

Solid Rocket Booster (SRB) - Evolution and Lessons Learned During the Shuttle Program

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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. Obsolescence issues occasionally required component recertification. Because the system was recovered, the SRB was ideal for data and imagery acquisition, which proved essential for understanding loads 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. Assembly and integration of the booster subsystems was a unique process and acceptance testing of reused hardware components was required 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, how the design evolved with time, and key areas where hardware reusability contributed to improved system level understanding.

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Nomenclature

ASA	= Altitude Switch Assembly	MLP	= Mobile Launch Platform
CRD	= Command Receiver/Decoder	MMT	= Mission Management Team
CST™	= Convergent Spray Technology™	MSA-1, -2	= Marshall Sprayable Ablator, 1st or 2nd Generation
DAS	= Data Acquisition System	MSFC	= Marshall Space Flight Center
DFI	= Developmental Flight Instrumentation	NASA	= National Aeronautics and Space Administration
EDAS	= Enhanced Data Acquisition System	psi	= Pressure. Pound per Square Inch
EPA	= Environmental Protection Agency	RSD	= Range Safety Distributor
ET	= External Tank	RSS	= Range Safety System
ETA	= External Tank Attach	SMP	= Small Main Parachute
FOS	= Factor of Safety	SRB	= Solid Rocket Booster
IEA	= Integrated Electronics Assembly	STS	= Space Transportation System
IRD	= Integrated Receiver/Decoder	TPS	= Thermal Protection System
KSC	= Kennedy Space Center		
LMP	= Large Main Parachute		
MCC-1	= Marshall Convergent Coating, 1st Generation		

I. SRB-101

The SRBs are the largest solid propellant rocket motors ever flown, and the first designed for reuse. 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.

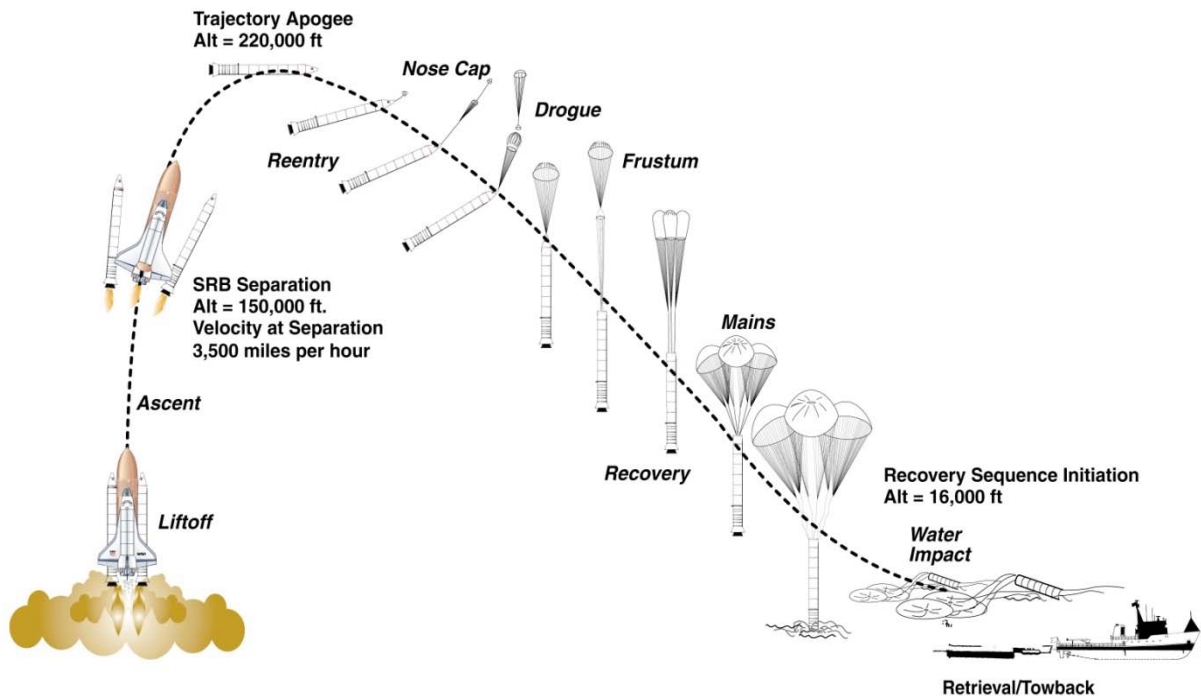


Figure 1. SRB Flight Sequence

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.

II. SRB History, Evolution and Key Lessons Learned for Five Selected Subsystems

Over the next few sections, this paper will provide insight into several of the key systems of the SRBs and how they have developed over the years. This evolution has been a result of the years of flight data and evaluation of the recovered hardware, something that would not have been possible if the SRBs were not recovered and reused.

III. Evolution of Sprayable Acreage Thermal Protection System (TPS)

Marshall Sprayable Ablative (MSA)-1 was used as a TPS on the frustum and forward skirts from STS-1. It was developed at NASA Marshall Space Flight Center (MSFC). The nose cap was also included starting with STS-4, replacing sheet cork that was manually bonded to the structure. MSA-1 was a glass and resin based material that was sprayed onto flight hardware and eliminated the prior labor intensive cork bonding process. MSA-1 had a maximum application thickness of 0.25 inches, which precluded application on several components, including the aft skirt. This limitation was based on observed stress cracking during the cure cycle for greater thicknesses. MSA-1 was a noted debris concern during STS-27 (December 1988), when material from the nose cap was associated with Orbiter tile damage.

MSA-2 was developed to replace MSA-1. It was intended to extend the application to more hardware components and improve performance. On STS-29 (May 1989), MSA-2 was first flown on the forward assembly. On STS-28 (August 1989), it was first flown on the aft skirt. The formulation changes from MSA-1 to MSA-2 reduced the TPS susceptibility to stress cracking during curing, thus the maximum application thickness was increased to 0.5 inches. Other improvements on its predecessor included the elimination of a carcinogenic curing agent, increased strength, improved adhesion, and shortened processing time, but MSA-2 was still considered hazardous waste, like MSA-1, due to use of solvents during the application process.

Marshall Convergent Coating (MCC-1) was developed to address Environmental Protection Agency (EPA) mandates, eliminating solvents and the classification as hazardous waste. Processing and the overall material capability for MCC-1 were also significant improvements over MSA-2 due to the use of Convergent Spray Technology™ (CST™). This application method was developed in-house to apply the coating by mixing multiple streams of materials at the application surface (Figure 3). CST™ is what eliminated the need for solvents. MCC-1 was first flown on the left-hand SRB during STS-79 (September 1996), and fully implemented for STS-80 (November 1996). In addition to Space Shuttle SRB applications, MCC-1 was used for the Air Force Titan program, eliminating its non-environmentally-compliant TPS.

The incorporation of MCC-1 resulted in significant process improvements, such as reduced setup time, mixing on demand and consistent surface finish. MCC-1 reduced the constituents required, from eleven to five, reducing material storage and handling requirements (MCC-1 constituents later increased to six, adding an accelerator to the epoxy). In addition, MCC-1 had superior strength over its predecessors, with flat-wise tensile capabilities in excess of 200 psi, vs. 50 psi for MSA-1 and 75 psi for MSA-2. MCC-1 also had improved thermal properties, indicated by improved recession characteristics (when exposed to the combination of heating and aerodynamic shear). MCC-1 was qualified to be applied over more substrates than previous sprayable ablators, thus further reducing hardware processing time. The only trade-off from MSA-2 was that MCC-1, despite allowing thinner applications, had a higher density, and thus resulted in a slight increase in TPS weight for the vehicle. However, the latest incarnation of the sprayable acreage TPS (with its associated top-coat of Hypalon) has been demonstrated as being very robust in the flight environment. It is tolerant of impacts from in-flight debris sources, and it has minimal propensity to self-liberate debris.

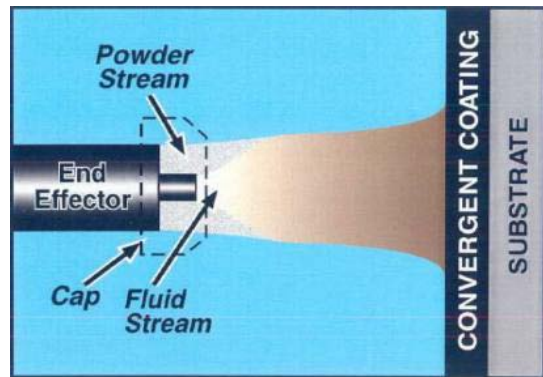


Figure 3. Convergent Spray Technology™ mixes solids and liquids during application process.

IV. 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) 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 TPS 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 4). All of these 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 5) and material liberation that could strike the Orbiter (Figure 6).



Figure 4. STS-114 (July 26, 2005) Views from SRB Forward and Aft Pointing Cameras.

From chase planes and boats, to on-board digital systems, data acquisition has been a key tool for supporting



Figure 5. STS-122 Parachute Failure Observed With Parachute Forward Skirt Dome Camera.



Figure 6. STS-116 In-Flight Anomaly of TPS Striking the Orbiter during SRB Separation.

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 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.

V. Command Receiver/Decoder (CRD) Design and Implementation

The Space Shuttle Vehicle has a flight termination system called the Range Safety System (RSS). This system is available to protect the general population or property in case either a major malfunction or errant flight path occur

during the boost stage of flight. The RSS terminates flight by splitting the motor cases of the SRBs, which eliminates thrust. If off-nominal conditions occur, a decision is made whether to allow continued vehicle flight (if hazards to life and/or property are decreasing) or to immediately initiate flight termination action. Each SRB was equipped with two command antennas in conjunction with associated electronics to interpret the Eastern Test Range range-safety command signals and, if needed, initiate the linear shaped charges affixed to the SRB motor case. The CRD is one of the associated electronics boxes.

The CRD implementation was originally developed for an RSS for the ET. However, an RSS for the ET was subsequently eliminated. Due to concerns of supportability and obsolescence, SRB evaluated the CRD design and determined it could be used to replace its aging RSS electronics boxes (Integrated Receiver/Decoder (IRD) and Range Safety Distributor (RSD)) (Figure 7).

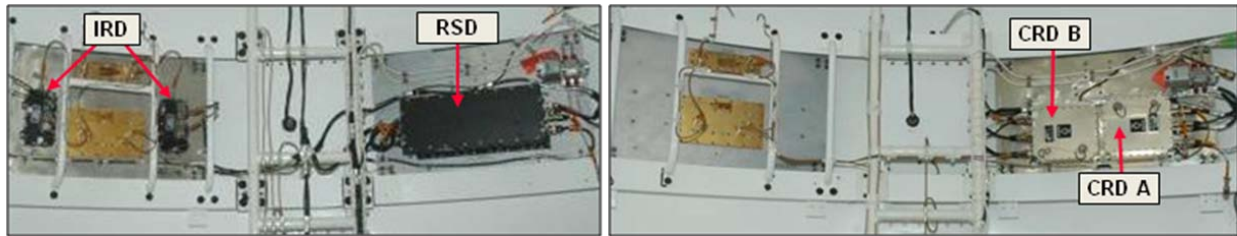


Figure 7. Previous IRD/RSD Configuration vs. New CRD Configuration.

The design configuration is such that there are redundant CRD A and B systems processing command signals independently. Unfortunately, it was not until integrated system level testing that a design deficiency was discovered. The CRD A and B electrical return paths for a particular command signal (Orbiter power) were not isolated from each other or the SRB structure. The consequence was a modification of the electrical circuit to separate the command signal return from the other paths. Subsequently, the redesigned CRD passed all qualification testing and successfully began flying on STS-118 (August 2007).

The design flaw could have been identified earlier in the development process. The root cause was identified as inconsistent terminology from the system to the component level. In this case, the Orbiter power was treated as a command signal during requirements development and design, and therefore the power isolation system requirement was not identified. System level testing was a key factor to identifying this design deficiency. For the CRD development, this occurred late into the cycle, which required additional efforts to bring the system into compliance with the design requirements. In addition, a strong involvement of systems engineering, particularly during the early development phase, would have greatly benefited the design, especially when dealing with multiple subsystems.

VI. External Tank Attach Ring Evolution

The External Tank Attach (ETA) Ring is the structure on the SRB where aft attach points to the ET exist, as well as the location for the aft Integrated Electronics Assembly (IEA) is mounted (Figure 8). The original design of the ring was such that it spanned 270° around the circumference of the SRB, providing a load path for the aft attachment to the SRB structure.

Following the Challenger accident, detailed structural analyses were performed on critical structural elements of the SRB, focused on areas where anomalies were noted during postflight inspection of the recovered and refurbished hardware. As a result, it was noted that the region where fasteners attach the ETA Ring to the SRB motor case experienced high levels of distress during thrust buildup. As a consequence of these assessments, the ETA Ring was redesigned to completely encircle the motor case (360°), which provided higher strength margins throughout the SRB flight and water impact (Figure 9).

In 2003, MSFC testing to support a fracture mechanics rebaseline analysis identified suspect material strength conditions for ETA Ring 4130 steel due to inconsistent heat treatment. This reduced the minimum Factor of Safety (FOS) from the requirement of 1.4 down to 1.25 for the design load case and worst case material properties. The actual FOS for STS-107 based upon flight specific loads was 1.3 (still greater than 1.0, but a violation of the requirement). The hardware for the next two flights, STS-114 and STS-121, underwent extensive (serial-number specific) material testing and analysis to certify compliance with the 1.4 FOS requirement.

For STS-115 (and subsequent flights), ETA Rings with a new grade of steel, 4340, were manufactured. This

Figure 8. ETA Ring Location.

material, being less susceptible to heat treat anomalies, eliminated the need for flight-by-flight testing and evaluation because they met the drawing material properties and FOS requirement.

The ETA Ring issue illustrates how appropriate design requirements can account for out-of-specification material properties, or any other variables. In this case, the use of a FOS was imperative for safe and reliable mission completion. Also, the original issue with the 270° ETA ring demonstrated through postflight inspection design weaknesses can be identified, and resolved - something that would not have been so easily identified for non-reusable hardware.

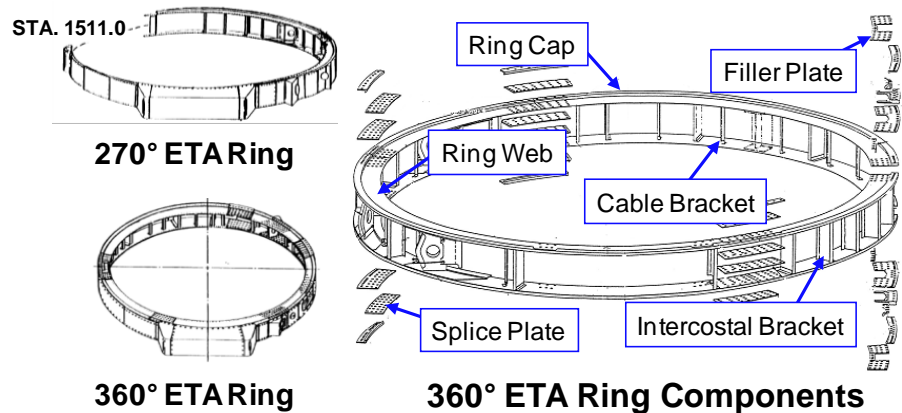


Figure 9. 270° vs. 360° ETA Ring.

VII. Evolution of SRB Recovery Systems (Parachutes)

The design requirement for reusability of the SRBs resulted in the development of a hardy recovery system. An Altitude Switch Assembly (ASA) located within the forward assembly initiates the parachute deployment process at the appropriate altitude as determined by pressure measurement (Figure 10, Figure 11). Then, through a series of hardware releases, parachute deployments and parachute disreefings, the SRBs are slowed down for a safe water landing, where retrieval ships recover the parachutes and flight structures, and bring them back to Kennedy Space Center for postflight inspection and refurbishment.

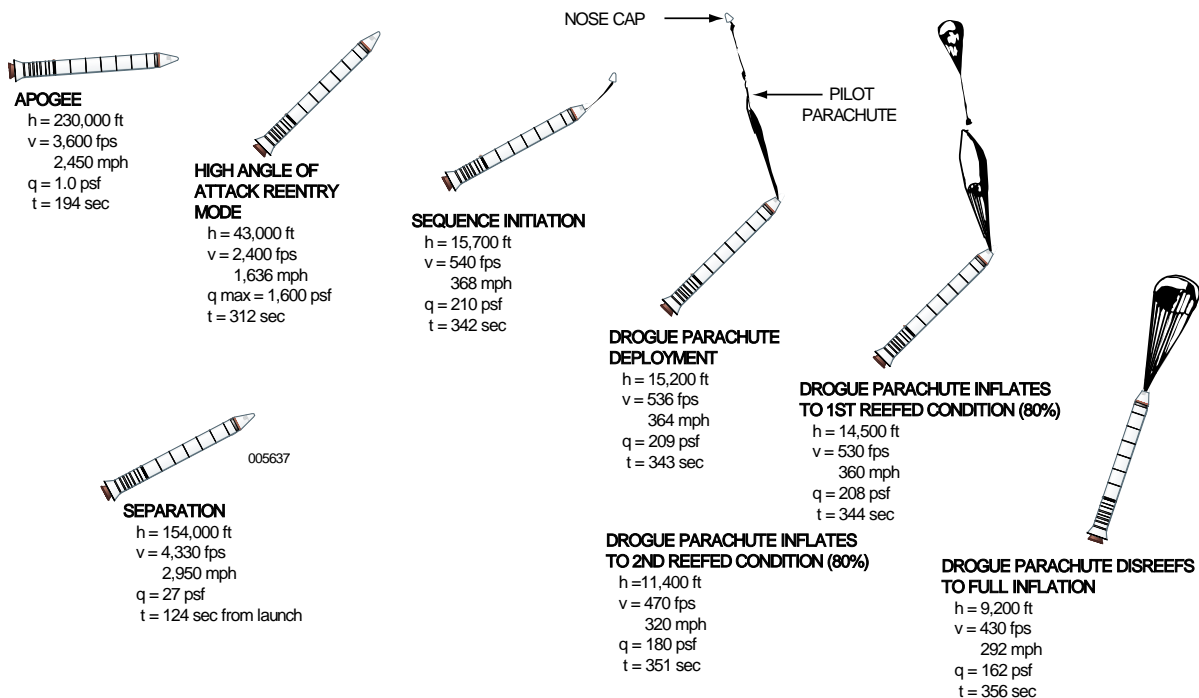


Figure 10. SRB Recovery Sequence Part 1: Descent through Drogue Parachute Disreef

The major evolution of the parachute system occurred early on the Space Shuttle Program after initial system failures. Improvements to the parachute recovery systems include modification of line release mechanisms, increase of the parachute canopy diameter, changes to the reefing ratios, implementation of ripstops and modifications to the canopy vent. Many of the changes were strongly influenced by the presence of in-flight imagery/video, which

allowed the SRB team to understand the flight environments and the dynamics of the descending SRBs, as well as insight into the various failure mechanisms that could occur.

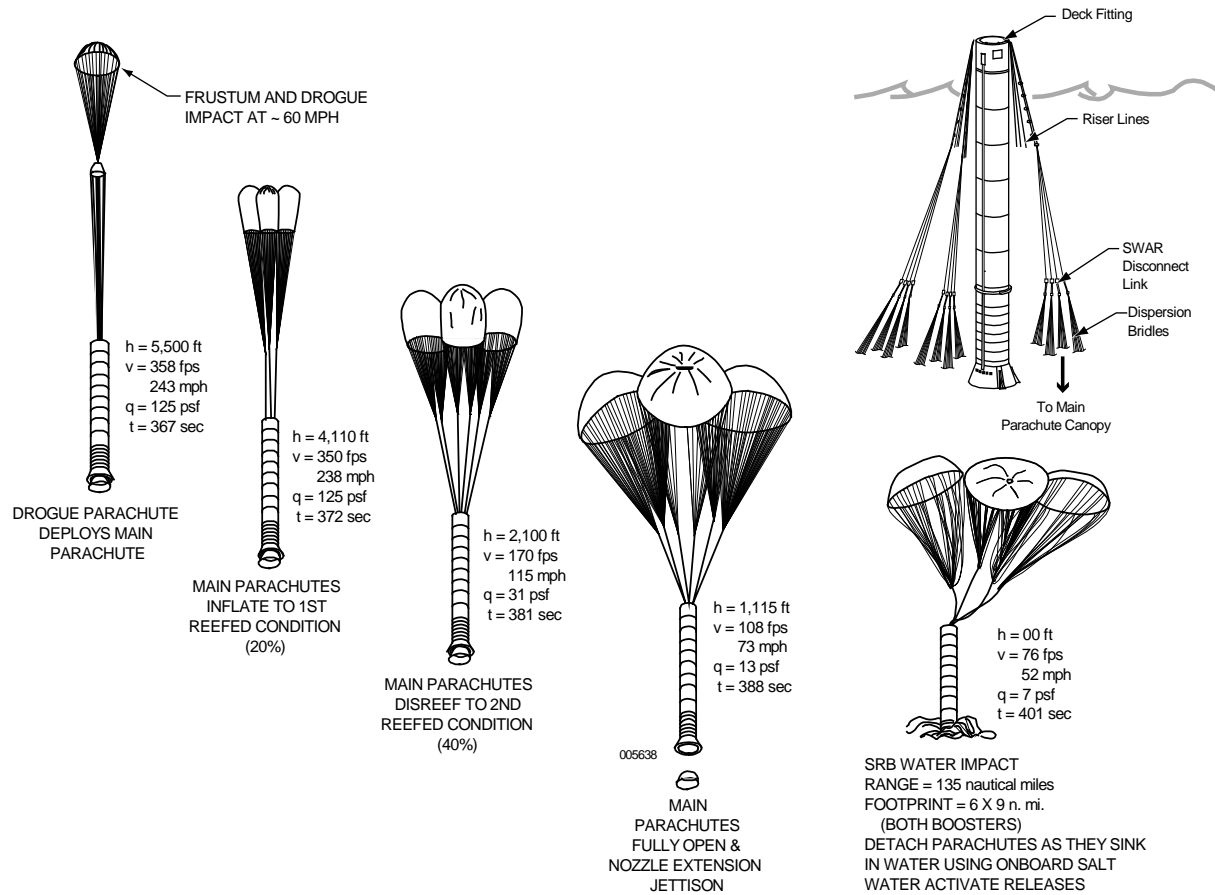


Figure 11. SRB Recovery Sequence Part 2: Main Parachute Deployment through Water Impact

The initial SRB main parachutes were called “Small Main Parachutes” (SMP). The SMP had a canopy diameter of 115 feet, and resulted in water impact velocities of approximately 90 feet per second. Starting with STS-41D (August 1984), larger parachutes, called the “Large Main Parachutes” (LMP), with a diameter of 136 feet and resultant water impact velocities of approximately 76 feet per second, were flown, and fully incorporated starting STS-51D (April 1985). The larger canopy parachutes provided a twofold benefit. First, they reduced the water impact velocity and consequently the impact loads and potential for structural damage. Second, they increased the SRB survivability from a single parachute failure, where the water impact velocity under two LMP would be comparable to that of three SMP, thus reducing the possibility of structural damage from a hard water impact.

The first failure of the recovery system occurred on STS-3, where a main parachute failed due to entanglement with floats installed for assisting in retrieval of the parachutes. Next, on STS-4 (June 1982), the floats were removed. However, an unrelated failure occurred where the parachute lines released from the deck fittings prior to deployment. The parachute lines utilized g-load activated release mechanisms to sever the lines upon water impact, minimizing the possibility of underwater diver entanglement in the vicinity of the SRB during recovery. The root cause was deemed that during frustum separation (when the drogue parachute was released), the g-load switch initiated the deck fitting pyrotechnics; thus pre-maturely releasing one of the two deck fittings on each main parachute. In such a configuration, the parachutes provided no drag during the remaining SRB descent resulting in an SRB water impact velocity of six times the predicted value, and the SRBs sank into the ocean. As a result of this failure, the switch was deactivated (from STS-5, November 1982, to STS-61C, January 1986), until a timer mechanism was incorporated that released the deck fittings about the time of water impact. During this time period, the retrieval divers manually cut the lines. After the timers were implemented to release the deck fittings, the SRBs started exhibiting structural damage that was associated with the slap-down of the SRB into the ocean (the SRBs

impact the water vertically, but then fall over and “slap” the surface horizontally before settling back to a bobbing spar/buoy position). Consequently, on STS-86 (September 1997), sea-water activated switches were incorporated to release the lines once the SRB settled more gently into the water as the parachutes settled into the ocean, and reduced the chance for structural damage.

Another parachute system improvement first flown on STS-33R (November 1989) was the incorporation of ripstops within the canopy (Figure 12). These consisted of six horizontal bands of high-strength nylon added to the LMP to mitigate a tear from propagating completely through the parachute canopy, thereby allowing the parachute to remain inflated during descent. The spacing of the ripstops was defined by analytical models of the canopy loading. Since incorporation, ripstops have been determined to have prevented total failure of a parachute on seven occasions.

A third (iterative) improvement to the SRB parachutes occurred in the main parachute vent, which is the top of the canopy. Starting on STS-51F (July 1985), a vent cap (i.e. additional horizontal canopy members) was added, decreasing the vent diameter from 11.6 to 5.6 feet. This design modification allowed the canopy to inflate more reliably to the first reefed condition. However, there were intermittent cases of major damage that was eventually attributed to the lagging inflation of the parachute that led to vent line entanglement. The vent cap consisted of 80 vent lines stacked in a constant clockwise sequence that created large openings and a large mass at the center. The openings allowed air to escape, slowing inflation, and the large mass of lines to tangle, causing parachute damage. The next improvement of the LMP vent occurred on STS-95 (October 1998), where the vent lines were woven together in an alternating stacking method called the Hengel Weave (Figure 13), which organized (eight groups of ten vent lines) and constrained the vent lines. This eliminated two large slots in the vent and prevented the concentration of a vent line mass, further helping the parachute inflate more reliably to its first reefed condition.

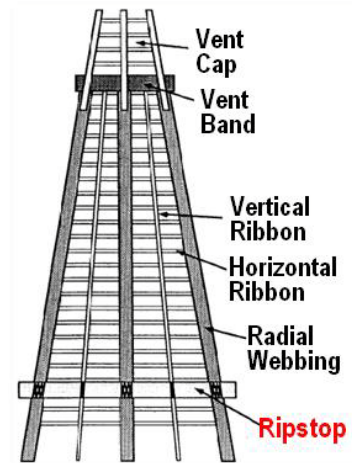


Figure 12. Rip Stop.

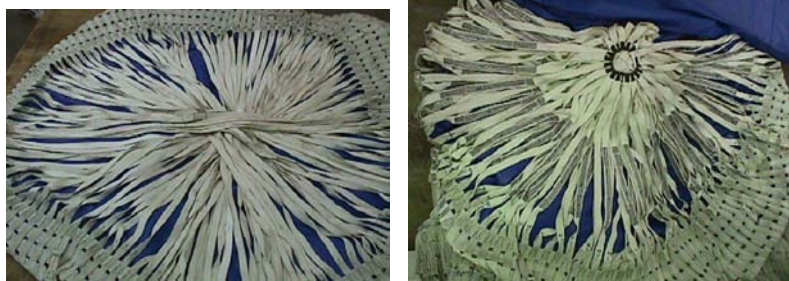


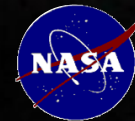
Figure 13. Sequential Stacking Design vs. Hengel Weave.

Once again, the usage of in-flight imagery had proven invaluable in the assessment of the various parachute system failures during the life of the program, helping to improve the understanding of parachute dynamics, their failure mechanisms and the implementation of design improvements.

VIII. Conclusion

Through the 30 years of flight and 135 shuttle missions, 270 SRBs have seen flight. Each flight, using data systems from air, sea, ground and flight hardware, the acquisition of flight environments, hardware performance and flight imagery data has proven to be invaluable to assessing and improving the hardware. The proper use of design safety factors ensures hardware will perform as expected even when the environments or source materials are outside the experience base.

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. It should be noted that the information gleaned from the postflight inspection/tests resulted in the development of the reuse standard, referred to as the SRB Refurbishment Specification (10SPC-0131). This detailed document specified the allowable defect criteria for each reusable part as well as levying the inspection and test criteria required to place that part back into serviceable stock.



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Presenter:
David Wood

September 26-29, 2011

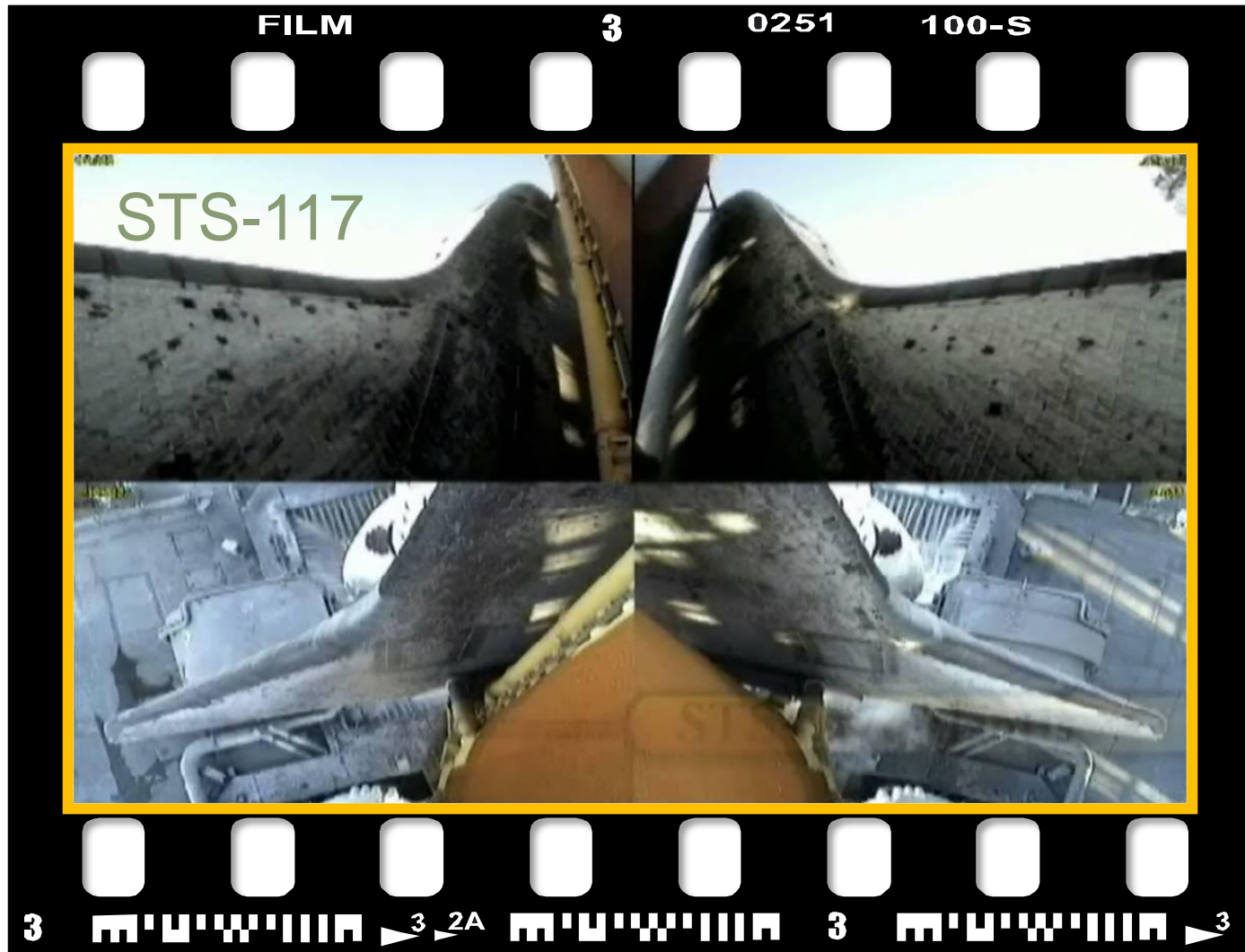


A dramatic photograph of a Space Shuttle launching from the launch pad. The shuttle is ascending vertically, leaving a massive, bright plume of fire and white smoke behind it. The launch pad structure is visible on the left side of the frame. The background is a dark, cloudy sky.

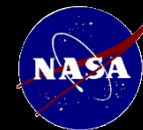
AGENDA

- ◆ **SRB Full Flight Video**
- ◆ **Overview of Booster Evolution**
- ◆ **Detailed Discussion on Lessons Learned**
 - Evolution of Sprayable Acreage TPS
 - SRB Camera and Data Acquisition Systems
 - Implementation of Command Receiver Decoder
 - External Tank Attach Ring Material Issue
 - Parachutes and Recovery Systems

SRB Full Flight Video



Reusable Solid Rocket Boosters



◆ Largest solid propellant rocket motors ever flown

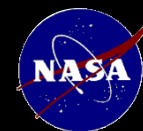
- First designed for reuse
 - Height = 149.2 ft; Diameter = 12.2 ft in
 - Launch Weight = ~1.3 million lbs

◆ Main thrust to lift Space Shuttle off launch pad and to altitude of 150,000 ft (28 miles)

- Sea level lift-off thrust ~2,800,000 lbs per SRB
 - Peaking to 3,300,000 lbs
 - ~83% of lift-off thrust
- SRBs attached to ET at SRBs aft frame by struts
- Forward end attached to ET on ball fitting
- On launch pad, SRBs secured to MLP by 8 bolts and frangible nuts
- Severed by explosives at lift-off
- SRBs carry entire weight of ET and Orbiter
 - 4,500,000 lbs



Reusable Solid Rocket Boosters

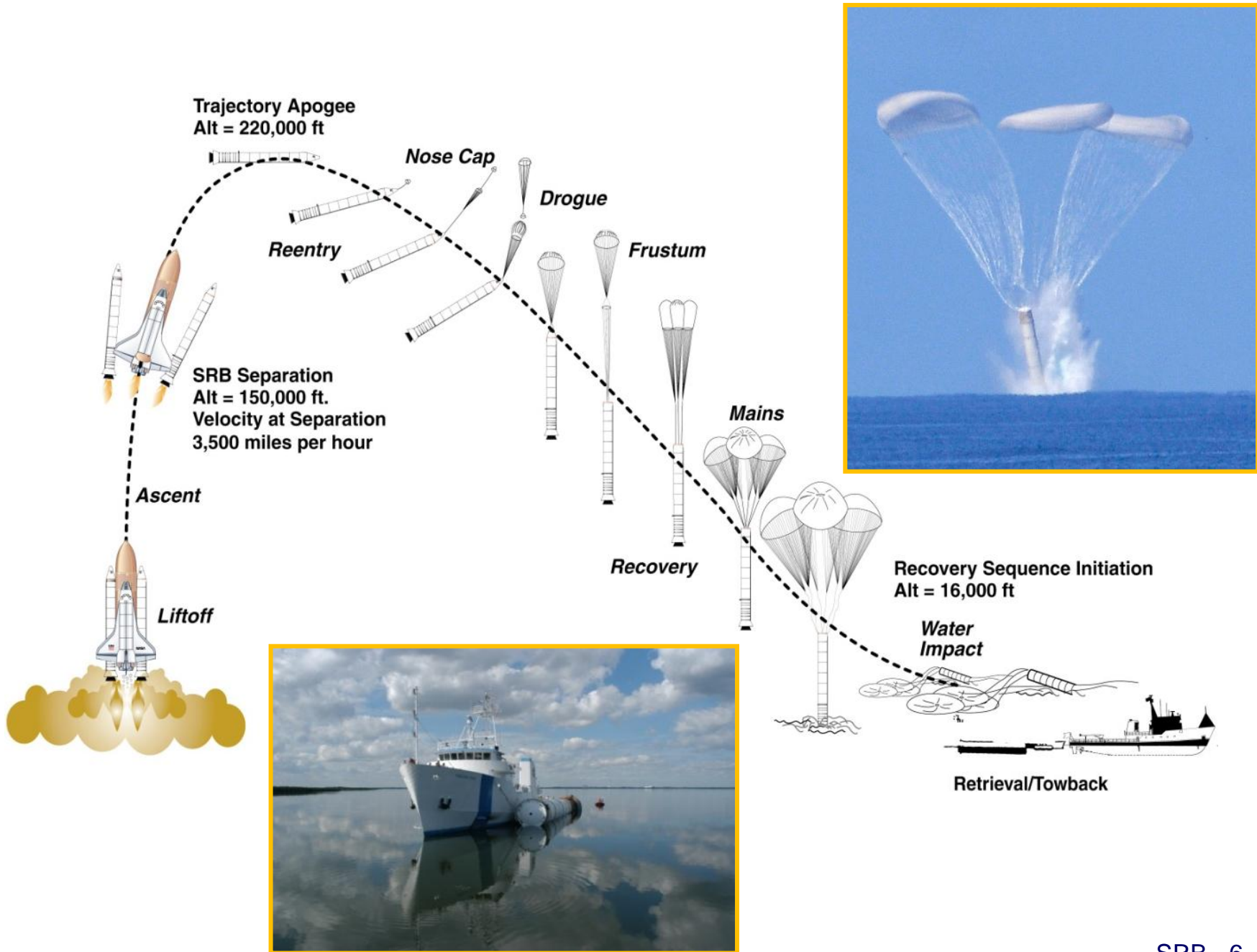


◆ SRBs burn for 123 seconds during ascent

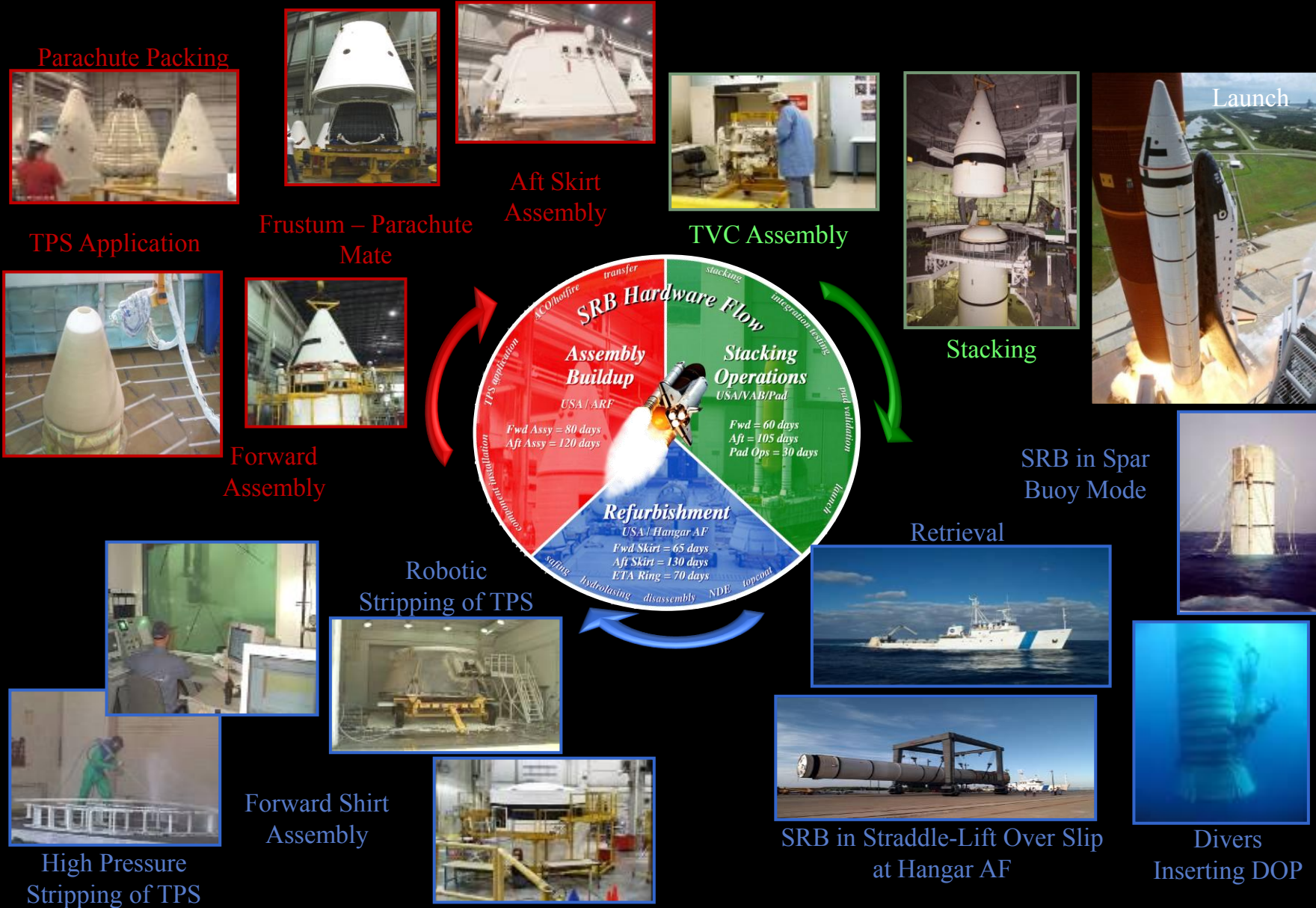
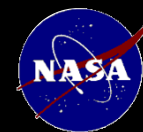
- ~1,100,000 lbs propellant per SRB consumed
 - Final SRB weight = ~192,000 lbs
- At 123 seconds/150,000 ft
 - pyrotechnic events disconnect SRBs from ET,
 - BSM ignition push safely away from ET/Orbiter
- 75 seconds after SRB sep, SRBs reach apogee
 - Altitude ~220,000 feet (41 miles)
 - Deceleration sequence initiation provides attitude and terminal velocity control for water impact
- SRBs & parachutes retrieved ~140 miles downrange from KSC
 - Towed back to KSC for reuse via recovery ships
 - SRBs inspected, disassembled, refurbished, re-assembled, stacked and integrated with ET and Orbiter
- Process begins anew



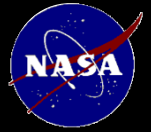
Reusable Solid Rocket Boosters



Reusable Solid Rocket Boosters



Overview Of Booster Evolution



Evolution of Acreage Sprayable Thermal Protection System



- ◆ **Utilized MSA-1 on frustum and forward skirts beginning STS-1**
 - Incorporated on nose cap STS-4

MSA-1 Summary	Benefit	<ul style="list-style-type: none"> • Spray application • Eliminated labor intensive cork bonding
	Limitation	<ul style="list-style-type: none"> • Maximum thickness of 0.25 in • Subjected to stress cracking during cure
	Comment	<ul style="list-style-type: none"> • Nose cap MSA-1 associated with Orbiter tile damage (STS-27)

- ◆ **MSA-2 developed for aft skirt application and to replace MSA-1**
 - STS-29 first flight on forward assembly and STS-28 for aft skirt

MSA-2 Summary	Benefit	<ul style="list-style-type: none"> • Increased strength and flexibility • Supports coating thickness up to 0.5 in <ul style="list-style-type: none"> • Incorporated ground cork and new epoxy resin system • Eliminated suspect carcinogens (catalyst curing agent)
	Limitation	<ul style="list-style-type: none"> • Formulated in solvent carrier to facilitate spraying • Hazardous waste (same as MSA-1)



Evolution of Acreage Sprayable Thermal Protection System



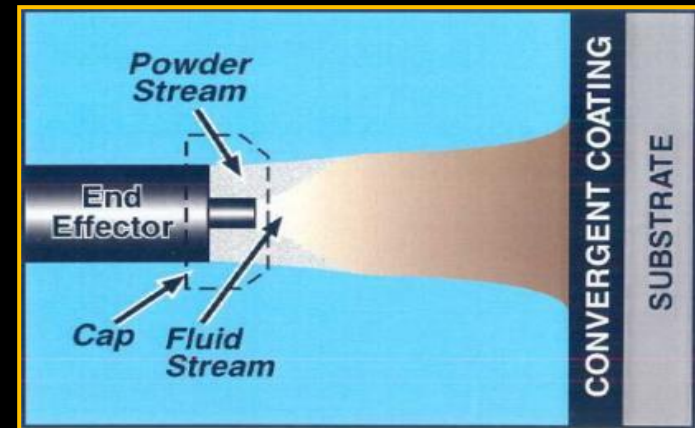
◆ MCC-1 developed and qualified between 1992 and 1995

- Address EPA mandate to severely limit hazard pollutant emissions
- Utilized Convergent Spray Technology™ developed by USBI

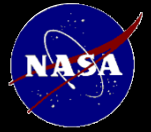
MCC-1 Summary	Benefit	<ul style="list-style-type: none"> • Not Hazardous - CST™ eliminated need for solvents • Significant process improvement <ul style="list-style-type: none"> • Reduce setup time, mix on demand, consistent surface finish • Superior strength capability <ul style="list-style-type: none"> • Strength 4x and 3x greater than MSA-1 and MSA-2, respectively
	Limitation	<ul style="list-style-type: none"> • None

◆ Convergent Spray Technology™

- Apply coatings by converging multiple streams of different materials
- Deliver dry filler materials and fluid binder materials separately to spray gun
- Proprietary nozzle convergently mixes constituents external to gun tip as sprayed



Evolution of Acreage Sprayable Thermal Protection System



- ◆ **MCC-1 first flown on STS-79 LH aft skirt**
 - Fully implemented as MSA-2 replacement on STS-80 (1996)
 - Experienced extremely successful flight history since

Lessons Learned

Trade-off between being environmentally friendly and performance not always required



SRB Imagery and Data Acquisition



- ◆ **Photographic coverage of SRB descent and parachute deployment important at beginning of Shuttle Program**
 - Provided by ship and aircraft
 - Redstone/Vandenberg ships and Starcast/Castglance aircraft
 - Discontinued after STS-35 (12-2-90)
- ◆ **STS-51A (11-8-84) first installed 16 mm camera into forward skirt dome to capture parachute deployment**
 - Implemented permanently STS-36 (2-28-90)
 - Upgraded to Data Acquisition System (DAS) with video camera STS-72 (1-11-96)
 - Included recording accelerometers data



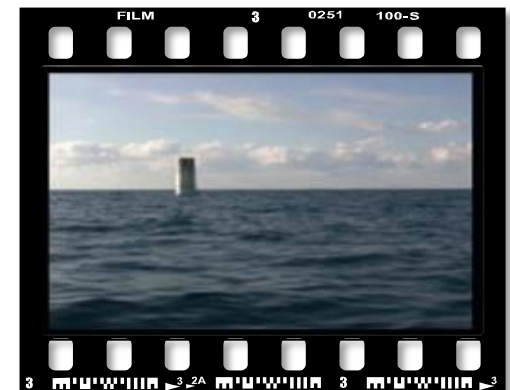
SRB Imagery and Data Acquisition



- ◆ **Postflight photographs of off-nominal items taken since STS-26 (9-29-88)**
 - Used for comparisons to build-up and previous missions photographs
 - Minimal photographic requirements established and controlled by engineering (10REQ-0033)
- ◆ **Additional photography during recovery from on-board observer initiated after STS-26 (9-29-88)**
 - Enhancements throughout follow-on missions including
 - Both stills and video and improved equipment
 - Detailed guidelines and recommendations
 - Underwater observations during dives



Aft Skirt Bluing
12-85-01



Recovery



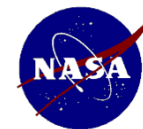
SRB Imagery and Data Acquisition



- ◆ **Second camera installed in forward skirt on STS-95 (10-29-98) to observe ET foam popcorning from intertank**
 - Utilized for five flights
 - Permanently implemented on STS-114 (7-26-05)
- ◆ **STS-121 implemented two additional standard SRB cameras to evaluate ascent debris conditions**
 - Forward skirt aft looking and ETA ring forward looking cameras
 - Refinements incorporated to improve camera settings and modify field of view



SRB Imagery and Data Acquisition



- ◆ Learned capability of hardware
- ◆ Expanded understanding of environments and associated variability from flight to flight
- ◆ Allows flight specific evaluations to assess time of occurrence and debris hazards
- ◆ Ultimately supports taking advantage of fact SRB recovered to improve designs and processing

Lessons Learned

- Picture = thousand words
- Some Criticality 3 systems are really important



Parachute Failure



Hypalon Off Gassing



Hardwater impact



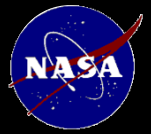
BTA from Aft BSM
Hits Orbiter



Riser Line Cut



Command Receiver/Decoder (CRD) Implementation



- ◆ CRD initially developed for ET Range Safety System (RSS)
- ◆ ET subsequently eliminated RSS
- ◆ CRD design evaluated and implemented in SRB due to Integrated Receiver/Decoder (IRD) and Range Safety Distributor (RSD) supportability/obsolescence concerns
- ◆ CRD combined IRD/RSD functions into single design



Previous IRD/RSD Configuration

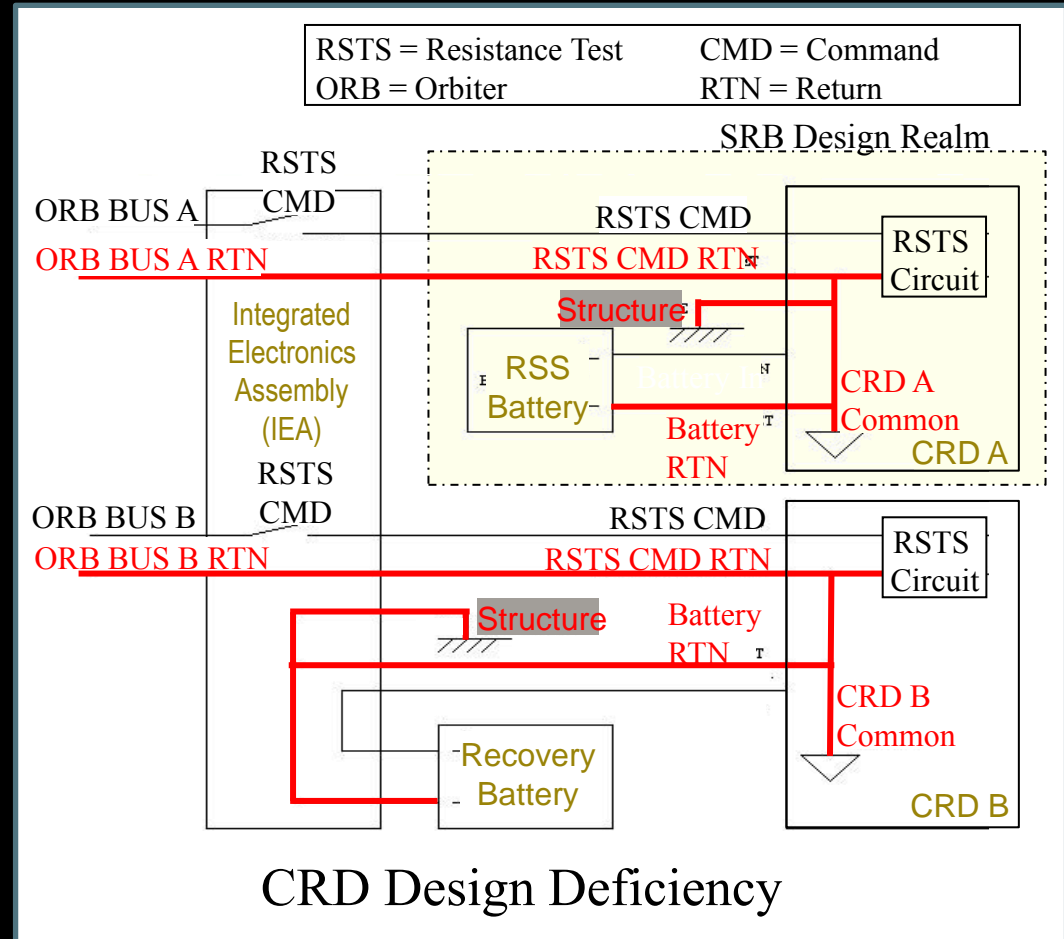


New CRD Configuration

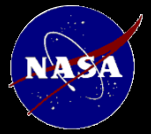
Command Receiver/Decoder (CRD) Implementation



- ◆ **CRD integrated system testing discovered design deficiency**
 - Orbiter A and B bus returns not isolated from each other or SRB structure
- ◆ **Root cause identified**
 - Orbiter power treated as command signal during requirements development and design
 - Likely discovered earlier if source (power) considered rather than function (RSTS CMD)



Command Receiver/Decoder (CRD) Implementation



Outcome

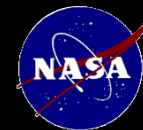
- ◆ **Modified circuit to separate RSTS command return from CRD common return and SRB structure**
- ◆ **Subsequently passed all qualification testing and successfully flown CRD design since STS-118/BI130 (14 total flights)**

Lessons Learned

- Maintain consistent signal terminology from system to component
- Perform system level testing early in development process
- Include systems engineering in all development phases



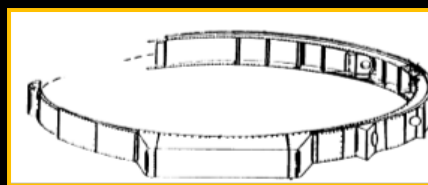
External Tank Attach Ring Evolution



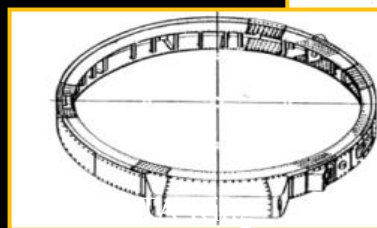
- ◆ Initial 4130 steel ETA ring spanned 270°
- ◆ Redesigned ETA ring to 360° for STS-26
 - Modified existing hardware
 - Eliminated negative margins of safety during thrust build-up



ETA Ring Location



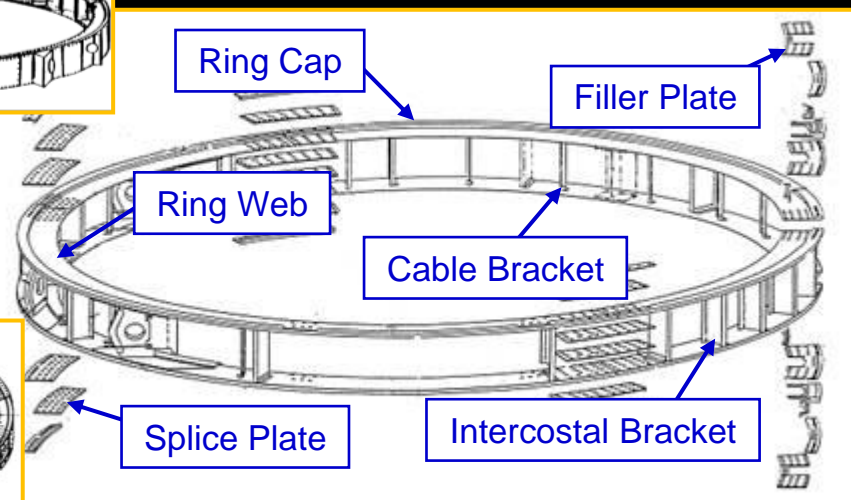
STA. 1511.0



270 ETA Ring

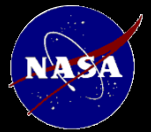


ETA Ring Buildup



360 ETA Ring Components

External Tank Attach Ring Evolution



- ◆ **MSFC found suspect strength properties during early 2003 testing for ETA ring fracture properties**

- Historically used generic properties for all alloy steels

ETA Ring Tensile Strength (ksi)		
	Yield	Ultimate
Test *	130-189	152-202
Requirement	163	180
* Performed on ETA Ring S/N 13		

- ◆ **Design load case analysis using worst case material properties resulted in minimum Factor Of Safety (FOS) of 1.25**

- Violated FOS requirement of 1.4
- Analysis completed day before STS-107 launch
- STS-107 flight specific loads analysis supported FOS of 1.3

- ◆ **SRB presented issue and waiver rationale at STS-107 ET Tanking Meeting 1-16-03**

- Tanking meeting not Mission Management Team (MMT) meeting
- Waiver CR S091496 approved
- STS-107 ETA rings performed successfully as expected



External Tank Attach Ring Evolution



Outcome

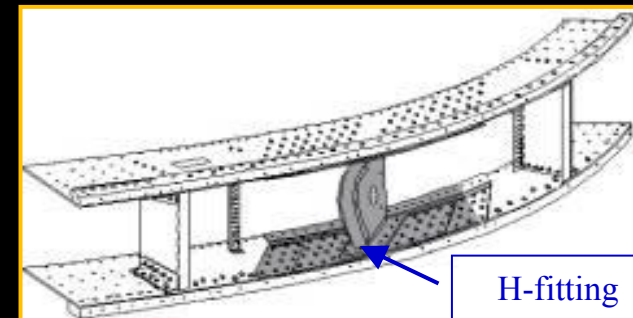
- ◆ Extensive testing and evaluation performed to certify 1.4 FOS requirement for STS-114 and STS-126
- ◆ Procured 4340 steel ETA rings for STS-115
 - New components manufactured under fracture critical and critical process control requirements
 - Web plates, splice plates, filler plates, ring caps, intercostal brackets, and cable brackets
 - Only Inconel 718 H-fittings common



ETA Ring
Hardness Testing

Lessons Learned

- Significant safety concerns require discussion at appropriate level to ensure full awareness of associated risks
- Reason for safety margins



Ring Segment

Parachutes and Recovery Systems



- ◆ **First 13 flights used Small Main Parachutes (SMP) – 115 ft diameter**
 - Observed damage during deployment due to reentry and parachute dynamics
 - Sometimes led to parachute failures
 - Resulted in significant splashdown damage and threatened booster retrieval
- ◆ **Large Main Parachutes (LMP) flew on STS-14RH – 136 ft diameter**
 - Sized for impact velocity of 2 LMP to be same as 3 SMP (~90 ft/sec)
 - Greatly decreased post flight damage on booster
 - Improved hardware survivability with one parachute failure

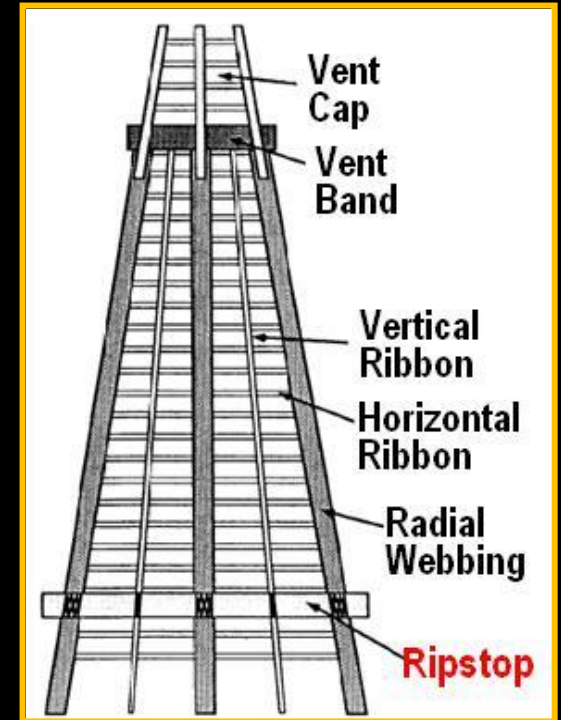


Parachutes and Recovery Systems



Story (cont.)

- ◆ **Implementation of Rip-stops began 17 flights after LMP**
 - Reinforced parachute in strategic locations
 - Reduced tear propagation and prevented total Gore failure
- ◆ **Incorporated Hengel Weave STS-95 at vent cap**
 - Design changed to organize and constrain vent lines
 - Reduced entanglement during deployment that led to parachute failure

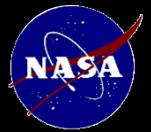


Stack Design



Hengel Weave

Parachutes and Recovery Systems



Lessons Learned

- Picture = thousand words
- Some Criticality 3 systems are really important

Parachute evolution focused on retrieving hardware and improving condition for reuse

