Success Legacy of the Shuttle Program

Space Shuttle Main Engine
Relentless Pursuit of Improvement

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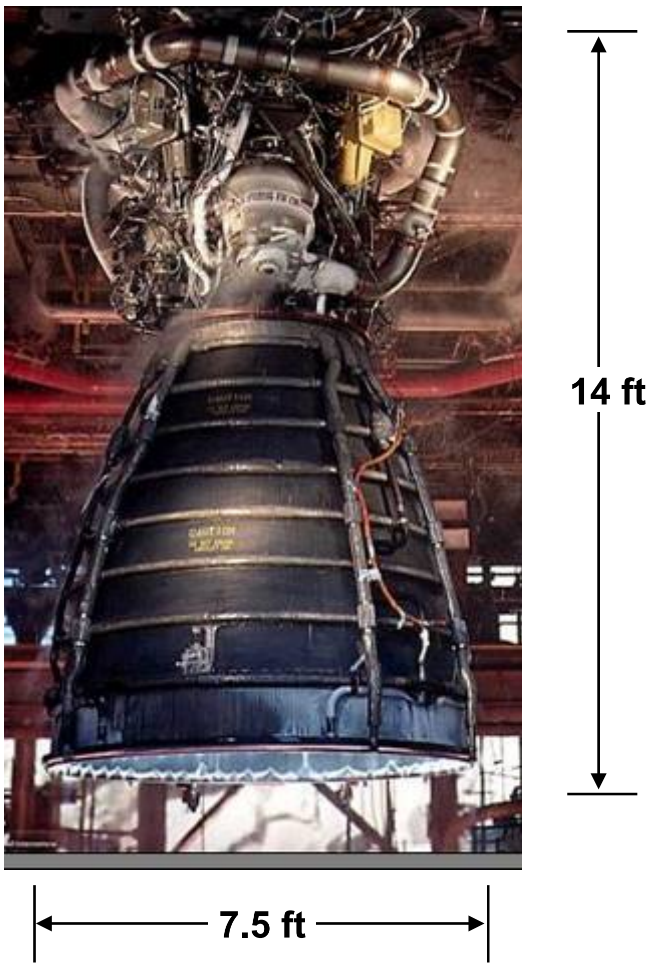
Space Shuttle Main Engine (SSME) Relentless Pursuit of Improvement

- SSME 101
- Design evolution
- Verification by ground test
- Analytical tool evolution
- Lessons

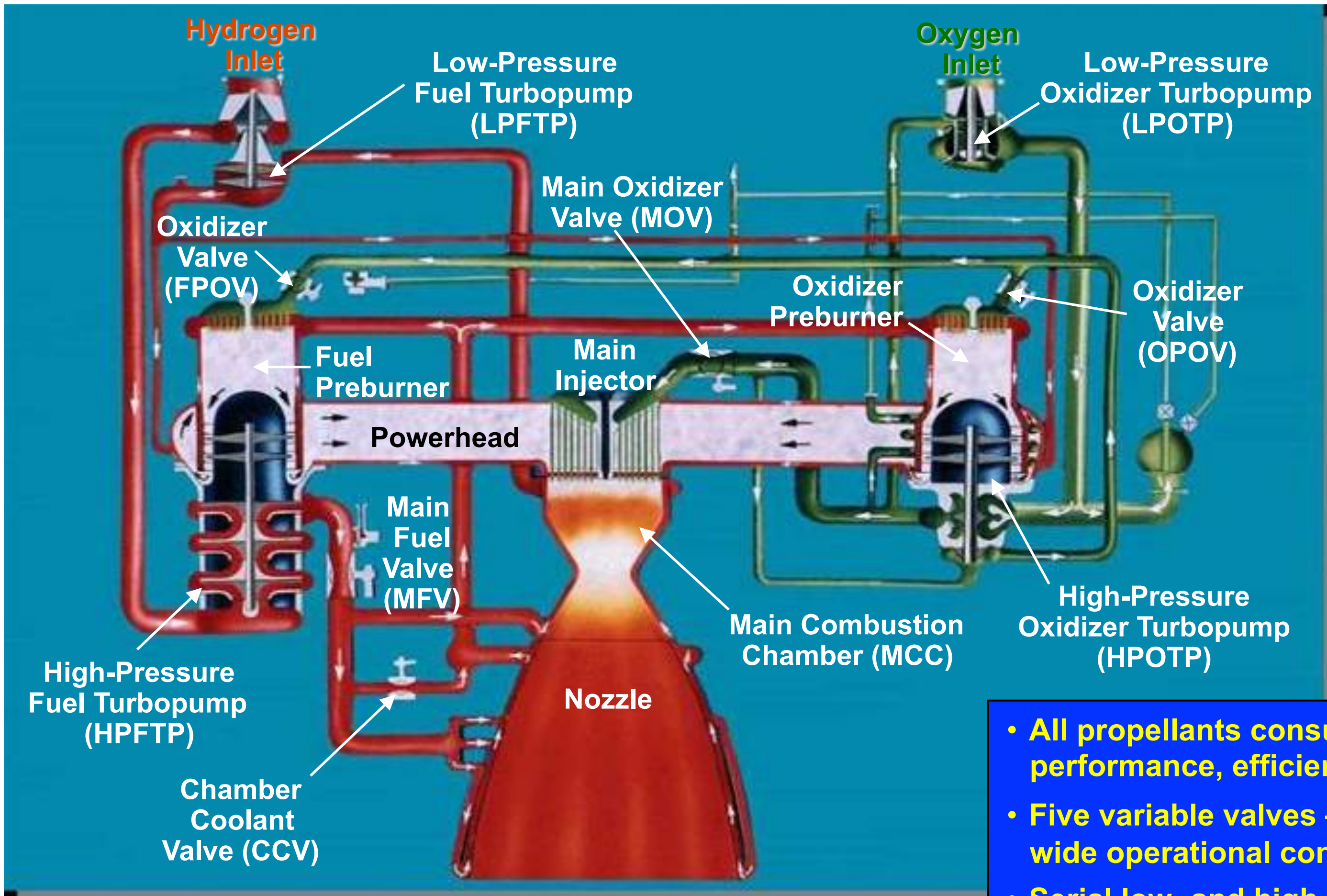
SSME is the First Reusable Large Liquid Rocket Engine



Propellants	O_2/H_2
Rated power level (RPL) 100%	469,448 lb
Nominal power level (NPL) 104.5%	490,847 lb
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
Gimbal range	+/- 11 °
Weight	7,748 lb
Service life	55 flights / 27,000 sec
Total program hot-fire starts	3,162 starts

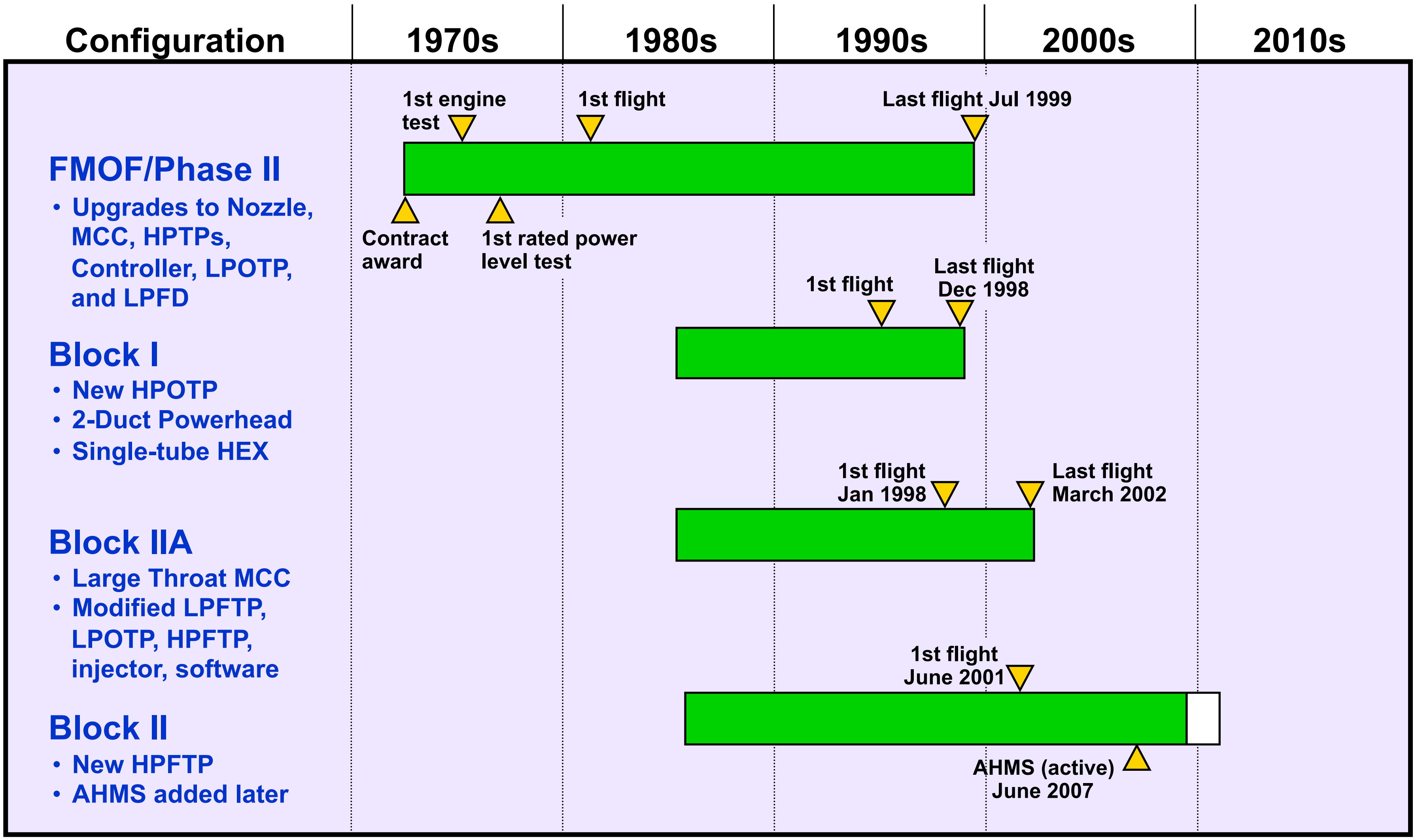
(as of January 2011)

High Performance Staged Combustion Cycle



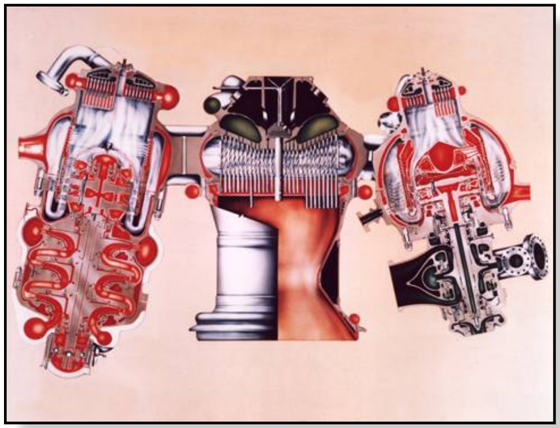
- All propellants consumed – performance, efficiency
- Five variable valves – flexibility, wide operational control
- Serial low- and high-pressure pumps – wide flow range
- Fail-op / fail-safe control system

SSME Block Improvements Timeline



Phase II SSME

First Flight — April 1983

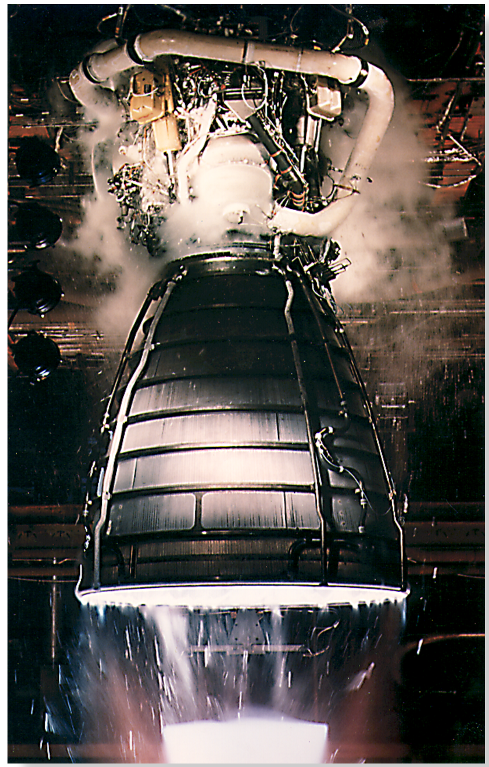


Powerhead
- Main Injector oxidizer inlet vane rework

MCC
- EDNi reinforced outlet neck

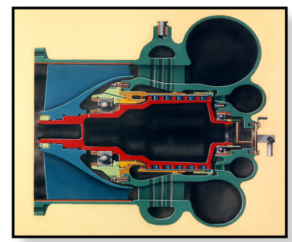
HPTPs
- Desensitize coolant system
- Bearing and blade improvements
- Rotor stability

Ducts
- Low Pressure Fuel Duct helium barrier

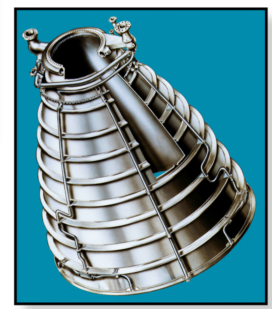


- Operational Since STS-6 (April 1983)
- Designed & Validated For Reusability
- World Class Booster Performance
- 0.9994 Demonstrated High Reliability
- Logged 231 Engine Flights
- 100% Mission Success

Block II Controller
- New type and increased memory
- Improved producibility and maintainability
- High order language for software



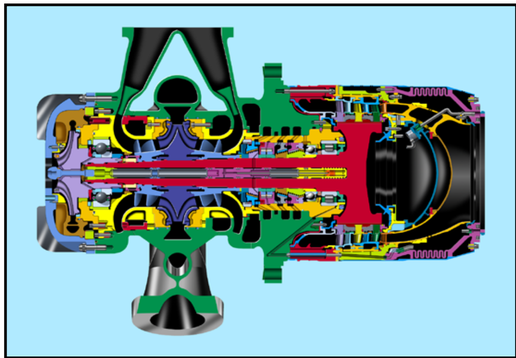
LPOTP
- Thrust Bearing lock-nut spacer



Nozzle
- Added insulation to aft manifold and drain lines

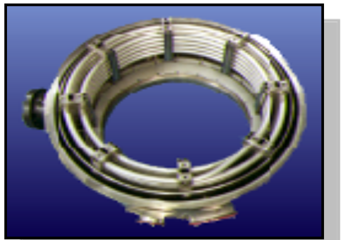
Block I SSME

First Flight — July 1995



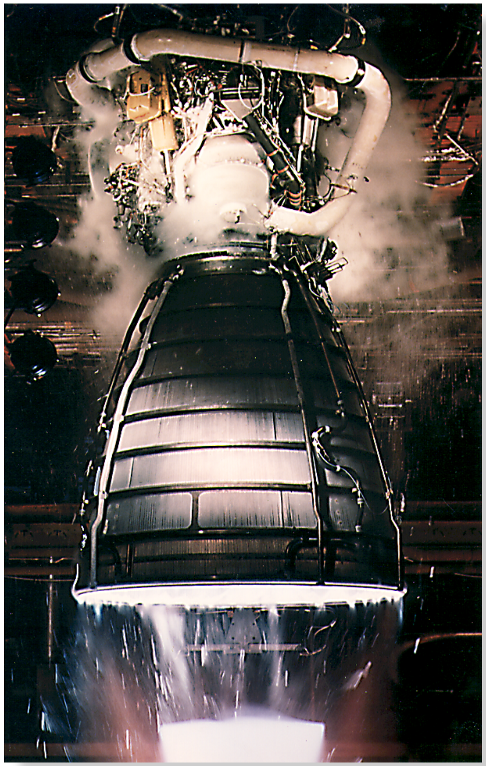
Alternate High Pressure Oxidizer Turbopump

- Precision castings
- Ceramic bearing balls
- Eliminated seal pressure redline

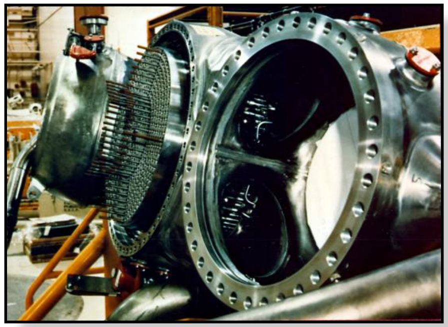


Single Tube Heat Exchanger

- Eliminated all 7 criticality 1 interpropellant welds
- FOD tolerant 25% thicker tubes
- Low maintenance

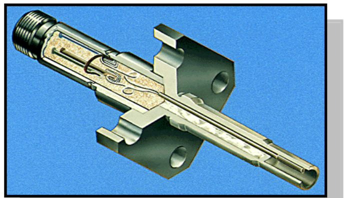


- 1st Flight STS-70 (July 1995)
- Improved Safety, Reliability & Operability



Two-Duct Powerhead

- Improved liner and injector life
- Baffleless main injector
- Thick, cut-back turning vanes
- Eliminated 74 welds
- Part count reduced by 52
- Cycle time reduced 40%



Hot Gas Temp Sensors

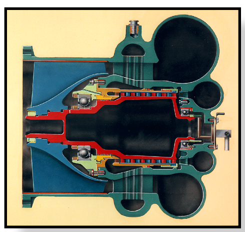
- Improved reliability

Block IIA SSME

First Flight — January 1998

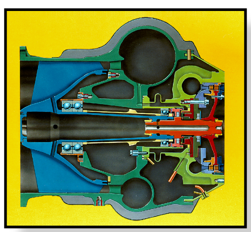
Large Throat Main Combustion Chamber

- Engine pressure & temperatures reduced up to 10%
- Increased channel wall cooling
- Simple cast manifolds, eliminated 52 welds
- Cost & cycle time reduction over 50%



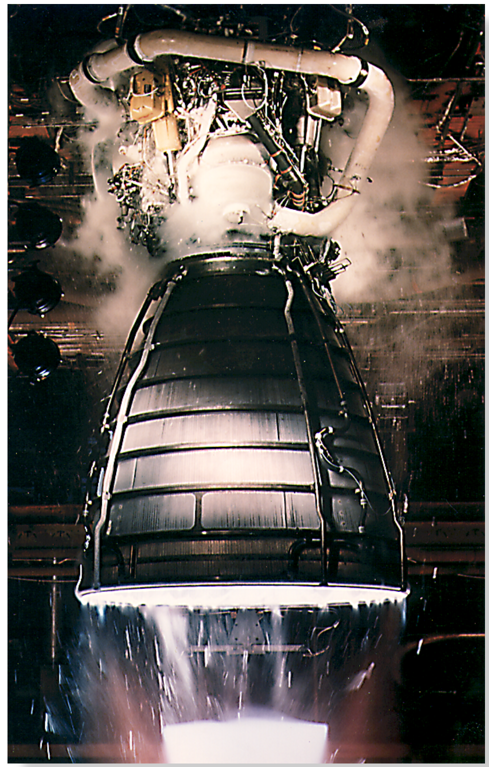
Low Pressure Oxidizer Turbopump

- Ceramic bearing balls
- Robust rotor alignment
- Increased performance inducer

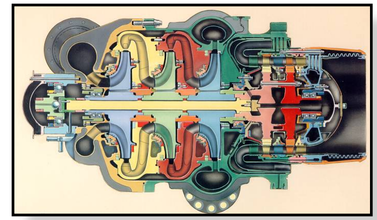


Low Pressure Fuel Turbopump

- Kevlar jacket insulation
- Reblocked nozzle
- Eliminated plug weld

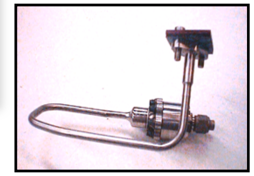


- 1st Flight STS-89 (Jan 1998)
- >2X Reliability Improvement
- Certified To 104.5% Nominal Thrust
- Improved Safety, Life & Operability
- Reduced Cost



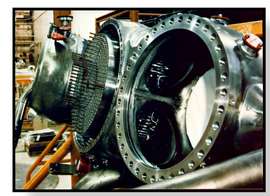
High Pressure Fuel Turbopump

- One-piece EDM turbine inlet
- Increased life turbine blades
- Improved rotor balance



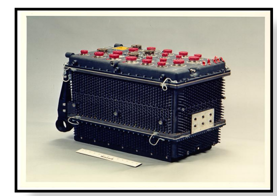
Purge Check Valves

- Added upstream Filters



Main Injector Specific Impulse Modifications

- Eliminated parasitic hydrogen losses
- 0.4 sec Isp recovery

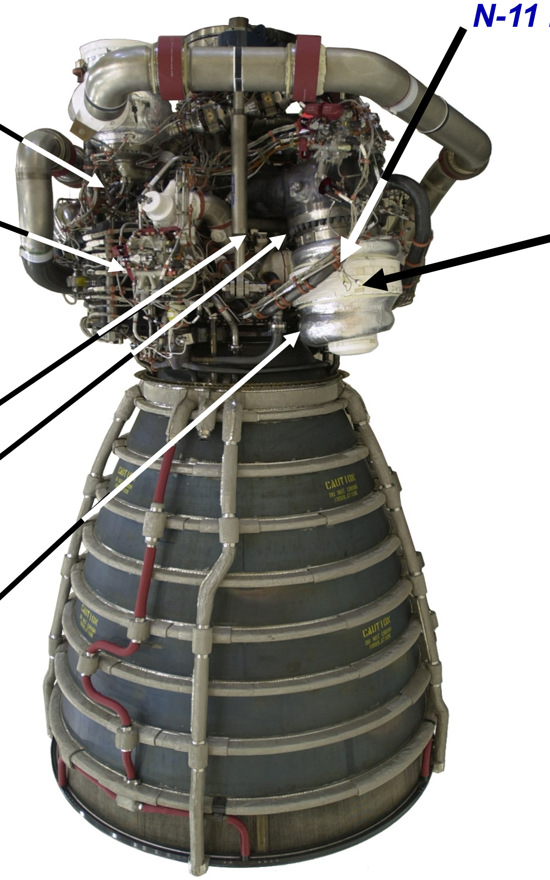


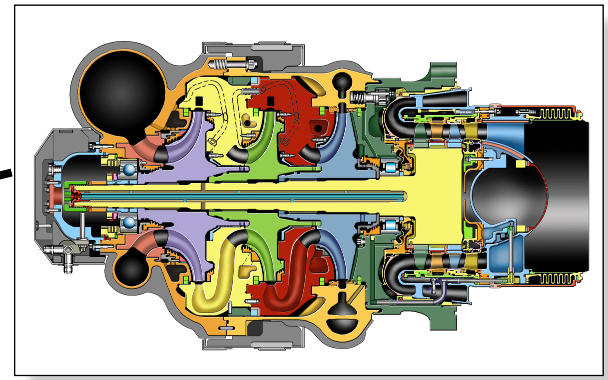
Software

- Self-calibrating actuators
- Nominal coefficients
- Improved logic
- Increased redundancy thermocouples

SSME Block II

First Flight — June 2001





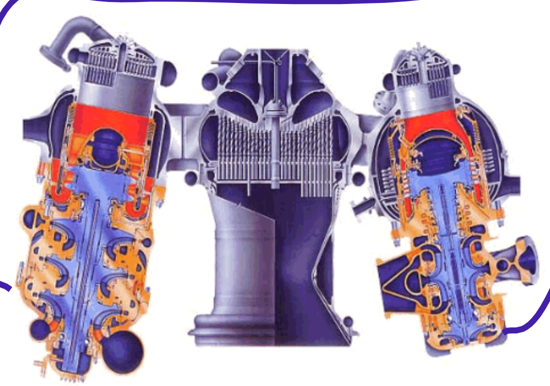
Block II High Pressure Fuel Turbopump

- Improved turbine blade fatigue capability
- Robust turbine housing
- Pump Inlet Housing burst margin increased
- Stiffer/heavier rotor
- Robust hybrid bearing systems
- Extensive use of precision investment castings
- Coolant liner redline eliminated

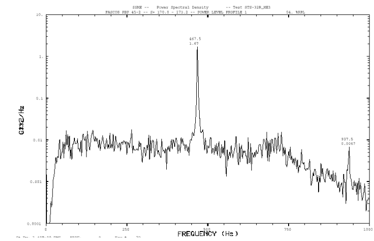
- 1st Block II flight June 2001
- Improved System Operability & Safety
- Goal of 10 Missions Between Overhauls

Advanced Health Management System
(AHMS)

HPOTP vibration and HPFTP vibration and speed signals from sensors sent to engine Controller for processing



Engine Controller filters and converts analog signals to digital data for further processing



Real-Time Spectral Analysis (Fast Fourier Transforms) Performed to detect and measure pump synchronous frequency

Sensors processed:

3 HPOTP accelerometers

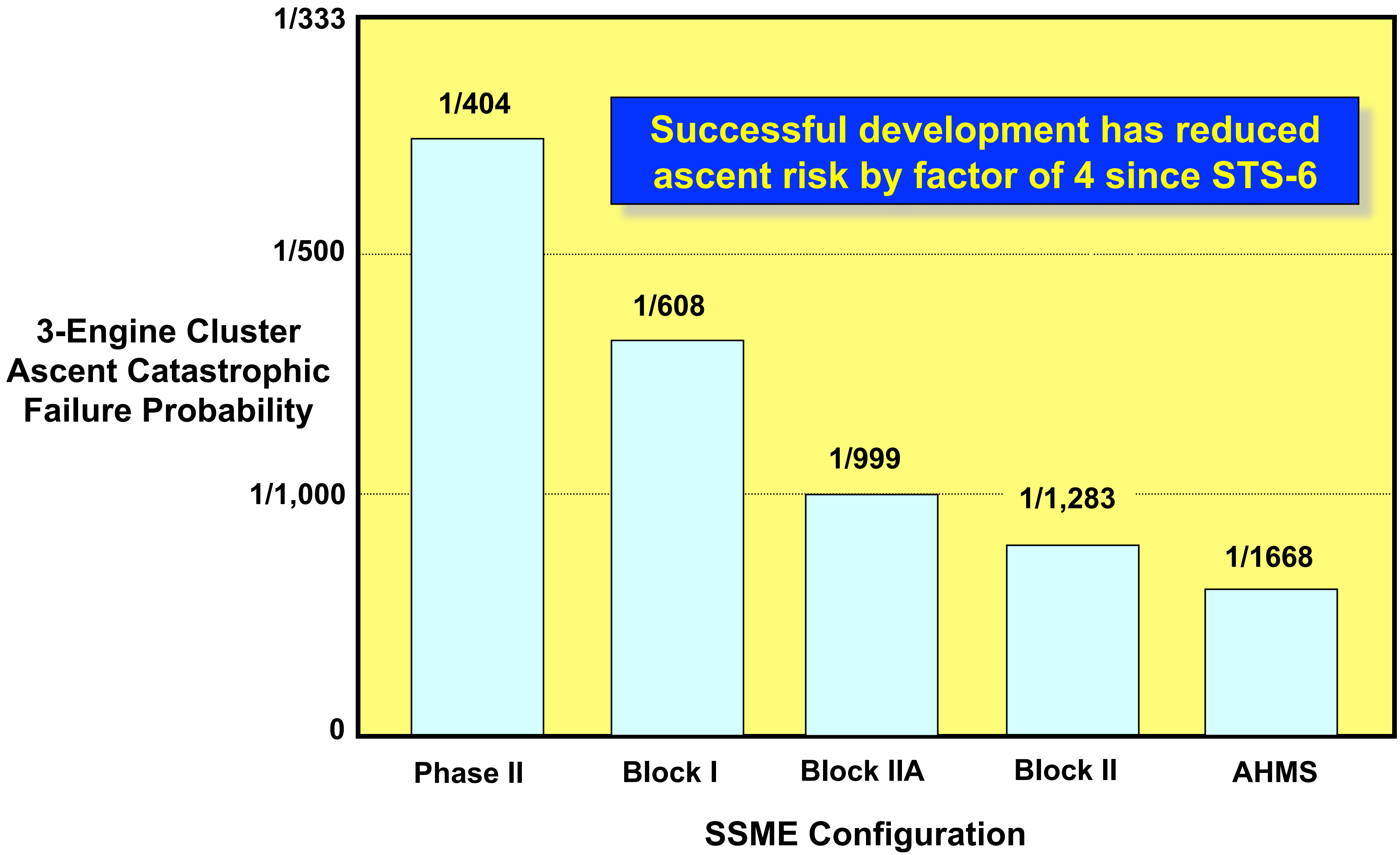
3 HPFTP accelerometers

2 HPFTP speed sensors

- **Engine Controller Response**
  - **Sensor Disqualifications**
  - **Engine Shutdown**

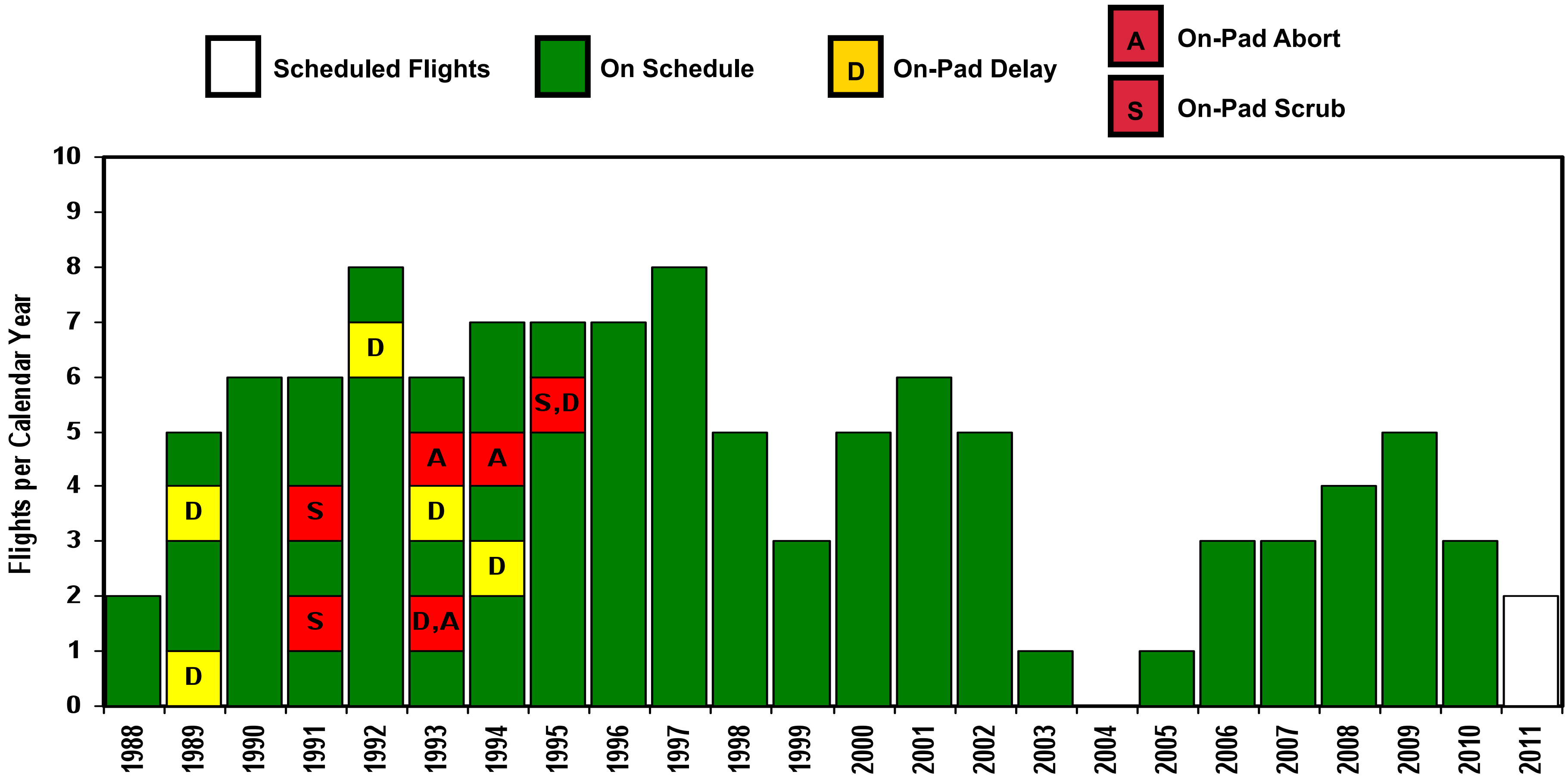
23% reduction in catastrophic SSME failure

SSME Ascent Risk Improvement



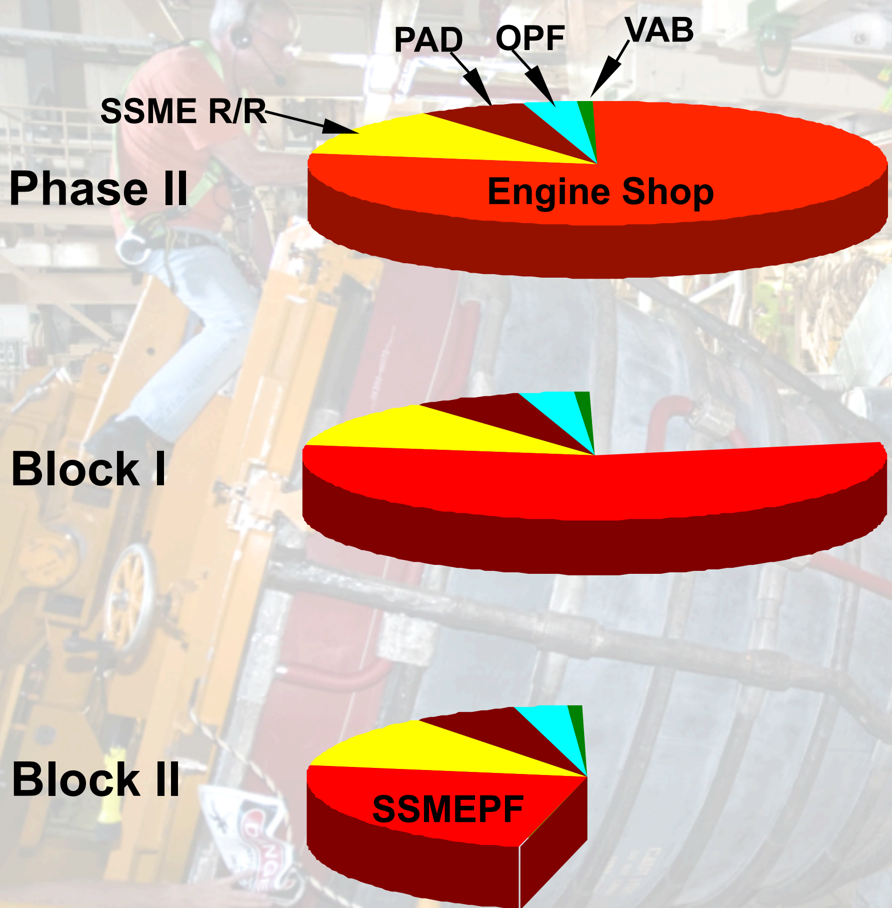
SSME Launch Performance

Goal: No Delays, Scrubs, or Aborts



60 consecutive launches since STS-73 (Oct-95) without an SSME-caused Delay, Scrub, or Abort.

SSME Maintenance Reduction



- Engine removal and shop maintenance
- Block I HPOTP
  - On-engine inspection
- 57% maintenance reduction from Phase II
  - Block II HPFTP
  - Check valve filters
  - MCC cavity pressure
  - Inspections reviewed

SSME Ground Testing

Key to Program Success

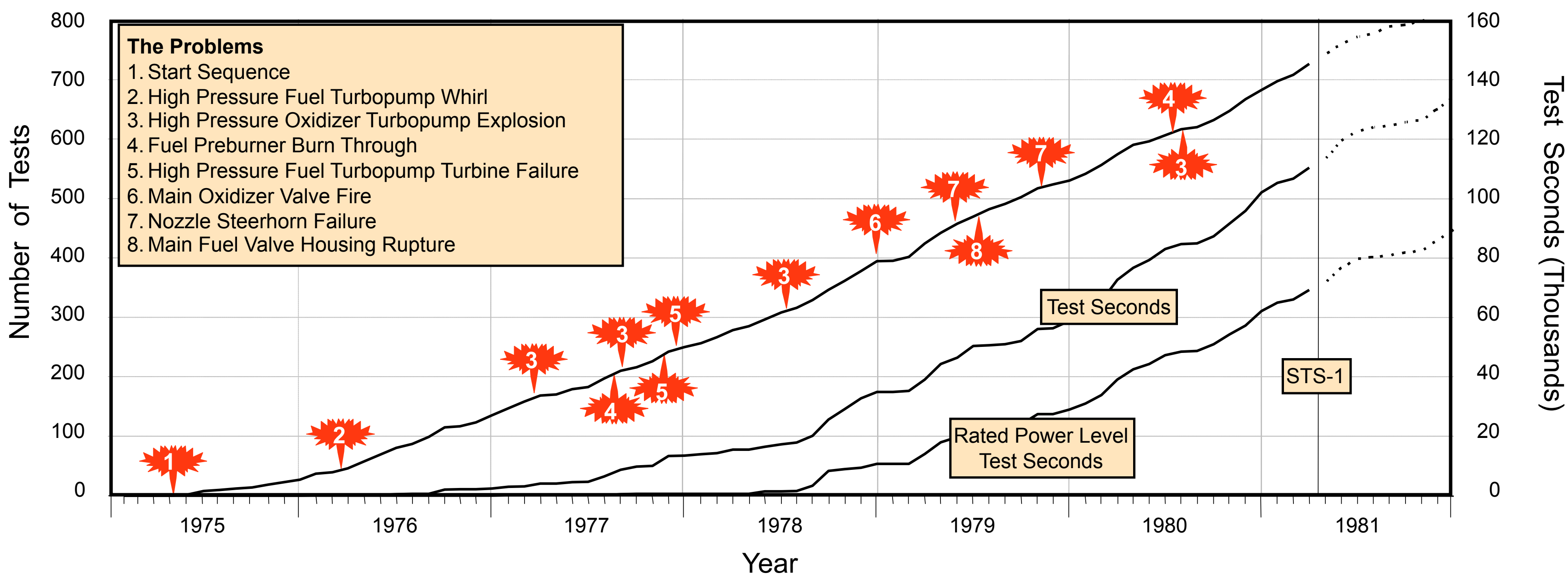
- **Testing has been used throughout the SSME program**
  - **In Development:**
    - To evaluate design integrity
  - **For Certification:**
    - To demonstrate the evolved design is ready for flight
  - **On the Production Design:**
    - To investigate and resolve anomalies
    - To verify & expand operating margins

2,730 Starts / 887,717 Seconds of SSME Testing

Development Testing

Data from Early in the Program

- Thirty-seven tests and thirteen turbopump replacements to achieve 50% Rated Power Level (RPL)
- Ninety-five tests to reach 100% RPL
- Late 1978 before first flight start sequence was finalized
- 147 design changes deemed necessary for Full Power Level (109% RPL)



Testing a Mature Design

- Determine acceptability of flight hardware
- Investigate issues / resolve anomalies
  - Issues affecting single components or engines
  - Issues affecting all units of a given component
  - In-Flight Anomalies
  - Issues requiring tests for flight rationale
  - Vehicle issues
- Verify or increase operational envelope
  - Flight Rule changes or demonstration
  - Off-nominal testing (operational extremes)
  - Malfunction testing to demonstrate redundancy
  - Overtest to demonstrate safety margins

Tests have been conducted for each one of these reasons since 2000, in spite of SSME's maturity.

Conclusions About Testing

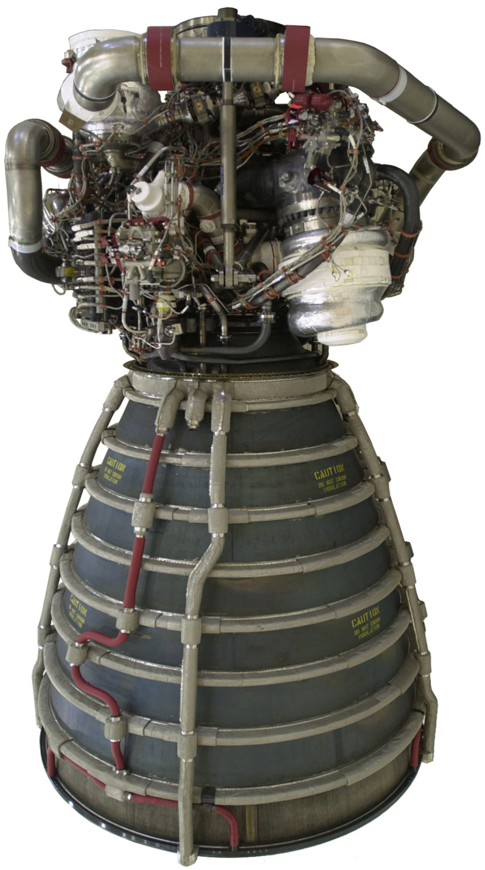
- **Testing is necessary even on a mature, well-understood, production engine**
  - **Acceptance testing sometimes reveals issues in new hardware**
  - **Some problems do not present themselves until late in production**
    - Many issues are related to the number of cycles on components
    - Small numbers of assets means not all tolerance stack-ups or environments can be explored
    - Process escapes can occur at any time

  - **Some design features (mating of certain components, for example) can only be demonstrated during a hotfire**
  - **Some issues are vehicle-driven or are related to flight operations that change outside the engine program's control**

Evolution of Analytical Tools, Materials Key to SSME Success

- Many engineering disciplines are required to achieve and maintain SSME's success
- SSME is:
  - A success because of the advances made in these disciplines
  - Responsible for the advancement in the state of the art in many engineering disciplines
- Advances in engineering disciplines include:
  - Fluid Dynamics: Extensive work conducted understanding cavitation and increasing abilities to model it
  - Structural Dynamics: Increased knowledge in finite element prediction techniques, data acquisition techniques, and structural dynamics of extremely high frequency responses
  - Rotordynamics: Better equipped to model and predict instability, synchronous responses, and external loading
  - Materials: Continuous improvements made in Materials and Processes for reliability, performance, producibility, and reduced cost

Lessons from SSME's Relentless Pursuit of Improvement



- **Test outside the comfort zone**
  - **Go beyond normal operation**
  - **Understand margins, engine characteristics**
  - **Use the lessons learned along the way**
  - **Identify problems on the ground, not in flight**
- **Drive for understanding**
  - **Define environments**
  - **Be thorough in data mining**
  - **Match models and experience**
  - **Utilize knowledge of hands-on technicians**
- **Fix problems, don't manage them**
  - **Incorporate multiple changes in blocks to reduce test costs**
  - **Listen to the "fringes" – don't be afraid of unconventional ideas**