

SHUTTLE PROPULSION OVERVIEW – THE DESIGN CHALLENGES

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ABSTRACT

The major elements of the Space Shuttle Main Propulsion System include two reusable solid rocket motors integrated into recoverable solid rocket boosters, an expendable external fuel and oxidizer tank, and three reusable Space Shuttle Main Engines. Both the solid rocket motors and space shuttle main engines ignite prior to liftoff, with the solid rocket boosters separating about two minutes into flight. The external tank separates, about eight and a half minutes into the flight, after main engine shutdown and is safely expended in the ocean. The SSME's, integrated into the Space Shuttle Orbiter aft structure, are reused after post landing inspections. The configuration is called a "stage and a half" as all the propulsion elements are active during the boost phase, with only the SSME's continuing operation to achieve orbital velocity. Design and performance challenges were numerous, beginning with development work in the 1970's. The solid rocket motors were large, and this technology had never been used for human space flight. The SSME's were both reusable and very high performance staged combustion cycle engines, also unique to the Space Shuttle. The multi body "side mount" configuration was unique and posed numerous integration and interface challenges across the elements. Operation of the system was complex and time consuming. This paper describes the design challenges and key areas where the design evolved during the program.

INTRODUCTION – A BUDGET CONSTRAINED ARCHITECTURE SELECTION

The post Apollo NASA had grand plans including Shuttle for earth to orbit space transportation, Space Station for low earth orbit research and staging for missions beyond low earth orbit, Mars human exploration, and Nuclear Engine for Rocket Vehicle Application (NERVA) to enable in space transportation beyond our planet. The political environment during the very early 1970's was, however, not conducive to such a grand plan for exploration. The Nixon administration, while supportive of continued human space flight, desired a sustainable fiscal outlay very much less than that which had been required for the Apollo Program. With that fiscal guidance the task was to define a post Apollo NASA human space flight mission, and to address a severe Aerospace recession within the country. The reduced budgetary outlook resulted in delaying development of Space Station, foregoing Mars and NERVA, and a Shuttle development constrained by development costs.

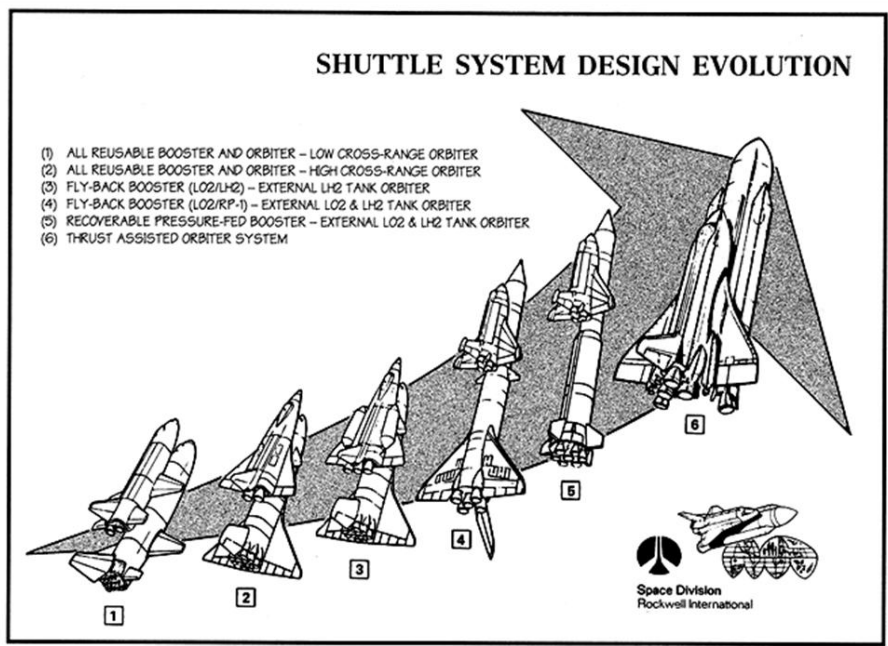
Justification for initiating development of the Space Shuttle revolved around economics. The Shuttle was to provide routine, reliable access to low earth orbit. Following the Apollo Program, NASA was seeking an initiative to dramatically reduce the cost of space flight. Below are excerpts from George Mueller's remarks October 1969 at a Space Shuttle symposium.

"The goal we have set for ourselves is the reduction of the present costs of operating in space from the current figure of \$1,000 a pound for a payload delivered in orbit by the Saturn V, down to a level of somewhere between \$20 and \$50 a pound..... Let me outline three areas which, in my view, are critical to the achievement of these objectives. One is the development of an engine that will provide sufficient specific impulse, with adequate margin to propel its own weight and the desired payload. A second technical problem is the development of the reentry heat shield, so that we can reuse that heat shield time after time with minimal refurbishment and testing. The third general critical development area is a checkout and control system which provides autonomous operation by the crew without major support from the ground and which will allow low cost of maintenance and repair."

Along with development of the Shuttle, an Orbit Transfer Vehicle (OTV) was planned to be developed to enable satellite servicing and adding to the economic benefits of the space transportation system. Even so, the cost analysis of the day projected that relatively high flight rates (~55 flights per year) would be required of the Shuttle system, to reap the economic benefits of reusable space transportation. Regardless, a consensus was reached within the administration that such a space

transportation system could be developed at a reasonable and sustainable yearly budget outlay for NASA.

Still budget projections were a problem as NASA's system of choice was development of a fully reusable 2 stage vehicle, each propelled by liquid rocket engines. This system would require significant budget in the early years of development, and reduced budgetary requirements during operation. As the concept matured, projected development cost, and the desire to reduce those projections shaped the final configuration. Shown in Figure 1 is a pictorial representation of the evolution of the system configuration. A significant development cost reduction was achieved by the use of an external, expendable propellant tank, the element known today as the External Tank. And the final configuration included solid propellant boosters (the element now known as the Solid Rocket Boosters), again projected to reduce development costs. The booster options had evolved from a fully reusable fly back system, to a pressure fed recoverable system, to a recoverable solid rocket motor. The use of solid rocket motors was new to NASA, as these systems had been developed predominately by the Air Force for the intercontinental ballistic missile program. The Orbiter configuration was also influenced by the Department of Defense (DoD) whose advocacy was sought by NASA for the Shuttle development program. The Air Force desired a high cross range capability to accomplish polar orbital missions with a rapid return to a landing site, which resulted in adoption of a delta wing Orbiter configuration. Also, the DoD desired a heavier and larger payload capability, for their unique mission requirements, which affected the Orbiter configuration and the propulsion system performance requirements.



At the end of the Phase B Extension, North American included this chart in their final report showing the conceptual evolution of the space shuttle from Phase A through Phase C. (North American Rockwell)

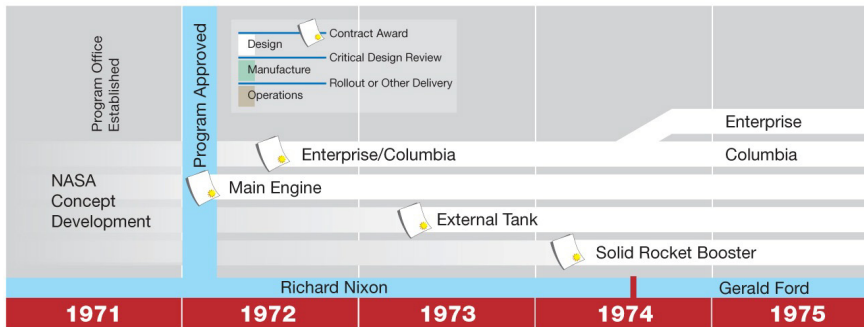
Figure 1. Evolution of the Space Shuttle configuration

Hence, an interim configuration solution was the chosen, called Thrust Assisted Orbiter Shuttle (TAOS), with a phased development approach which included an external fuel tank, parallel burn of the booster and core stage propellant systems (called a "stage and a half" configuration), and an Orbiter constructed from aluminum with a ceramic tile heat shield. External influences had modified the

configuration including a cross range requirement, the lift capability and size of the payload bay, and development cost caps imposed by the budget office. The propulsion performance and weight constraints had been amplified by the choice of system configuration, but the magnitude of the challenge would not be understood until the development and flight program began to mature. Any evolution of the booster system to the fully reusable fly back system, if feasible, would have to wait until the interim system was developed and operating. The Orbit Transfer Vehicle was never developed.

PROGRAM AT A GLANCE – FOUR DECADES OF DEVELOPMENT AND OPERATION

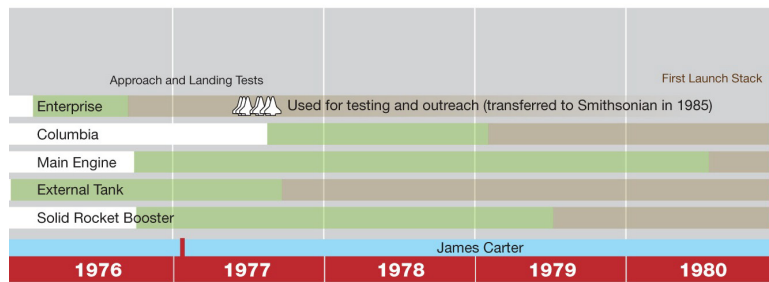
The 30 year flight program demonstrated reusability; accomplished deployment, servicing, retrieval, and repair of satellites, including the remarkable recovery of the Hubble Space Telescope mission; demonstrated improved extravehicular capabilities; significantly advanced robotics; and accomplished servicing and/or assembly of two space stations culminating with a the magnificent International Space Station. Research was accomplished in microgravity in the areas of materials science, biotechnology, and human physiology. Great observatories were launched to spectrally map the universe, and missions were launched to study planets and the sun. The Earth’s atmosphere was studied, the earth’s surface was mapped, and space environments were further defined. These missions of exploration and discovery have forever advanced human knowledge. The timeline below, from “Wings in Orbit” shows the evolution of the development and flight program.



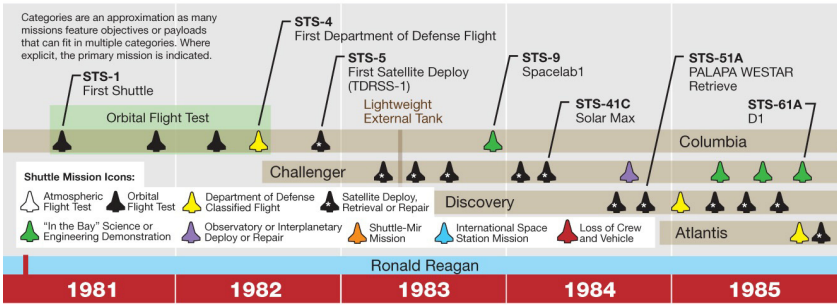
President Nixon & Dr. James Fletcher, NASA Administrator, discussing proposed Space Shuttle



Shuttle Orbiter Enterprise at the Dynamic Test Stand at MSFC



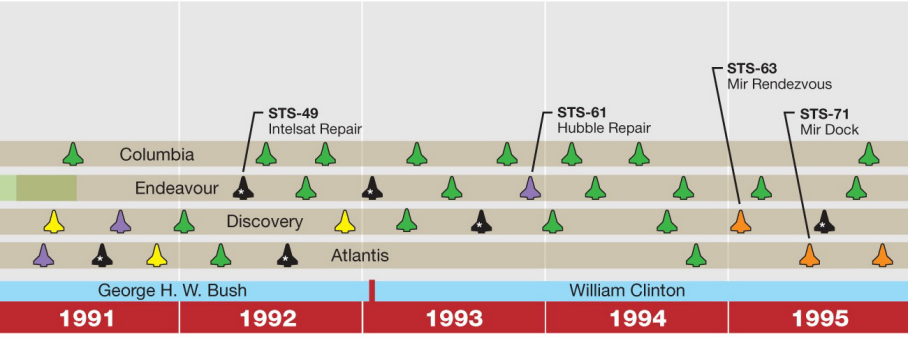
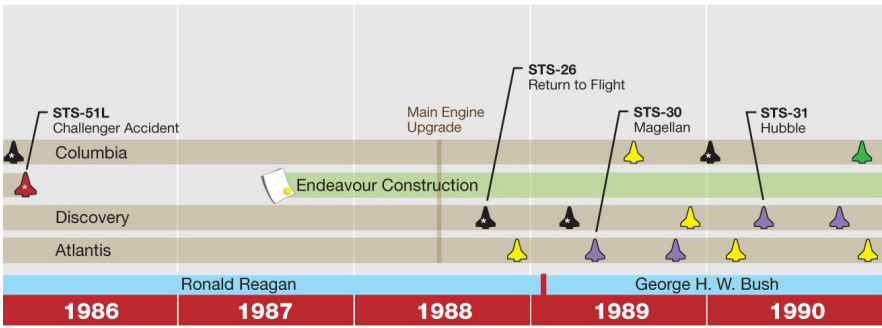
Main Propulsion Test Article



STS-1



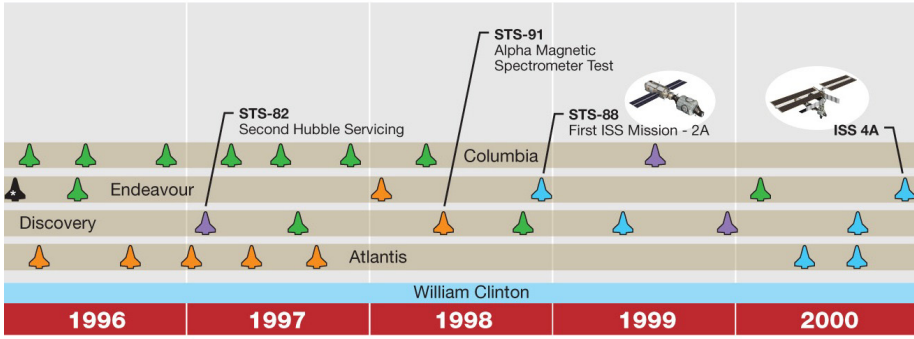
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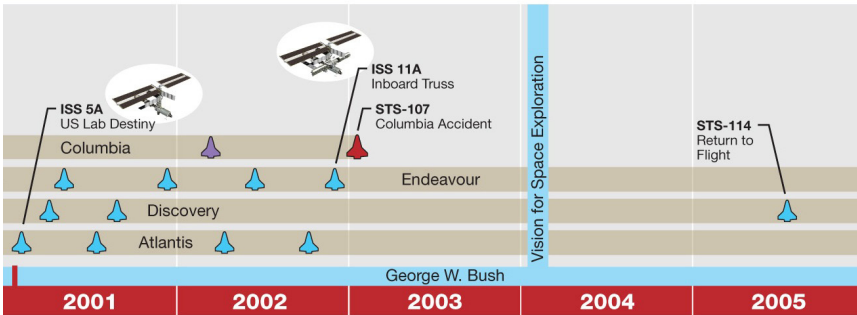


STS-61 Hubble Repair



ISS Mission 2A

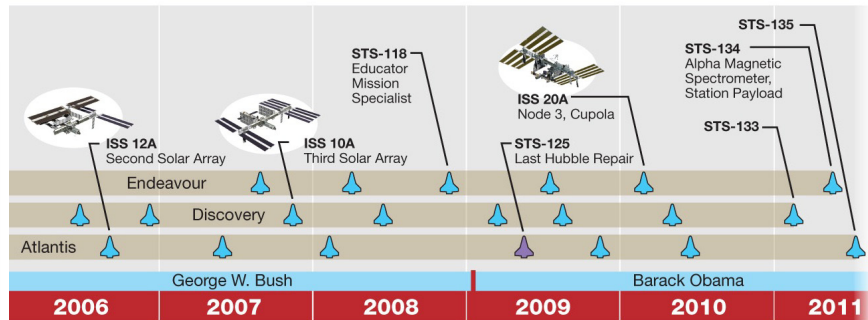




STS-107
Rick Husband, William McCool, Michael Anderson, Kalpana Chawla, David Brown, Laurel Clark, Iian Ramon



STS-135
Landing



Twenty-three missions were dedicated to satellite launch and deployment. Following STS-51L no more satellite deployment missions were planned, as space policy was modified (commercial satellites and science missions would be accomplished by expendable launch vehicles). Shuttle would be planned for missions requiring crew. Satellite repair included Intelsat, Solar-Max, and Hubble Space Telescope. Following the initial repair mission the Hubble was serviced an additional five times. Eleven missions were dedicated to Department of Defense objectives but no more were planned following STS-51L, and the Vandenberg launch site for access to polar orbit was also cancelled after STS-51L. The Shuttle demonstrated satellite retrieval including the Long Duration Exposure Facility (LDEF), PALAPA, and WESTAR bringing these back to earth, demonstrating a significant down mass capability. Thirty-five missions were dedicated to on-orbit science with crew operated experiments (including Spacelab missions). Interplanetary launch included Magellan, Ulysses, and Galileo spacecraft utilizing an Inertial Upper Stage. Ten missions were dedicated to the Shuttle MIR space station. And finally 37 missions were dedicated to International Space Station (ISS) assembly and servicing. Down mass, the ability of the Shuttle to bring large structures back to earth was an important feature for ISS hardware anomaly resolution, and repair. As a result of the STS-107 accident the program was slated to end after assembly complete of ISS. The 40 year program represents 80% of NASA's existence and the nation's human space flight program.

THE SPACE SHUTTLE PROPULSION ELEMENTS

The Propulsion elements consisted of the Space Shuttle Main Engine, the liquid oxygen/liquid hydrogen reusable rocket engine envisioned by Dr. Mueller in 1969, recoverable solid rocket boosters, and an expendable fuel tank. The propulsion elements are shown pictorially in Figure 2. The design of each element matured during the flight program.



Figure 2. The Space Shuttle Propulsion elements

The largest element of Space Shuttle is the External Tank (ET), which serves as the structural backbone of the vehicle during ascent and provides liquid propellants to the Orbiter's three Main Engines. The ET absorbs most of the seven million pounds of thrust exerted by the Solid Rocket Boosters and Main Engines. Structural efficiency and light weight were essential to increase payload mass to orbit. The design evolved through several block changes, reducing weight each time.

The Space Shuttle Main Engine is the only reusable rocket engine ever developed and is the highest performance earth to orbit engine system. A significant design challenge for the SSME was development of a dual pre-burner staged combustion engine, which represented an advance in technology. The efficiency (specific impulse) delivered by the staged combustion cycle, was substantially higher than previous rocket engines. The dual pre-burner configuration permits precise mixture ratio and thrust control while the fully redundant controller and avionics provide a very high degree of system reliability and health diagnosis. The main engine controller design was the first rocket engine to incorporate digital processing. The engine was required to operate at a high chamber pressure to minimize engine volume and weight. Power level throttling was required to minimize structural loads on the vehicle early in flight, and acceleration levels on the crew late in ascent flight. Over a million seconds of total hot fire time was accumulated during the 40 year program.

Each Reusable Solid Rocket Motor (RSRM) provides approximately 3 million pounds of thrust to lift the integrated Space Shuttle vehicle from the launch pad. The motors burn out approximately 2 minutes later, separate from the vehicle and are recovered and refurbished. The size of the motor and the need for high reliability were challenges. Development of a solid rocket motor of this size required

scaling from smaller scale systems, and addition of design margins to account for human rating. Thrust shaping, via shaping of the propellant grain, was needed to limit structural loads during ascent.

The Solid Rocket Booster element integrates all the subsystems needed for ascent flight, entry, and recovery of the combined Booster and Motor system. These include the thrust vector control, auxiliary power unit, avionics, pyrotechnic, range safety system, parachute system, thermal protection, forward and aft structures, and water recovery systems. This represents the only recoverable and refurbishable solid rocket ever developed and flown. Challenges included subsystem integration and severe loads, including water impact which sometimes resulted in hardware attrition. Extensive acceptance testing was done to assure hardware functionality at each level of stage integration. A benefit of recovering the booster was the ability to monitor the performance of all aspects of the system prior to subsequent flights.

EARLY PERFORMANCE CHALLENGES

The early development program, in particular the space shuttle main engine, was plagued by technical difficulties including high and low cycle fatigue issues and numerous tests to develop the engine start sequence. Significant failures occurred during development testing. Since the SSME was an advanced technology, understanding of environments, hardware response to environments, and understanding of the staged combustion cycle was developed via extensive ground testing, maturing during the late 1970's and early 1980's.

A major propulsion system test series, the main propulsion test article, was accomplished during the late 1970's and early 1980's. The Main Propulsion Test Article consisted of an orbiter aft fuselage and thrust structure, electrical system, main propulsion system plumbing, a flight like external tank, and three space shuttle main engines. The planned test program involved 12 hot firings, 1 propellant loading test, and 2 structural resonant survey tests. Numerous issues were worked during the test series, and it prepared the team for launch operations with development of operational procedures.

As the design and development program matured the Orbiter weight grew by approximately 27,000 pounds. Also, the initial design of the solid rocket motors included fixed nozzles, as vehicle steering was to be provided by maneuvering of the main engines. As the design matured it became apparent the vehicle would not be controllable by the main engines alone. Loads increased, including lift off loads, and redesigns such as addition of a gimbaled nozzle on the solid rocket motors (to provide adequate vehicle control) resulted in addition of another 7,200 pounds, an additional performance impact. When the flight program began, instrumented development flights uncovered missed aerodynamic predictions resulting in operational constraints which cost another 5,000 pounds of performance. And specific impulse of the main engines and solid rocket motors was slightly lower than early design estimates. The total impact on payload to orbit was a whopping 45,000 pound reduction in capability (from the initial 65,000 pound requirement). So at the beginning of the flight program, shown pictorially in figure 3, the Shuttle system had a technical performance deficit, its economic viability was yet to be proven, and a very high flight rate was desired. If management had used color graphics back then, they might have colored everything red. And the trade space was limited!



Figure 3. Notional program risks at the beginning of flight operations

The performance deficit was largely recovered during the life of the program, through a number of design changes, briefly outlined below (for the propulsion system elements). Maintenance improvements were also accomplished during the program. Recovery of the lost performance became essential when the international space station (ISS) program partnered with the Russian Space Agency during the early 1990's. This necessitated a high inclination orbit accessible to Russian launch systems, which resulted in additional performance requirements for Shuttle. The Shuttle propulsion system met requirements enabling successful completion of the ISS.

THE PROPULSION ELEMENTS EVOLVED VIA BLOCK UPGRADES

REUSABLE SOLID ROCKET MOTOR

The reusable solid rocket motor design matured during the 1970's and significant ground testing was accomplished to fulfill development and qualification objectives. In the early 1980's a performance enhancement was implemented called the "high performance motor" to regain roughly 3,000 pounds of payload performance. Following the Challenger accident, a significant redesign was implemented to assure all the joint sealing systems within the motor, which included a number of innovative design features. These will be discussed in more detail in following papers. During the program process control, a robust ground test program, and a rigorous post flight assessment process added to understanding of these solid rocket motors, and contributed to improved reliability. Along with a solid propulsion integrity program, many instrumented motors were evaluated at both full and sub scale, to understand fundamental physics of solid rocket motors. Analysis capabilities improved with advanced technology and multi-discipline capability. Understanding of internal environments and material response to induced environments matured. Truly the solid rocket motor industry and the reliability of solid rocket motor systems improved as a result of these efforts (when the tide comes in, all ships rise). The improved design proved to be very reliable and the flight program was concluded in 2011 with 220 successful motor flights of the redesigned motors. Depicted in Figure 4 is the evolution of the design through major block upgrades along with significant accomplishments. Some of the significant changes and milestones are described below.

- Following the Challenger (STS-51L) accident the motor case and nozzle joint sealing systems were redesigned, with the addition of numerous features to add sealing system redundancy and robustness, including improved case metal hardware with a capture feature and third o-ring. An innovative insulation feature called a "j-leg," which prevents gas intrusion within the joint, was added. Heaters were added to thermally condition sealing systems.
- Processing controls, subscale and full-scale ground-scale testing, and a thorough post-flight assessment process added to system safety.

- Keys to process control included chemical fingerprinting to assess the consistency of delivered materials required for manufacturing the motor, and implementation of process failure modes and effects analysis.
- A ground-testing program included small motor and full-scale motors to assess material and design changes and incorporate special instrumentation to characterize performance. By the end of the program, 52 full scale static motors had been tested.
- In 2003, a space shuttle solid rocket motor was tested and pushed beyond typical launch performance boundaries. The five-segment test motor test, which ran for 118 seconds and generated more than 3.6 million pounds of thrust, performed flawlessly.
- Post flight assessment provided a thorough evaluation of hardware condition, and the ability to identify any items of interest requiring corrective actions. This capability is unique among solid rocket motors, as the space shuttle solid rocket motors are recovered for reuse.
- Other innovative design improvements included use of a carbon fiber rope thermal barrier material in the nozzle joints implemented in 2008.
- An improved resiliency o-ring material was implemented in 2009.
- An innovative intelligent pressure transducer was flown to assess pressure oscillations for future motor designs.

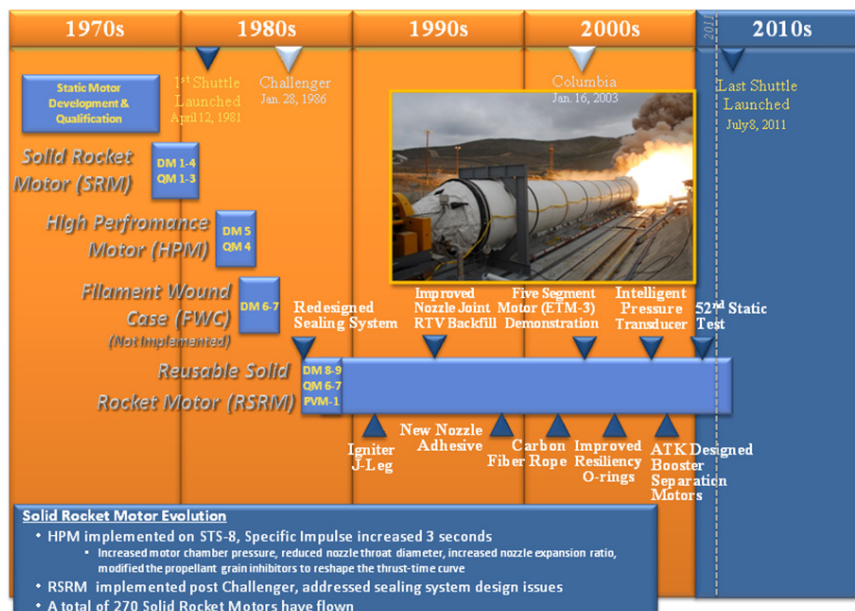


Figure 4. Evolution of the solid rocket motor

SOLID ROCKET BOOSTER

The solid rocket booster subsystems also matured via design evolution during the program. Functions included integration of all the subsystems needed for ascent flight, entry, and recovery of the combined Booster and Motor system. These subsystems included the thrust vector control, auxiliary power unit, avionics, pyrotechnic, range safety system, parachute system, thermal protection, forward and aft structures, and water recovery systems. The original integrator for the booster was the Marshall Space Flight Center, in a cost savings measure early in the program. As the system matured, a prime contractor was hired during the mid 1980's for booster integration. Eventually this responsibility transitioned to the Shuttle Processing and Operations contract, during the 1990's. This was of course the first recoverable booster system and a great deal of learning occurred during initial flight operations. Attrition of hardware from severe water impact loads sometimes occurred. The main parachutes were enlarged to slow water impact velocities. Also the thermal protection system material, applied to assure a hardware reuse capability, evolved through several design improvements to become a state of the art, environmentally friendly robust system. And the boosters, because of their recoverability, were ideal for

acquisition of flight data and imagery during the boost phase. This became vital during the final flights as the ascent debris environment was characterized utilizing imagery assets coupled with engineering analysis. A number of the significant changes in the booster subsystems are given below.

- The parachute system, essential for booster recovery, was redesigned with larger parachutes in 1983.
- The booster thermal protection system has evolved from a Marshall sprayable ablator initially used in 1982 to a Marshall convergent coating first used in 1996.
- The aft skirt structure was modified in 1998 to add a bracket to increase structural safety.
- The external tank attach ring was redesigned in 1988 from a 270-degree to a full 360-degree ring, and in 2006 the material was changed to improve structural margins.
- The solid rocket boosters provided stand-alone data acquisition systems beginning in 1996 to record flight accelerations and recovery loads.
- An enhanced data acquisition system to support the post-Columbia Return to Flight external tank modifications flew in 2005; these systems also were used in 2008 to acquire pressure oscillation and structural response data for use by future programs.
- Cameras were added in 1996 to observe parachute performance, and again in 2005 to observe ascent debris performance.
- Frangible nuts, used in the space shuttle pad hold-down and release system, were redesigned in 2008. They featured an innovative pyrotechnic design to ensure proper pyrotechnic timing during separation from the pad for lift off.
- Environmental compliance was implemented for coatings, thermal protection systems and for post-flight operations.
- Booster separation motors were redesigned and first flew in 2008. This was accompanied by conducting a substantial ground-test program to certify the new motors for flight.
- The thrust vector control system auxiliary power unit incorporated a fuel pump redesign in 2011.

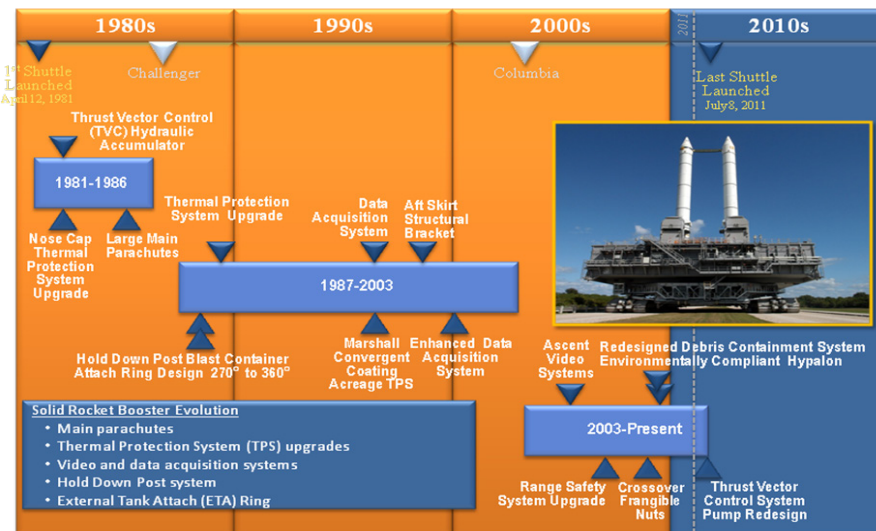


Figure 5. Evolution of the solid rocket booster subsystems

SPACE SHUTTLE MAIN ENGINE

The Space Shuttle Main Engine, the only reusable rocket engine ever developed, was very high performance, and evolved through a number of design upgrades. Testing during the 1970's led to the initial configuration, the first manned orbital flight configuration, available for the initial flights during the early 1980's. The complex staged combustion rocket engine proved to be quite sensitive to internal environments, and numerous tests were devoted to understanding the engine start sequence and determination of life limits. The design evolved through several block changes during the 30 year flight program. Significant improvement in reliability was achieved. The operation of the engine was increased to 104.5% of rated (initial) power level to increase ascent performance. A robust ground test program

was maintained until 2009, when the last SSME test stand was transferred to the Constellation Program for J2-X engine development. The final 21 months of flight operation was supported without a test stand, quite a testament to operability and reliability. The high pressure pumps and the advanced health management system were particularly innovative and represented substantial improvements in rocket engine capability. The block upgrades are depicted in Figure 6, and will be discussed further during this session. A number of the significant upgrades are described below.

- The space shuttle main engine transitioned from its first manned orbital flight configuration to a phase II configuration in 1983. The phase II engine logged 231 engine flights and included improvements to the controller to increase memory, main injector improvements, turbine blade improvements within the turbopumps and additional nozzle insulation.
- The engine transitioned to Block I configuration in 1995 with significant changes. The Block I featured a new high pressure liquid oxidizer turbopump developed using a casting process which eliminated all but six of the more than 300 welds from the previous turbopumps. It included a new two-duct powerhead that improved fluid flows within the engine to decrease pressures and loads. A new single-coil heat exchanger eliminated seven weld joints inside the engine to reduce wear, maintenance and post-flight inspections. New ball bearings made of silicon nitride (30 percent harder and 40 percent lighter than the old steel bearings) provided an ultra-light smooth finish to decrease operating friction. Improved hot gas sensors were also incorporated.
- A Block IIA configuration flew in 1998 with a large throat main combustion chamber, ceramic ball bearings in the low pressure oxidizer turbopump and improvements in the main injectors. The large throat combustion chamber reduced internal pressures in the space shuttle main engine, leading to reduced operating environments and improved component life.
- The Block II configuration added a new high-pressure fuel turbopump in 2001. The advanced turbopump featured precision castings to significantly reduce welds in the pump.
- The Advanced Health Management System, which flew the first time in 2006, interrogated the high-pressure turbomachinery during flight to detect precursors to a problem, and in the event of a problem, was capable of shutting an engine down prior to failure.
- Development and operational ground testing, conducted at Stennis Space Center in Bay St. Louis, Mississippi and Santa Susana Field Laboratory in California was a key element of achieving success. Marshall initiated a space shuttle main engine technology test bed program to test fire highly instrumented space shuttle main engine components in 1988.
- The space shuttle main engine reached a significant milestone in 2004 when it surpassed one-million seconds of successful test firings and launches. The space shuttle main engine compiled a remarkable record of demonstrated reliability and successful flight operations.

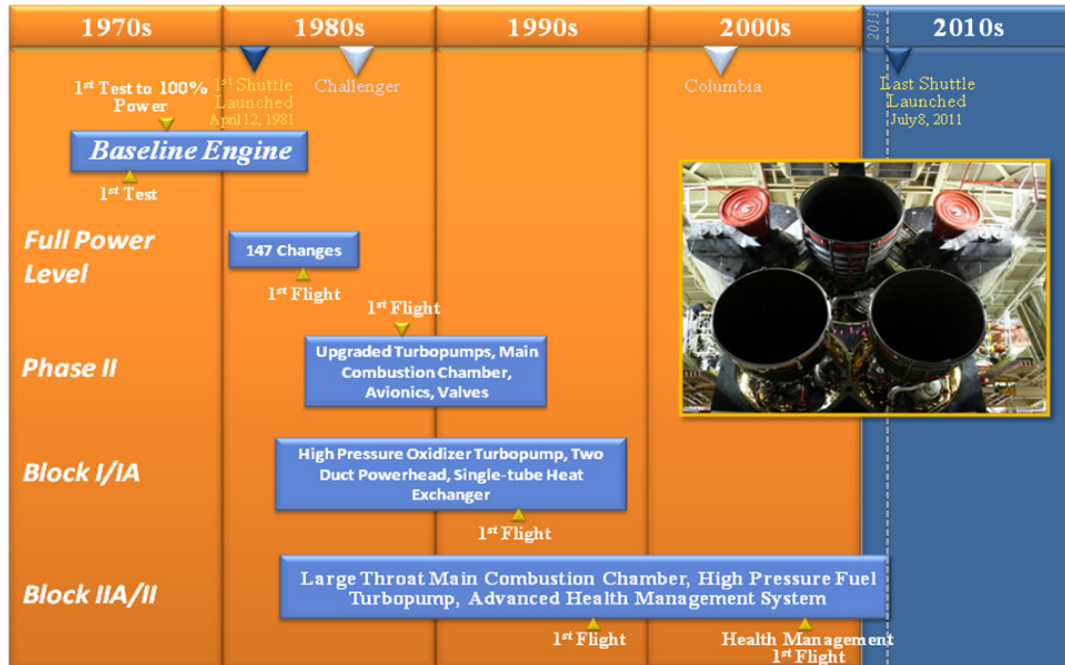


Figure 6. Evolution of the Space Shuttle Main Engine

EXTERNAL TANK

The largest element of Space Shuttle is the External Tank (ET), which serves as the structural backbone of the vehicle during ascent and provides liquid propellants to the Orbiter's three Main Engines. The ET absorbs most of the seven million pounds of thrust exerted by the Solid Rocket Boosters and Main Engines. The design evolved through several block changes, reducing weight each time. Much of the Shuttle payload capability was regained by structural weight reduction within the External tank. A number of innovative technologies were integrated into the design during the 30 year program including use of a lightweight aluminum lithium alloy, introduction of friction stir welding in the manufacturing process, and use of a composite nose cone. Following the Columbia accident, attention shifted to reduction of the ascent debris hazard. Processing improvements and an innovative post flight assessment process (for an expendable element) were very effective. The resulting debris performance resulted in greatly reduced damage to the Orbiter thermal protection system. Many of these improvements are discussed in a paper to follow during this session. Some of the significant milestones are delineated below.

- In the early 1980s, the External Tank Project office implemented a redesign called "light-weight tank," reducing the structural weight from 76,000 to 66,000 pounds – a significant accomplishment given that the tank flies to orbital velocity with the shuttle orbiter, and each pound saved results in an additional pound available for payloads. The first light-weight tank was launched in 1983.
- In the early 1990s, a composite nosecone, manufactured at the Marshall Center, was added to eliminate the need for thermal protection material, eliminating a possible debris source.
- During the mid-1990s, additional payload capability was required to meet International Space Station payload requirements. The External Tank Project again implemented a block redesign called "super light weight tank," which removed an additional 7,500 pounds of structural weight by using a light-weight aluminum lithium alloy. This significant accomplishment enabled partnership with the Russian Space Agency for assembly of the space station in a high-inclination orbit. The first flight of the super light-weight tank was in 1998.
- Following the Columbia accident in 2003, the External Tank Project implemented significant design and processing improvements to reduce the ascent debris risk. The bipod fitting that attaches the tank to the orbiter was redesigned, heaters were added at strategic locations to reduce ice formation and foam ramps were redesigned or removed. A camera was added to

provide video during ascent flight, enabling enhanced post flight assessment of ascent debris performance. These changes resulted in the risk due to ascent debris being reduced by more than a factor of 100, a remarkable achievement.

- Friction stir welding, a process that uses a rotating pin to soften, stir and forge a bond between two metal plates, was implemented in the external tank manufacturing process. Because the method does not melt the material as fusion-welding techniques do, the weld has excellent mechanical properties and exhibits very little shrinkage or distortions even in long welds. The first friction stir welded tank flew in 2009.
- In 2005, Hurricane Katrina devastated the Gulf Coast and significantly damaged NASA's Michoud Assembly Facility in Louisiana, where the tanks were manufactured. Recovery from this natural disaster was a significant achievement and production was resumed within a month. During the program, 139 tanks were manufactured for flight and testing, concluding with a remarkable record of continuous improvement.

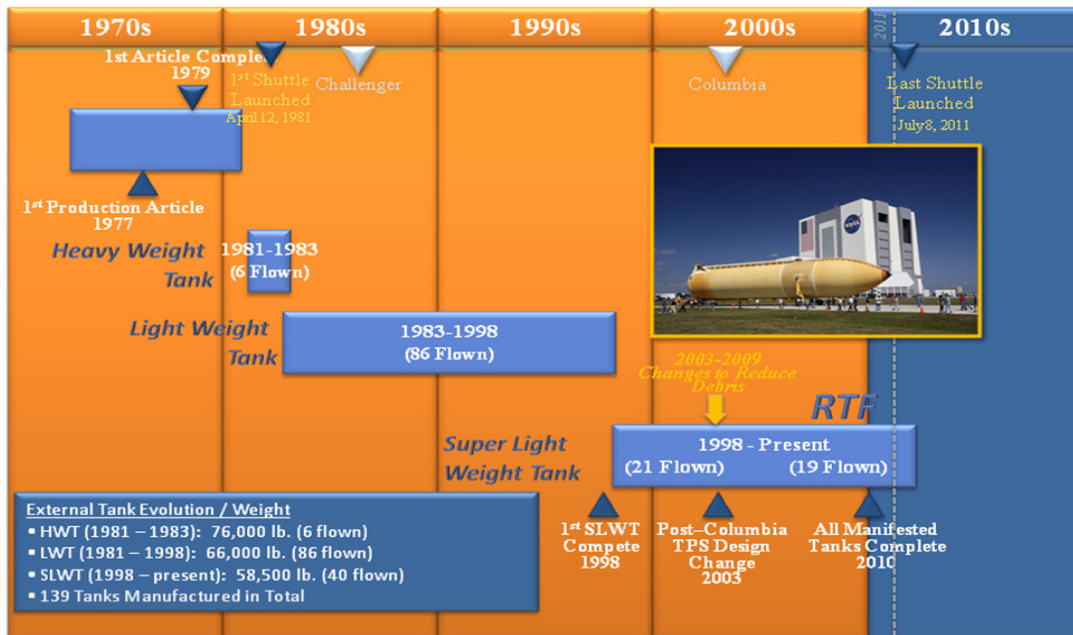


Figure 7. Evolution of the External Tank

SUMMARY – RELIABLE, HEAVY LIFT PROPULSION ELEMENTS

While the Shuttle system never achieved the economic goals envisioned in the 1970's, the propulsion elements evolved to become very well characterized and highly reliable, largely reusable systems applicable to future heavy lift launch vehicle concepts. The propulsion elements provided a remarkable, high performance, reusable rocket engine; evolved to provide highly reliable, large solid rocket motors; provided a fully integrated, recoverable and reusable booster system; and provided a structurally efficient propellant tank with truly significant debris risk reduction. The Shuttle propulsion system at the completion of mission was far from the one the program started with in 1981; the propulsion system and launch of the Space Shuttle was a continual source of national pride during the 30 years of flight and at the end "we finished strong". Many of the system performance deficits noted early in the flight program were overcome via optimization and evolution of the propulsion system. Figure 8 illustrates the performance evolution with time.

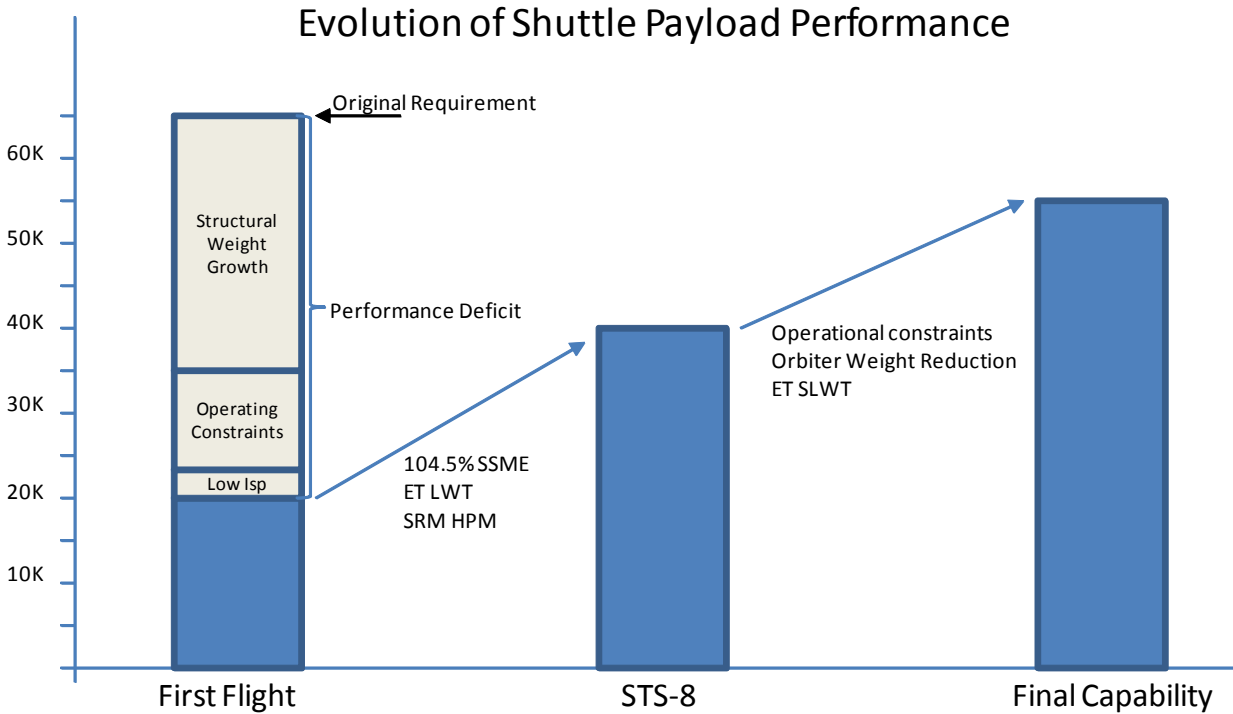


Figure 8. Shuttle Performance Evolution

In addition to performance a number of factors drove design and processing improvements during the 30 year flight program. These included design issues, a need to understand flight environments, safety and reliability upgrades, improvements to better enable hardware reuse, obsolescence issues, improved manufacturing methods, improvements in hardware processing, and response to ever changing environmental regulations. Shown below is a summary of major upgrades and what drove the change.

Major upgrades	Design issues	Performance Upgrade	Flight Environments	Safety	Reliability	Reuse	Obsolescence	Manufacturing	Processing and Operations	Environmental regulations
External Tank										
Light weight tank		X								
Super light weight tank		X								
Debris reduction	X			X						
Friction stir welding								X		
Thermal protection system formulations										X
Solid Rocket Motor										
High Performance Motor		X								
Redesigned Solid Rocket Motor	X			X						
Booster Separation Motor							X			
Solid Rocket Booster										
Main parachutes						X				
Thermal protection system									X	X
Video and data acquisition			X							
Aft Skirt structural bracket	X									
Hold down post debris containment system				X						
Frangible nut cross over	X			X						
External Tank attach ring	X									
Space Shuttle Main Engine										
Phase II	X	X		X	X					
Block I/IA	X			X	X				X	
Block IIA/II	X			X	X				X	
Advanced Health Management System				X	X					

Evolution of the booster system to a fully reusable fly back system was never attempted, the system was too sensitive and complex, and this was simply too big a change (not to mention the cost). Integration of the existing propulsion system however enabled reliable earth to orbit performance with very small performance margins. During the final flights imagery analysis and integrated risk assessment became routine practices enhancing situational awareness and understanding of risk. The technical accomplishments for each element are discussed in the papers to follow, with a detailed assessment of the final 22 flights along with observations related to engineering and project management improvements provided in the final paper of the session.

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