Space Shuttle Propulsion Master's Forum Presentation Mitigating Risk through Testing

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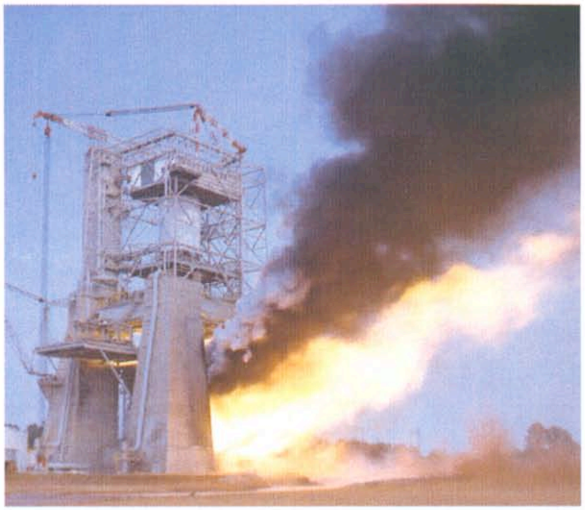
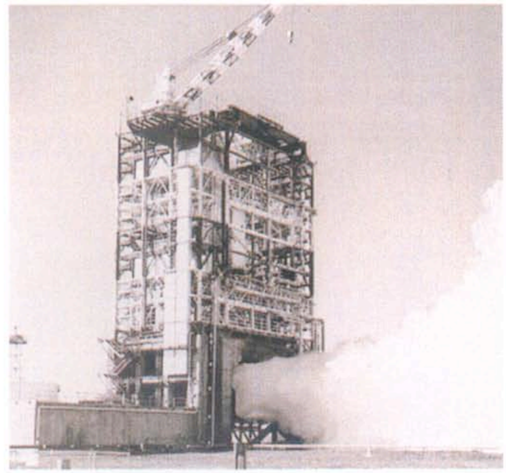
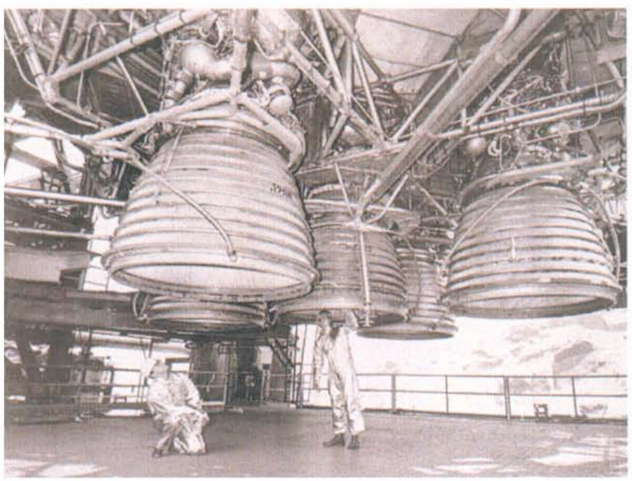
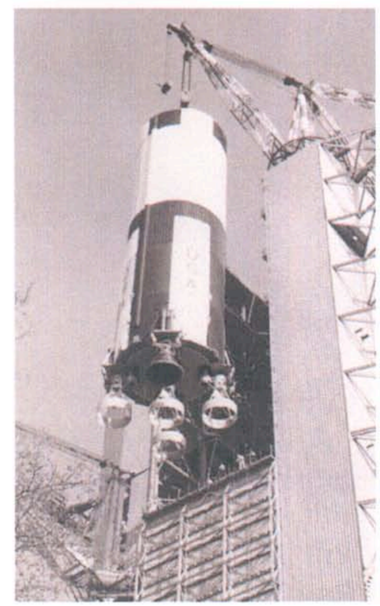
Mitigating Risk Through Testing









What is the Space Shuttle?

- World's first reusable heavy-lift spacecraft
- It is the most complex machine ever built
- Launches vertically (a rocket), carries crew, logistics, experiments and maneuvers in Earth orbit (a spacecraft), lands like a airplane
- Each Space Shuttle has a design life of 100 missions
    - 125 total missions to date; 12 since *Columbia* accident
- Space Shuttle is a unique national asset

It has more than 2.5 million parts

230 miles of wire

nearly 1,100 valves and connectors

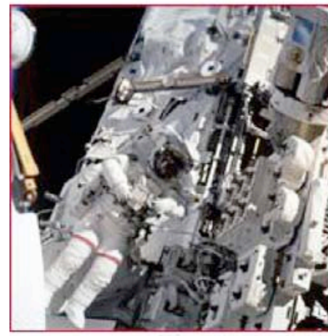
almost 1,500 circuit breakers

and over 27K insulated tiles and thermal blankets

Space Shuttle Capabilities

- Cargo/payload delivery and retrieval
  - Up to 25 tons of payload to orbit
  - Up to 20 tons of payload on re-entry
- On-orbit assembly and service (ISS, HST)
- Crew transfer (ISS)
- Satellite retrieval and repair
- On-orbit, point-to-point maneuvering of people and cargo
- Science payloads/Space Lab/SpaceHab
- EVA capable


Satellite Retrieval and Repair

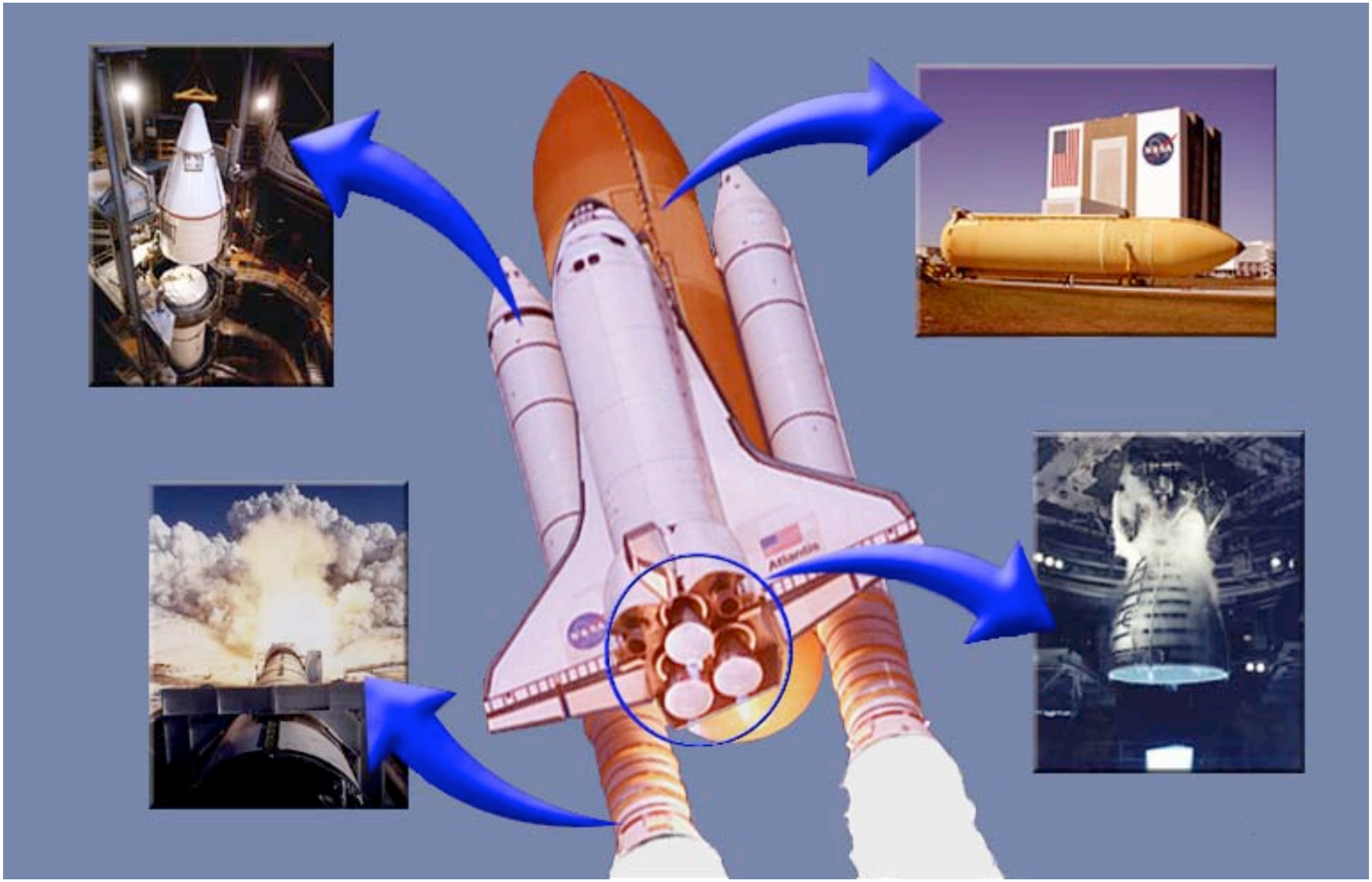

On-orbit Assembly

Crew Transfer

Point-to-point Maneuvering


Cargo Return

Shuttle Propulsion Office

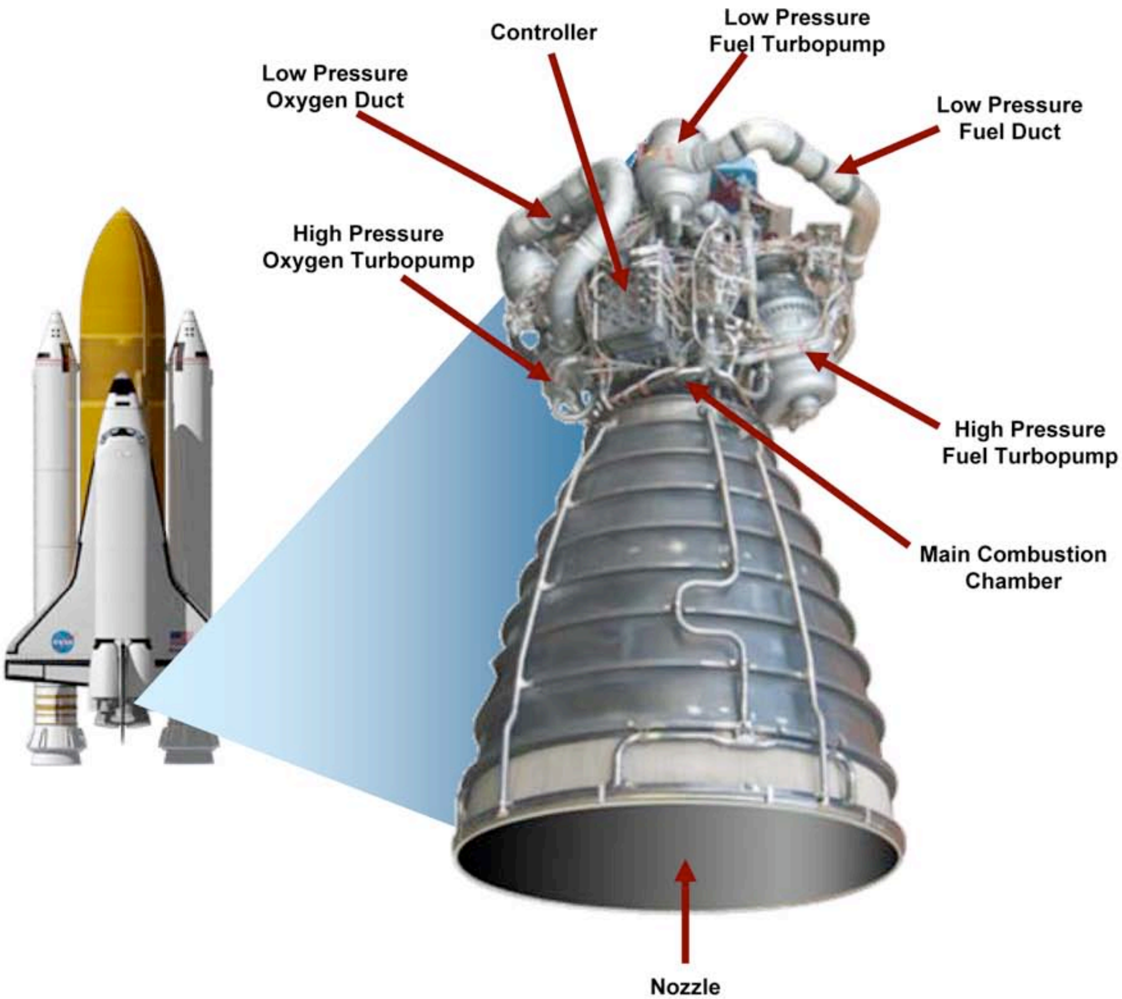


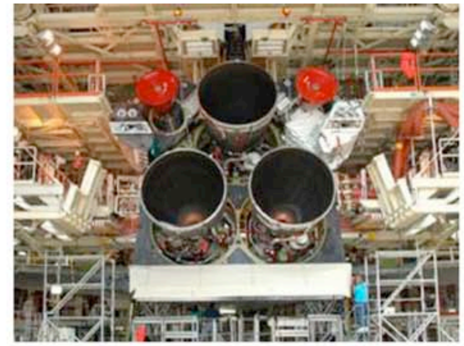
Space Shuttle and Contractor Partners

1/14/08
SSP-97-023

SSP-09-1778

Space Shuttle Main Engine (SSME)



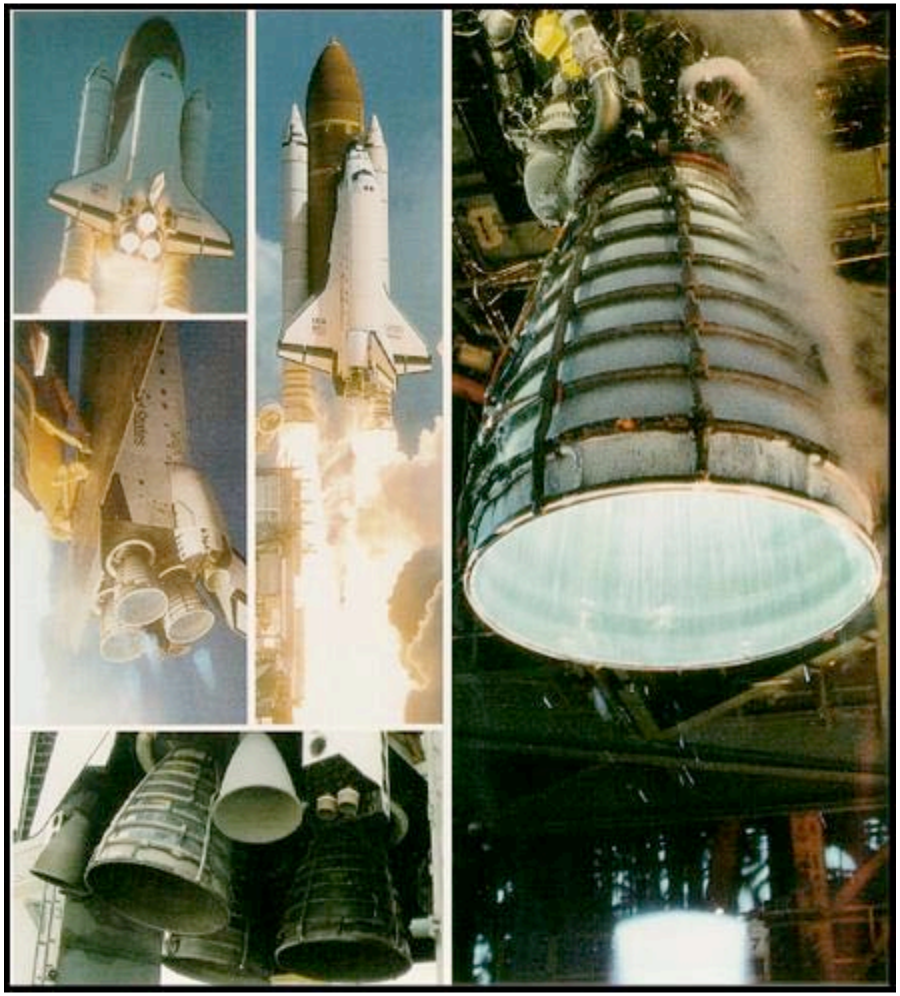


Manufactured by:
Pratt & Whitney/
Rocketdyne Power, Inc.
Canoga Park, CA

LENGTH	14 ft (4.3 meters)
DIAMETER	7.5 ft (2.3 meters)
# PER FLIGHT	3
PROPELLANTS	liquid hydrogen and liquid oxygen from the External Tank
THRUST	418,000 lbs (189,600 kg) sea-level
Ignition to MECO	Approx. 8.6 mins
LIFETIME	7.5 hours, 55 starts

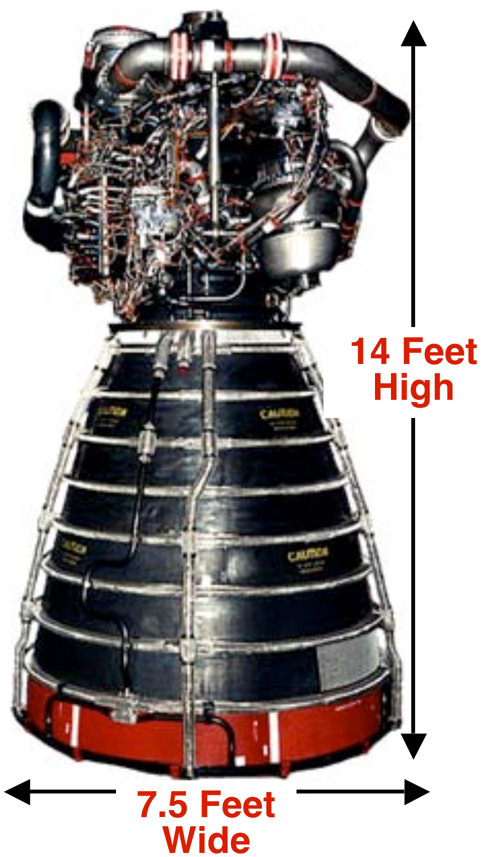
Space Shuttle Main Engine (SSME) Overview

- 3 main engines operate for 8 1/2 minutes during ascent
- Sole source of propulsion once the Solid Rocket Motors are separated at T+120 seconds
- Engines have performed safely for all 124 launches
- 55 engines have flown 372 engine missions
  - One in-flight shutdown (STS–51F July 29, 1985)
- Engines have operated for over 3,128 hotfires and 1,075,208 seconds during flight and ground testing



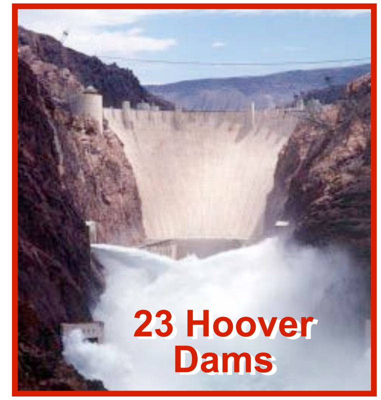
Space Shuttle Main Engine Amazing Facts

- High Pressure Fuel Turbopump (HPFTP) alone delivers as much horsepower as 28 locomotives and can drain an average-size swimming pool in 28 seconds!



First Stage Turbine Blade

- Turbine Blades are one of the most critical components on the <u>Shuttle</u>
- The turbine blades spin at 600 revolutions per second



- Three main engines operate for 8 minutes and 40 seconds for each flight, with a combined output of 37 million horsepower.
- Engine operates at temperatures from -423° F (liquid hydrogen to cool engine) to 6,000° F (hotter than the boiling point of iron!)
- Three engines produce equivalent power of 23 Hoover Dams
- World's highest efficiency reusable LOX/Hydrogen engine

Space Shuttle Main Engine (SSME)

Characteristics

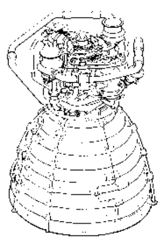
Propellants	Oxygen/Hydrogen
Thrust @ Rated power level (RPL) 100%	469,448 lb
Thrust @ Nominal power level (NPL) 104.5%	490,847 lb
Thrust @ Full power level (FPL) 109%	512,271 lb
Chamber pressure (109%)	2,994 psia
Specific impulse at altitude	452 sec
Throttle range (%)	67 to 109
Weight	7,748 lb

Operational

Main Combustion Chamber Pressure	2,871 psia
Main Combustion Chamber Temperature	6,000° F
Fuel Flowrate	155 lb/sec
HPFTP Turbine Discharge Temperature	1,119° F
HPFTP Discharge Pressure	5,943 psia
HPFTP Speed	33,913 rpm
Oxidizer Flowrate	933 lb/sec
HPOTP Turbine Discharge Temperature	768° F
HPOTP Discharge Pressure	4,040 psia
HPOTP Speed	22,357 rpm

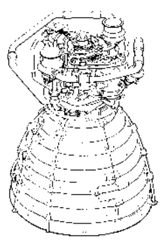
Space Shuttle Main Engine (SSME) Design Improvements

First Manned Orbital Flight



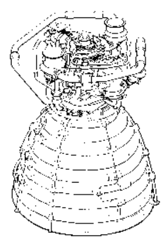
Baseline Engine

Full Power Level



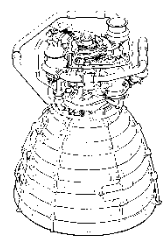
- Powerhead
- Ducts
- HPFTP
- HPOTP
- LPFTP
- LPOTP
- Avionics
- Nozzle

Phase II



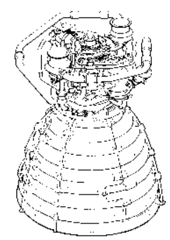
- HPFTP
- HPOTP
- MCC
- LPF Duct Helium Barrier
- Avionics/Valves

Block I



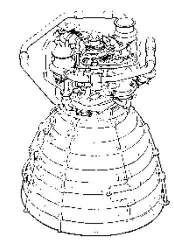
- Two Duct Powerhead
- Single Tube HEX
- HPOTP
- HPFTP EDM Inlet
- Thermocouples

Block IIA



- Large Throat MCC
- Main Injector Modifications
- Block II LPOTP
- Block II LPFTP
- A-Cal Software
- Pressure Sensor

Block II



- HPFTP
- Main Fuel Valve
- Non-Integral Spark Igniter

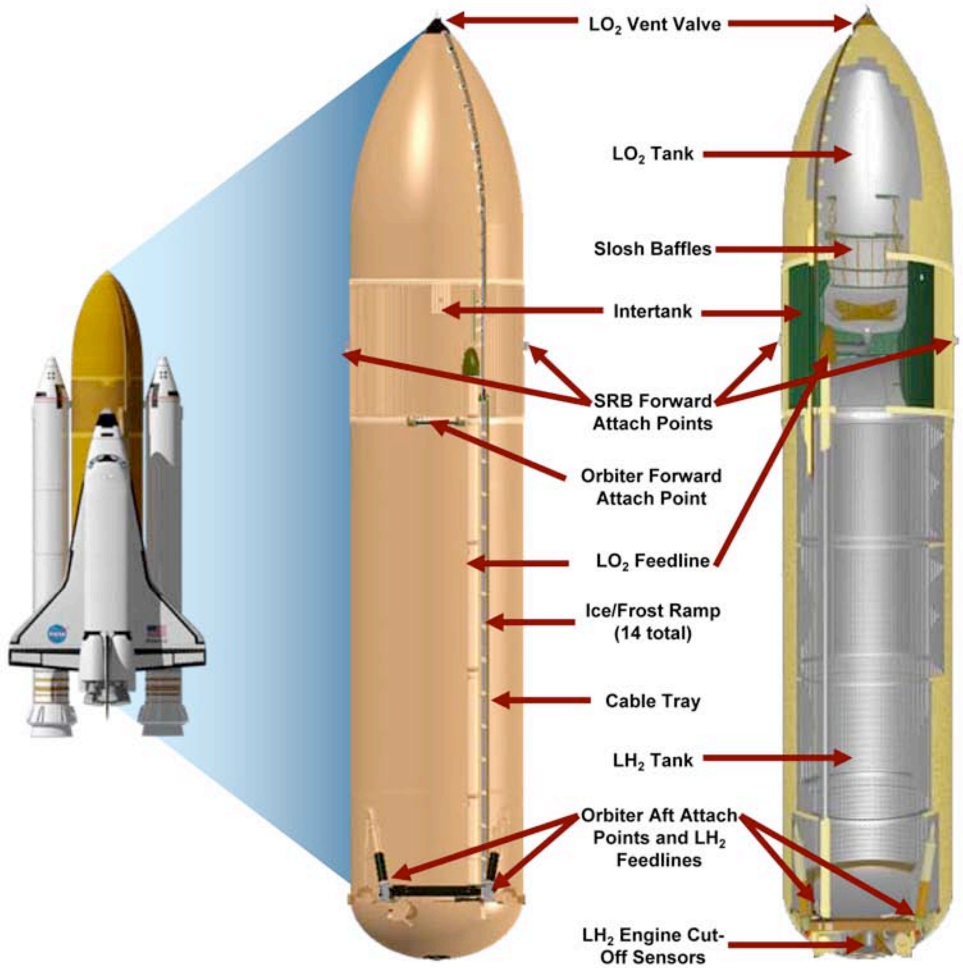
- Advanced Health Management System (active)

STS-1 1981	STS-6 1983	STS-26R 1988	STS-70 1995	STS-89 1998	STS-104 2001	STS-117 2007

Space Shuttle Main Engine (SSME) Hotfire History

- Through 2008, SSME has been hotfired 3,128 times for 1,075,208 seconds during flights and ground tests
- First SSME tests conducted on May 19, 1975 at the Mississippi Test Facility (now the Stennis Space Center)
  - 37 tests required to reach minimum power level (50% RPL at the time) during initial start sequence development
  - 95 tests required to reach 100% power level
  - Initial flight start sequence implemented in 1978
    - 10 engine failures incurred during this time period
    - Further modifications to start sequence required as engine upgrades implemented
  - 726 tests on 24 engines were tested for 110, 252 seconds prior to STS-001
- Several design improvements have been implemented throughout the history of the program

External Tank



Manufactured by:
Lockheed Martin Space Systems Company (LMSSC)
Michoud Assembly Facility
(GOCO Facility)
New Orleans, LA

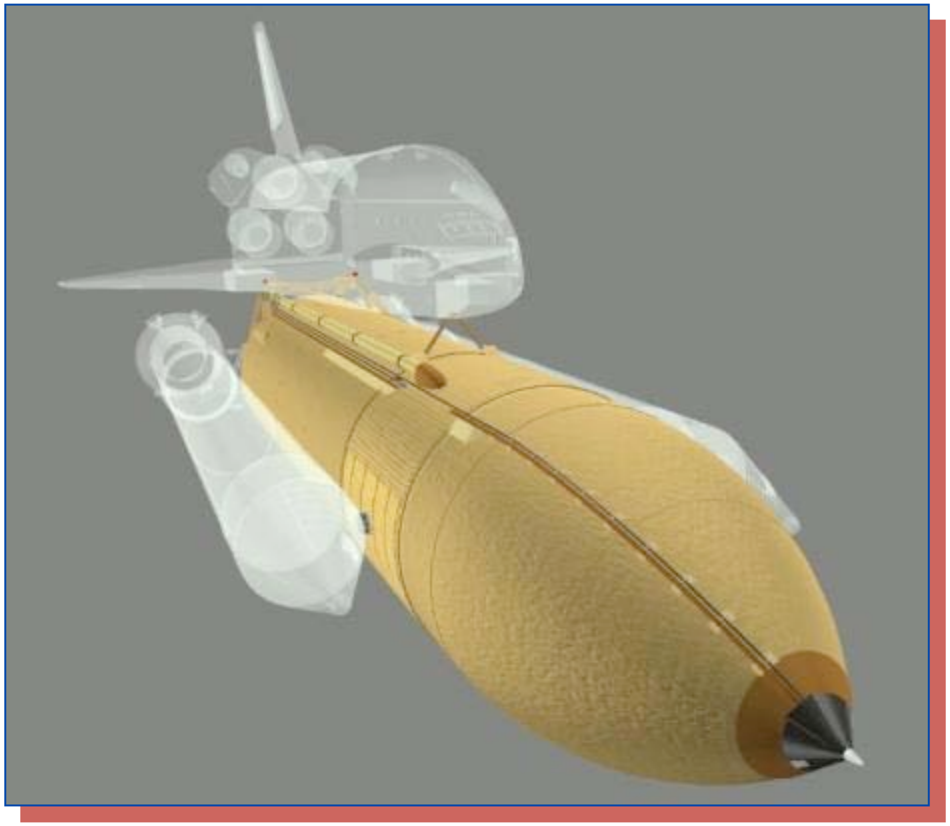
LENGTH	153.8 ft (46.9 meters)
DIAMETER	27.6 ft (8.4 meters)
FUEL	liquid hydrogen 385,265 gallons -423°F
OXIDIZER	liquid oxygen 143,351 gallons -300°F
WEIGHT, EMPTY	66,000 lbs (29,937 kg)
WEIGHT, FUELED	1,655,600 lbs (750,967 kg)

External Tank Evolution / Weight

- **SWT (1981 – 1983): 77,086 lb.**
- **LWT (1981 – 1998): 70,660 lb.**
- **SLWT (1998 – present): 58,550 lb.**

External Tank Overview

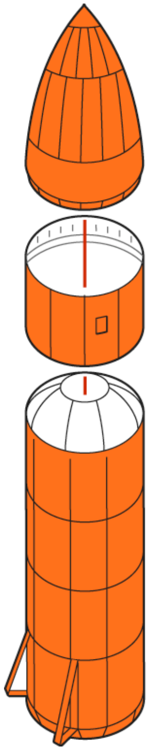
- ***The External Tank***
  - Serves as the structural backbone of the shuttle during launch operations
  - Contains and delivers Liquid Hydrogen (LH2) and Liquid Oxygen (LO2) propellants for the Orbiter's three main engines



- ***Three structural elements***
  - The LO2 tank and LH2 tank pressure vessels are welded assembly of machined and formed panels, barrel sections, ring frames and dome sections
  - The Intertank is a cylindrical mechanically joined assembly with flanges at each end for joining the LO2 and LH2 tanks

Space Shuttle External Tank (ET) Amazing Facts

- The External Tank is manufactured at Michoud Assembly Facility in Louisiana. The building is 43 acres under *one roof*!



- Expends enough fuel in 25 seconds to drain the average swimming pool
- Holds 380,000 gallons of liquid hydrogen (–423° F)
- 140,000 gallons of liquid oxygen (–300° F)
- Only major expendable Shuttle element

- ET covered with spray-on foam insulation that keeps the LH_2 at –423° F even in the hot sun ~ 1/3 acre of foam surface
- Weighs 1.6 million pounds at liftoff: equal to 32,000 elementary school children

- Skin of the ET is less than 0.25 inches thick, yet holds more than 1.5 million pounds of propellant
- The ET is taller than the Statue of Liberty and is the structural backbone of the Shuttle vehicle

Main Propulsion Test (MPT)

ET Developmental Testing

- ***MPT Test Hardware Description***
  - Full size SWT External Tank (ET), Space Shuttle Aft compartment complete with full Main Propulsion Systems (MPS) and three Space Shuttle Main Engines(SSME). Propellant Tanking and Full Duration MPS Static Firing tests on B2 Test Position at Stennis Space Center (1979).

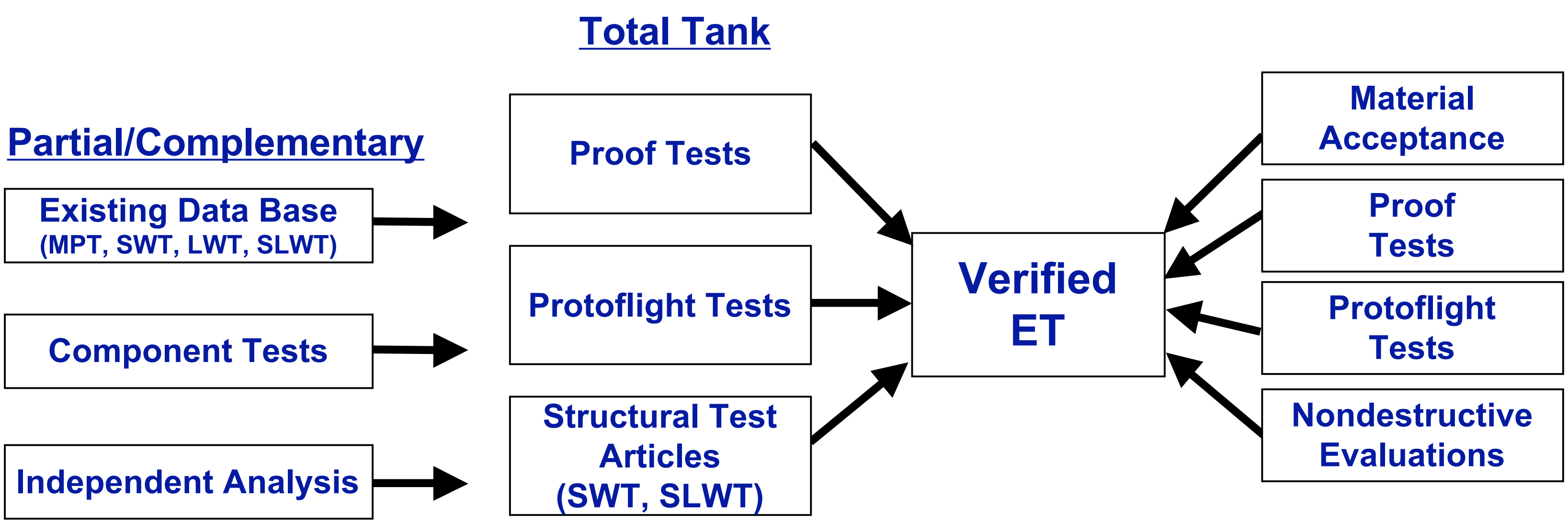
- ***ET MPT Test Objectives***
  - Verify Subsystem Performance Requirements
    - SSP Volume X Requirement Verification
    - Instrumentation and Electrical Performance Verification
    - Thermal Protection System performance Verification
    - Environmental Conditioning (Purges) and compartment venting Verification
  - Validate and Anchor Analytical Models
    - Thermal Models
    - Pressurization Models
    - Structural Load Models
    - Resonate (Vibration) Models
  - Develop Propellant Loading and De-tanking Procedures
    - Tanking Tables
    - Launch Commitment Criteria (LCC)
    - KSC Ground Operations - Maintenance and Requirement Specification Documents (OMRSD)
  - Identify Problematic Hardware, Optimize Requirements and Procedures Prior to Flight

Verification Process

- **Methodology**
  - Verification approach consistent thru SLWT, LWT and SLWT verification programs

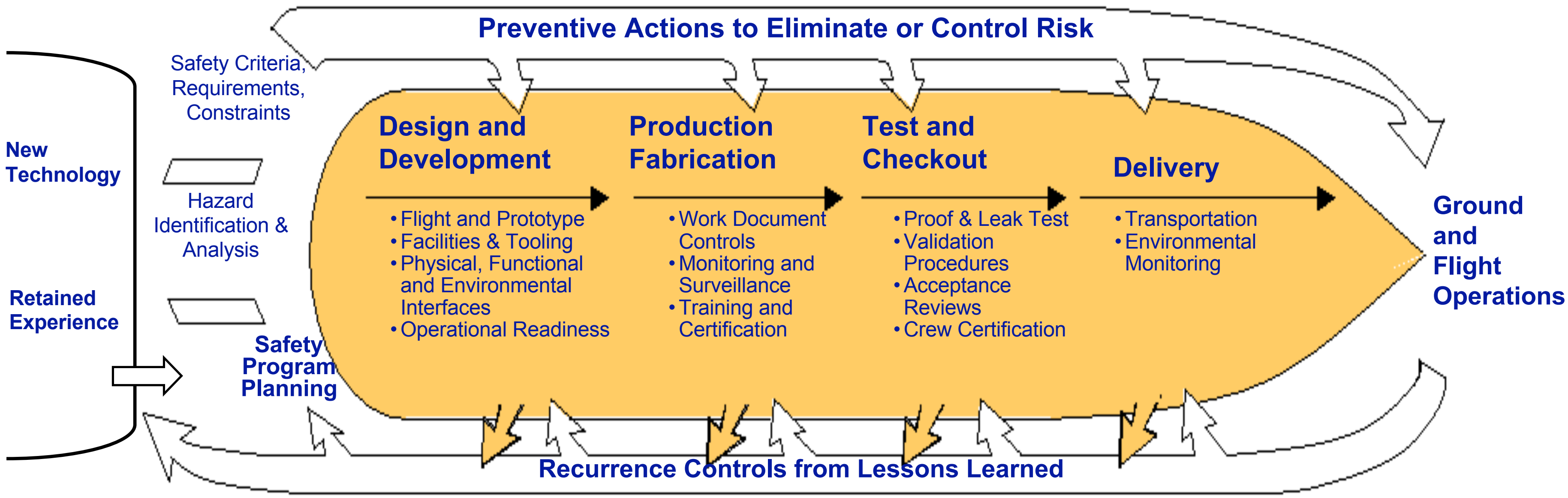
Design Verification
(Assure design meets required Factor of Safety)

Acceptance Verification
(Assure workmanship and absence of any flaw that will cause failure in use)



Quality Assurance Process

- **Safety**
  - A Systems Approach to Safety Program Management



• **Failure Analysis** • **Accident/Incident Investigation** • **Performance Evaluation and Trends** • **Post Flight Analysis**

Summary

- *MPT ET Pre-Flight Testing*
  - Verified Subsystem Performance Requirements
  - Validated and Anchored Analytical Models
  - Developed Propellant Loading and De-tanking Procedures
  - Identified Problematic Hardware, Optimized Requirements and Procedures Prior to Flight

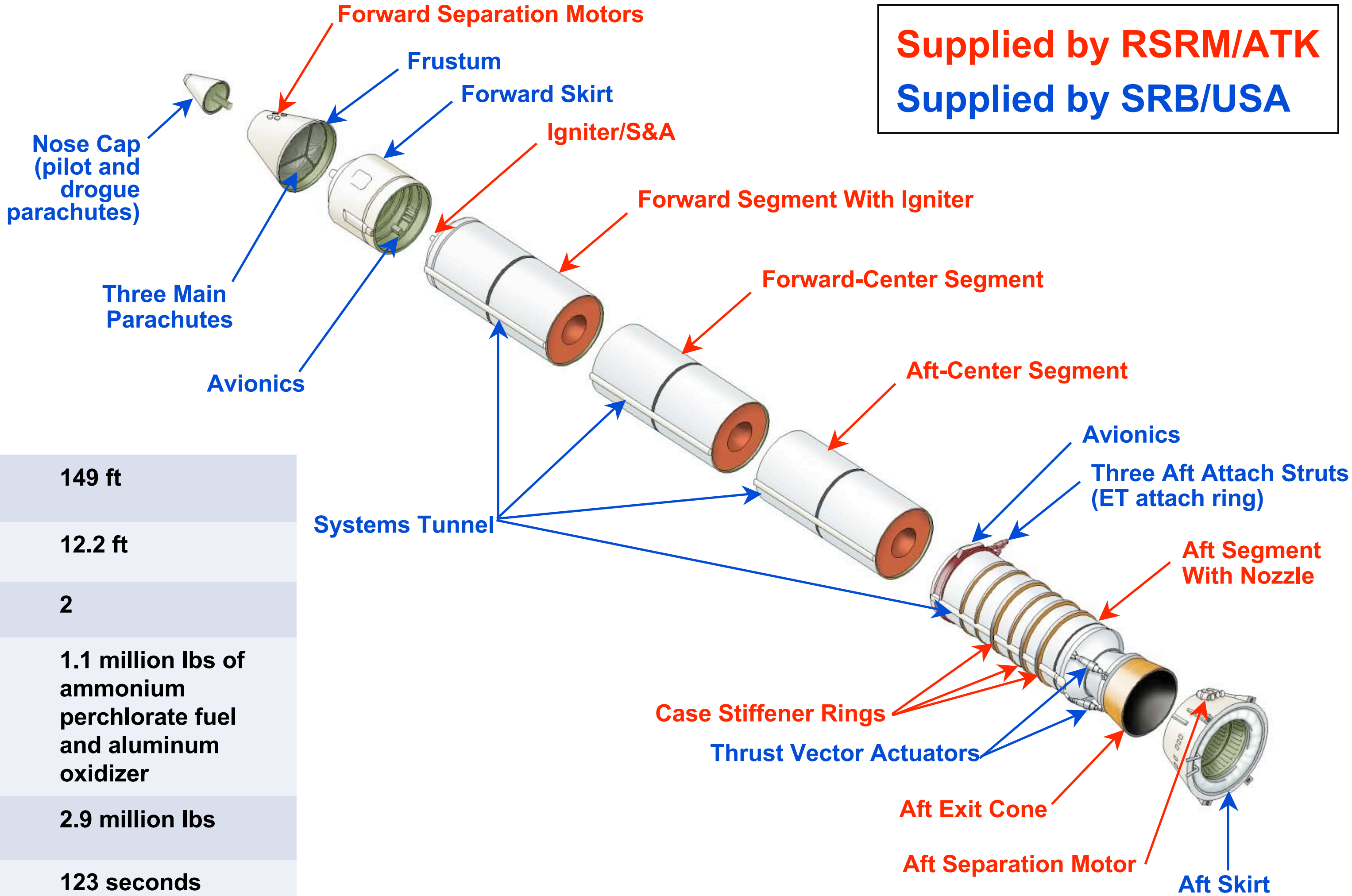
- *ET Production Test and Verification*
  - LH_2 and LO_2 Systems Proof and Leak Testing
  - Propulsion Systems Verification Testing
  - Electrical Systems Verification Testing

- *ET Flight Development*
  - MPT – Development of Pre-Flight Data
  - SWT – Generated Developmental Flight Loads Data
  - LWT – Reduced ET Weight from SWT Flight Loads Data
  - SLWT – Optimized ET Weight from LWT Flight Loads Data

- *1.4 Factor of Safety to 1.25 weight but after extensive structural tests were completed*

- *ET Successfully Evolved and Continues to Fly Based on Testing and Verification Approach*

Reusable Solid Rocket Booster (RSRB)



Supplied by RSRM/ATK

Supplied by SRB/USA

Length	149 ft
Diameter	12.2 ft
# Per Flight	2
Propellant	1.1 million lbs of ammonium perchlorate fuel and aluminum oxidizer
Thrust	2.9 million lbs
Burn Duration	123 seconds
Chamber Pressure	906.8 psia (Ignition)
Weight	1.3 million lbs each

SSP-09-1778

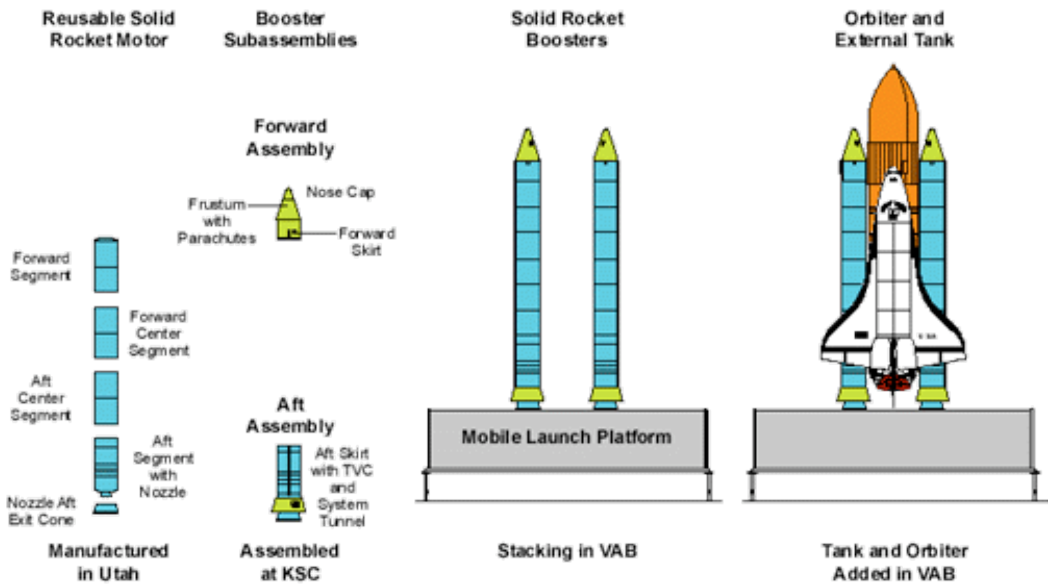
Reusable Solid Rocket Booster (RSRB) Overview

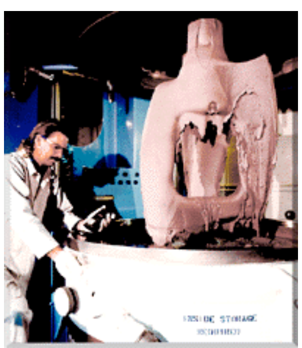
- Twin RSRBs burn for 123 seconds during ascent
- Provide 80% of thrust required to achieve liftoff
- Recovered 120 to 160 miles downrange from KSC
- Case segments are returned to manufacturer in Utah for refurbishment
  - Four cast segments per motor
  - Designed for 20 flight reuse
  - Each segment filled with approx. 280,000 lbs of propellant
  - Shipped via rail to/from KSC
- Segment cases made from D6AC steel
- RSRM shelf life is five years
  - Flight specific age life extension to 5.5 yrs
- 250 motors launched (RSRM and SRM)
- 51 full scale static tests
  - Development, Qualification, Engineering Test, Disposal
  - Includes one 5-segment Engineering Test Motor

Reusable Solid Rocket Booster (RSRB) Overview

Shuttle and MLP interface Transmit RSRM thrust to Shuttle Attach ET and SRB	Structures	Aft Skirt Hold Down Studs and Frangible Nuts Forward Skirt ET Attach Ring and Struts
Shuttle steering through SRB Separation	Avionics and Flight Controls	Aft Integrated Electronics Assembly (IEA) Rate Gyro Assemblies (RGA) Thrust Vector Control System (TVC) Batteries
Shuttle Destruct System	Range Safety System (RSS)	RSS Safe and Arm Device Linear Shape Charge (LSC) Command Receiver Decoder RSS Antennae
SRB Separation	Separation System	Booster Separation Motors Forward Separation Bolt Aft Separation Bolts/Attach Struts
SRB Descent and Recovery	Recovery System	Altitude Switch Assemblies (ASA) Nose Cap Thrusters Pilot and Drogue Parachutes Ordnance Separation Ring and LSC Main Parachutes Salt Water Activated Release (SWAR) System

Space Shuttle Solid Rocket Booster/ Reusable Solid Rocket Motor Amazing Facts





- **World's largest solid rocket**
- **149.1 feet high and 12.2 feet wide (1/2 football field long only 2 feet shorter than the Statue of Liberty)**
- **Each RSRM equivalent output during flight is 15,400,000 hp or about 51,300 Corvettes.**
- **Two RSRMs produce more thrust than thirty-two 747 jets at takeoff power or 14,700 six-axle diesel locomotives.**
- **RSRM combustion gas temperature approaches 6,000° F, approximately two-thirds the temperature of the sun's surface. At this temperature steel does not melt, it boils.**
- **Produces 2.6 million pounds of thrust at liftoff - more than 32 747s at take-off power**
- **Boosters go to full power in 2/10th of a second – the heat they produce in the first 2 minutes could heat 87,000 houses for one full day.**
- **After 2 minutes, boosters separate at 28 miles altitude at a speed of 3,100 mph. They coast upward for 13 miles before beginning their fall.**
- **Three 136-foot wide parachutes slow the SRBs to a safe splashdown in the Atlantic Ocean.**
- **Boosters are recovered, refurbished and reused.**
- **The boosters are the heaviest object ever to be parachuted safely back to the surface!**

Reusable Solid Rocket Booster (RSRB)

Reusable Solid Rocket Motor Process Flow

Reusable Solid Rocket Booster (RSRB)
RSRM Development & Qualification Program Philosophy

- **Solid Rocket Motor (SRM) – Pre-51L Design**
  - **Full scale static tests before first flight**
    - **Four Development Motors (DM)**
    - **Three Qualification Motors (QM)**

- **Reusable Solid Rocket Motor (RSRM) – Post 51L Design**
  - **Full scale static tests before first flight**
    - **One Engineering Test Motor (ETM)**
    - **Two Development Motors (DM)**
    - **Two Qualification Motors (QM)**

Philosophy:
"Test before you fly"

Reusable Solid Rocket Booster (RSRB)
RSRM Ground Test Program Philosophy

Philosophy: "Test before you fly"

FSM (Flight Support Motor): Full-scale test motor (typically one per year) with focus on testing all finalized changes before first flight

- 15 FSMs (one more planned)

FVM (Flight Verification Motor): Special designation for two "Mid-Life and Full-Life" full-scale aged test motors built for flight (RSRM-89 de-stacked and returned to Utah)

- FVM-1 was 3.9 yrs old
- **FVM-2 was 7.2 yrs old**

PRM (Production Rate Motor): Full-scale test motor fired prior to post-Columbia return-to-flight that provided process validation during periods of reduce production rates

TEM (Technical Evaluation Motor): Full-scale test motors with a variety of purposes including evaluation of extended exposure to Florida environment (returned to Utah due to age life)

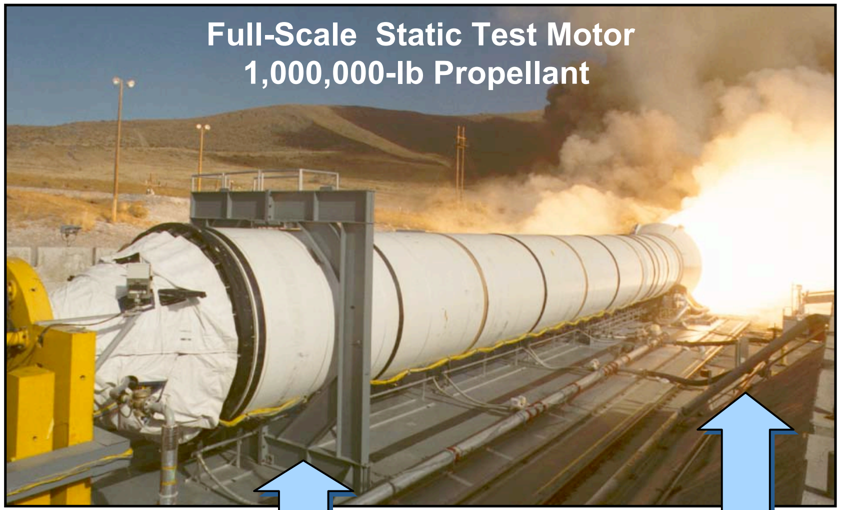
- 2 TEMs for RSRM (11 pre-RSRM)

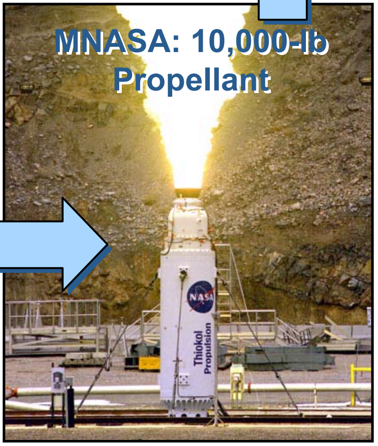
ETM (Engineering Test Motor): Full-scale test motor focused on the "off-nominal" — flaw, margin, and "physics based" knowledge testing

- **3 ETMs (including one 5-segment motor)**

MNASA (48") and SRTM (24"): Subscale test motors — focus is evaluation and down-selection of material and design changes, analytical model anchoring, etc.

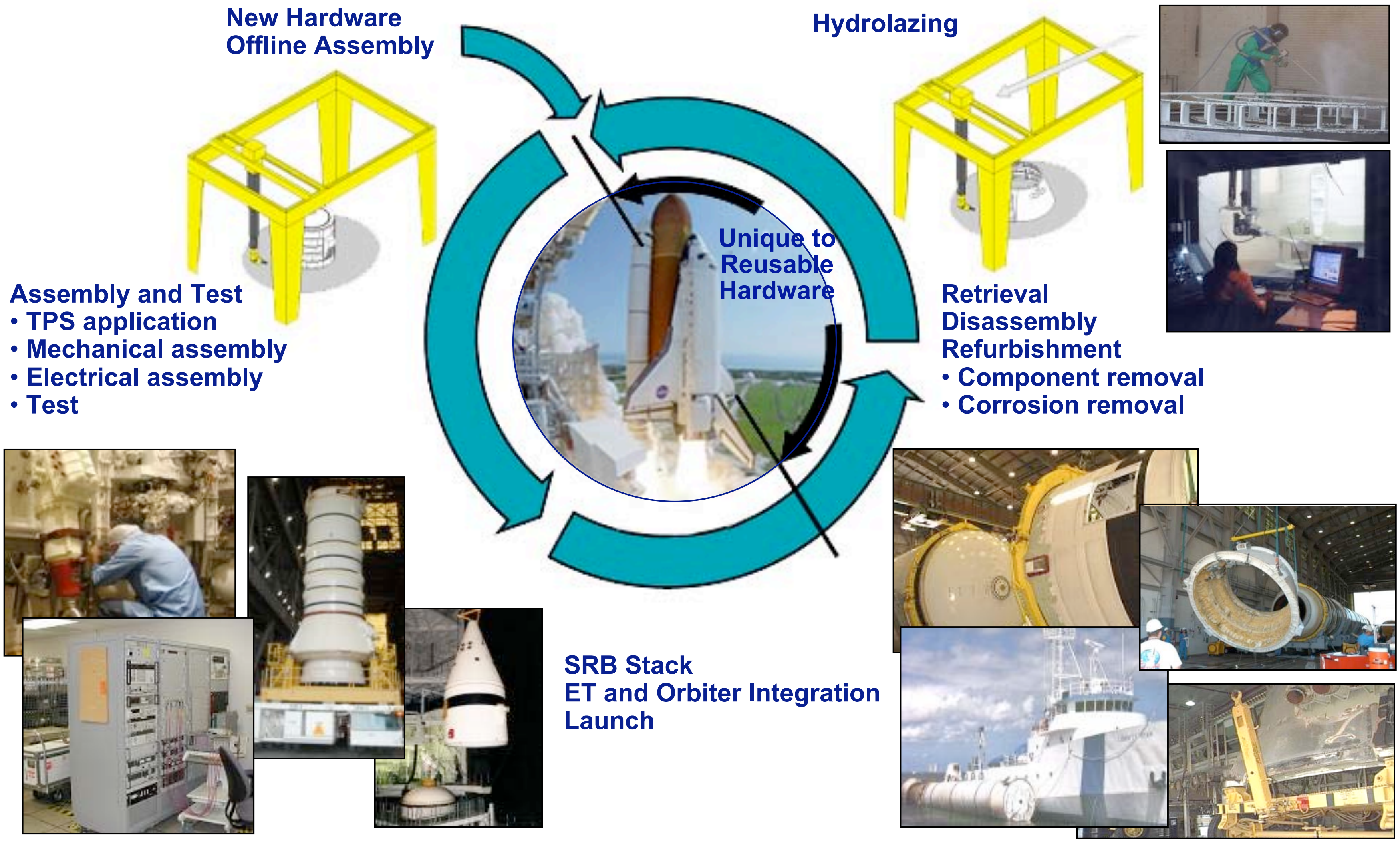
- 24 MNASA and 14 SRTM



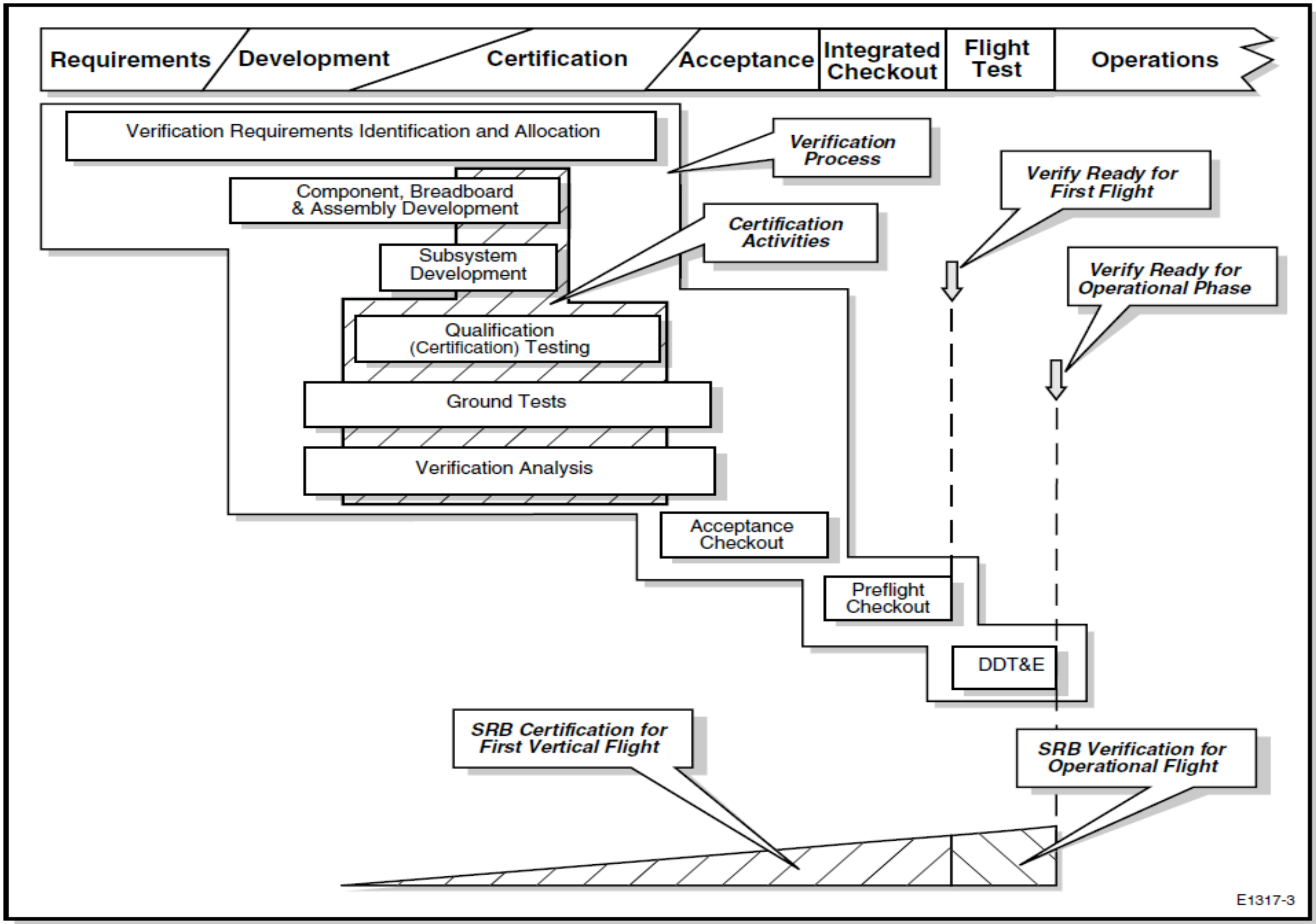


Commitment to a Robust Motor Test Program

Reusable Solid Rocket Booster (RSRB)
SRB Process Flow



Reusable Solid Rocket Booster (RSRB)
SRB Overall Verification Program



Reusable Solid Rocket Booster (RSRB) SRB Development Tests

- **SRB Hardware Verification Description**
  - SRB Primary Structures were analyzed and tested.
    - Mated Vehicle Ground Vibration Test (MVGVT)
    - Static Test Articles (STA)
  - Electrical and Instrumentation (E&I) System was developed and Flight Certified at the component level and tested in integrated system level
  - Recovery and Separation Pyrotechnics systems and Booster Separation Motors were developed and Flight Certified at the component level
  - Range Safety Destruct System was developed and Flight Certified at the component level
  - Thrust Vector Control (TVC) System was developed and Flight Certified at the component level and performance tested as a full TVC system at MSFC
  - Thermal Protection System (TPS) was developed, tested and verified at MSFC
  - DDT&E Flights

Reusable Solid Rocket Booster (RSRB)
SRB Structural Testing

Structural Tests

- Structural tests were performed to determine the ability of SRB structure to withstand predicted static and dynamic forces which may be encountered in assembly, storage, transportation, handling, flight, and recovery. Structural tests were performed on the largest practical assemblies of structural hardware.

Mated Vehicle Ground Vibration Test (MVGVT)

- Full size Solid Rocket Booster structures, Solid Rocket Motor inert segments, External tank and Orbiter Simulator were integrated and vibration tested at MSFC.

Static Test Article (STA)

- All major SRB structures were subjected to static loads equivalent to 140 % of flight loads.
- Aft Skirt – Forward Skirt - Frustum – Nose Cap – External Tank Attach Ring

Main Propulsion Test Article (MPTA) Testing

Scope:

The Main Propulsion Test Article will integrate the main propulsion subsystem with the clustered Space Shuttle Main Engines, the External Tank and associated GSE. The test program consists of cryogenic tanking tests and short- and long duration static firings including gimbaling and throttling. The test program will be conducted on the S1-C test stand (Position F-2) at the National Space Technology Laboratories (NSTL).

Configuration:

The main propulsion test article shall consist of the three space shuttle main engines, flightweight external tank, flightweight aft fuselage, interface section and a boilerplate mid/fwd fuselage truss structure.

Main Propulsion Test Article (MPTA) Testing

Results:

3 tanking tests and 20 hot fire tests conducted between December 21, 1977 and December 17, 1980

MPTA Data

•Attempts to static fire	20
•Failure to get SSME ignition	2
•Tests planned for full duration (500+ secs)	14
•Tests full duration accomplished	6
•Tests planned duration accomplished	10
•Tests with high percentage of objectives meet	12
•Engine Total Seconds	10,813

Main Propulsion Test Article (MPTA) Testing

<u>MPTA Accomplishments</u>

- Qualification of the Shuttle cross-feed system (ET along side the Orbiter)
- Integration of SSME into the Orbiter
- Qualification of liquid delivery system hardware
- Qualification of gaseous pressurization system hardware
- Validation of structural and POGO models
- Development of loading and draining procedures/software