROPELLANT

During postflight disassembly inspection of STS-100 forward Booster Separation Motors (BSMs), one motor exhibited an unusual amount of residual propellant (4-5 of the original 75 pounds) (Figure 7). All other forward (7) BSMs were in nominal postflight condition. As a result of this observation, the postflight assessment process required the calling of a "Squawk" which is a means to document and assess off-nominal observations. The Squawk was subsequently elevated to an Anomaly, and a formal investigation team (Anomaly Resolution Team) was formed to determine the cause and corrective action of the incident. The combined team included members from Design Engineering, Materials & Processes, Quality Engineering and the BSM sub-vendor, among other subject matter experts on the design and handling of the BSMs. Hardware build-paper was reviewed, computer modeling was performed, propellant testing was completed, and other material compatibility testing was performed. A fault tree was created to properly access the observation and determine the root cause. The investigation determined the cause of the unburned propellant was due to the intrusion of 2 cups of water past the seals and into the motor case. Detailed forensic investigation determined that the cover seal was not likely in its "normal" position prior to flight. The moisture intrusion was concluded to have occurred at the launch pad during a heavy rain event 20 days prior to launch (Figure 8). Long-term exposure of the moisture degraded the retained propellant, reducing the propellant burn rate and inhibiting ignition.



Figure 7. STS-100 Forward booster Separation Motor (BSM) Residual

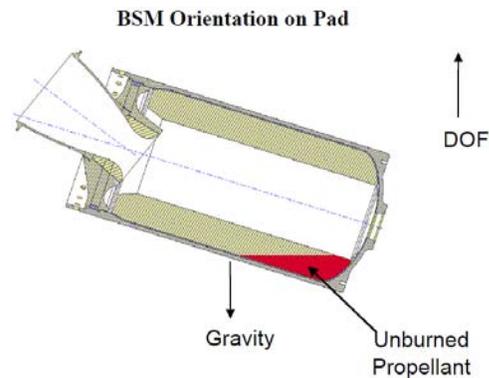


Figure 8. BSM Water Intrusion

The corrective action for this issue was to perform dimensional checks as well as pressurization and vacuum leak checks. The intent of these checks was to verify the integrity of the seals. Additional improvements to the processing of the BSMs included replacing o-ring grease with one that results in less swelling, defining tighter dimensional tolerances on the final configuration, enhancing the controls on chemical use around the seal and to provide access to the BSMs at the launch pad. Without recovery and assessment this condition would not have been known and future water intrusion could have occurred potentially affecting multiple motors.

STS-57 BROKEN FUEL PUMP SHAFT

During refurbishment of an SRB APU that flew on STS 57 (1993), a broken fuel pump shaft was discovered in the hydrazine fuel pump. The break occurred about 0.7 inches from the

gearbox end of the shaft. (Figure 9) Following flight during the GN2 spin portion of Thrust Vector Control (TVC) deservicing, technicians at KSC noticed significant alcohol leakage from the overboard drain. The unit was immediately sent to the OEM for disassembly whereupon the sheared shaft was discovered following removal of the fuel pump. The fuel pump shaft failure was attributed to improper installation of a preload beam. The purpose of the preload beam is to bias the bearings to the low pressure side of the pump. Review of flight data indicates the anomaly fortunately occurred after SRB separation therefore not affecting ascent performance. All four APU turbine speed traces tracked together and were nominal. Radiographic inspection of the fuel pump prior to disassembly identified an arc-shaped object lodged between the drive gear and the pumps inlet window (low pressure side). The same x-ray identified a preload beam missing from the driven bearing on the pump load piston side (high pressure side). A metallurgical analysis of the fractured shaft (15-5 ph steel) did not identify any material or chemical anomalies which could lead to a premature failure. The fuel pump was disassembled and a preload beam was confirmed to be lodged between the drive gear and the inlet window which prevented fuel pump rotation. The bearing preload beams and mating slots were dimensionally inspected and found to be within drawing specifications. A preload beam migration test confirmed a pathway the beam could travel to arrive at the gear inlet window. Although the beam must move upwards to arrive at the inlet core, the fluid has enough momentum to lift the preload beam and position it at the inlet window. It was determined that the preload beam could not enter the gear tooth opening when the pump was running therefore it was concluded that the beam must have entered the gear teeth after SRB splash down. The failure is believed to have occurred during fuel system decontamination.

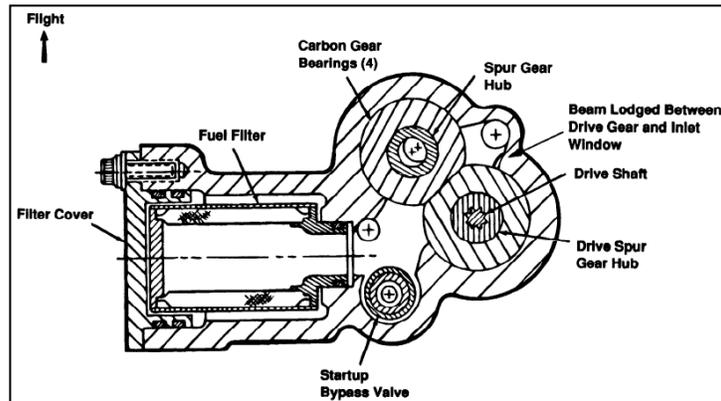


Figure 9. Fuel Pump S/N 152 Off Nominal Configuration

Recurrence control was implemented to prevent a repeat of this failure in the future, including the addition of a caution note and a visual inspection during fuel pump assembly. Radiographic inspection of all units in the field was necessary prior to flight to verify that this critical assembly did not exist, and the preload beam was properly installed.

STS-97 NSI INITIATION FAILURE

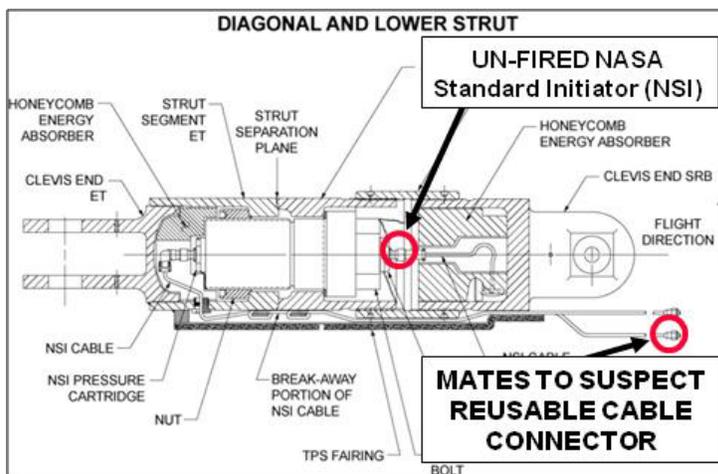


Figure 10. Lower Strut

During postflight disassembly of STS-97 technicians were surprised to find an unexpended pyrotechnic device installed on an aft separation bolt utilized between the SRB and ET. A NASA Standard Initiation (NSI) pressure cartridge located on the SRB side of the left lower strut on STS-97 failed to initiate at SRB separation (Figure 10). The aft separation bolts are designed to accommodate two NSIs for redundancy, but only one NSI functioned properly at the

aforementioned location. Electrical tests determined intermittent continuity, which varied with positioning, on the cable assembly at the NSI connector end. The entire cable assembly was x-rayed where a defect was observed in the braided shield, but no damage of the two inner conductors could be visually ascertained from the x-rays. The subject cable assembly was then transferred for failure analysis. Upon disassembly of the J2 connector, it was evident that the braided shield had been entirely broken, and both of the conductors were also completely fractured at the connector pin crimps. A microscopic examination of the wires composing the braided shield and the wires of both conductors revealed that the cable assembly failed as a result of tensile stress overload.

While the failure was possibly caused by multiple tensile stress applications, there was no evidence to indicate that the failure was not caused by a single event. No manufacturing defects of the cable assembly were found. There was no evidence of electrical arcing inside either of the two pin barrels or on any of the wire strands. There was no evidence of fatigue, corrosion, or any other deleterious condition other than tensile stress overload. Due to this critical failure the vehicle on the pad was rolled back to the Vertical Assembly Building for further interrogation. Several corrective actions were taken including radiographic inspection of all cables, flex tests prior to connection, and limiting use of reusable cables.

CONCLUSION

The Shuttle program spanned over 30 years of flight with 135 missions consisting of 270 SRB flights. Following each SRB flight the performance was evaluated utilizing telemetry, recorded data and flight hardware inspection to assess and improve the hardware when necessary. With the number of years and flights the Shuttle endured it was unique relative to being programmatically viable to retrieve and reuse the hardware.

Although the reusability of the SRB has been highly successful, it never fulfilled the program's original goal of "wash, dry and fly". The primary structures and Line Replaceable Units were qualified to 40 and 20 missions respectively. The qualification tests were done without disassembly between mission exposures. That said, due to the harsh environments the Booster hardware was exposed to each flight, including highly variable water impact loads (driven by horizontal velocity, sea state, and slap-down loads) the necessity of performing a more comprehensive refurbishment was required for certification of each additional flight. Refurbishment included significant disassembly, inspection, reassembly and bench tests that defined the booster circle of life each mission flow.