Overview of RS-25 Adaptation Hot-Fire Test Series for SLS, Status and Lessons Learned

Naveen Vetcha
ERC Inc./Jacobs Space Exploration Group
NASA Marshall Space Flight Center
7/9/2018

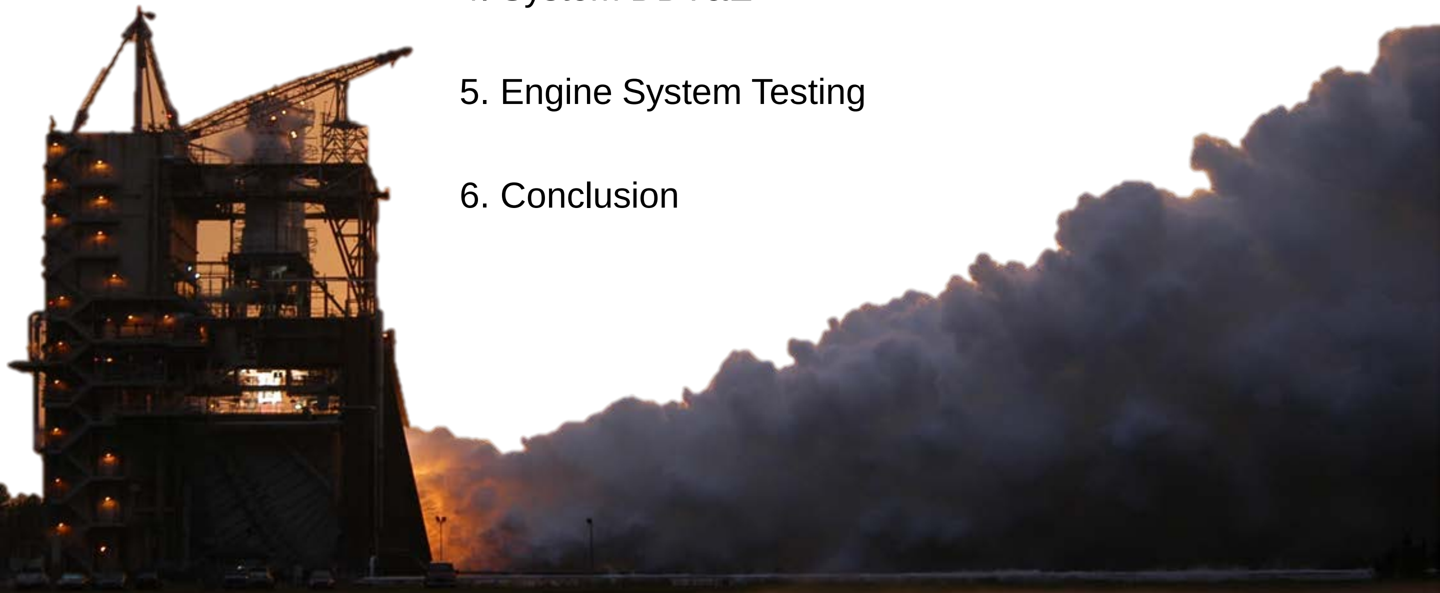
Contributions from:
Matt Strickland, Jacobs Space Exploration Group
Ken Philippart, BRC/Jacobs Space Exploration Group
Tom Giel, ERC Inc./Jacobs Space Exploration Group

JACOBS

www.jacobs.com | worldwide

Outline

1. Introduction
2. System Requirements
3. Controller Development
4. System DDT&E
5. Engine System Testing
6. Conclusion



Introduction

NASA authorization act - 2010

42 USC 18322.

SEC. 302. SPACE LAUNCH SYSTEM AS FOLLOW-ON LAUNCH VEHICLE TO THE SPACE SHUTTLE.

(a) UNITED STATES POLICY.—It is the policy of the United States that NASA develop a Space Launch System as a follow-on to the Space Shuttle that can access cis-lunar space and the regions of space beyond low-Earth orbit in order to enable the United States to participate in global efforts to access and develop this increasingly strategic region.

Minimum Capability requirements for the launch vehicle are:

- Capability to lift payloads weighing between 70 to 100 metric tons into low-Earth orbit (LEO) in preparation for transit for missions beyond LEO,
- Capability to carry an integrated upper Earth departure stage bringing the total lift capability to 130 metric tons or more,
- Capability to lift the Orion Multi-Purpose Crew Vehicle (MPCV), and
- Capability to serve as a backup system for supplying and supporting International Space Station (ISS) cargo requirements or crew delivery requirements not otherwise met by available vehicles.

Product ID: JPID-FY18-01508

Space Launch System (SLS)

CPL = Co-manifested Payload

EUS = Exploration Upper Stage

ICPS = Interim Cryogenic Propulsion Stage

LEO = Low Earth Orbit

PLF = Payload Fairing

SLS = Space Launch System

USA = Universal Stage Adapter

SLS EM-1 Launch Animation

JACOBS

Product ID: JPID-FY18-01508

Space Shuttle Main Engine (SSME)

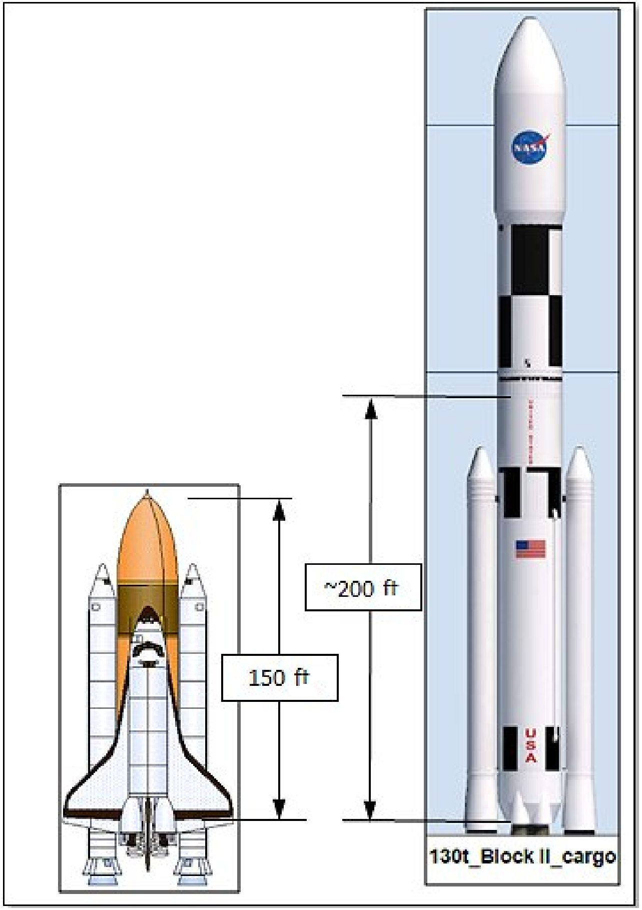
Propellants	O2/H2
Rated power level (RPL)	469,448 lb
Nominal power level (104.5% RPL)	490,847 lb
Full power level (109% RPL)	512,271 lb
Chamber pressure (109% RPL)	2,994 psia
Specific impulse at altitude	452 sec
Throttle range (% RPL)	67 to 109
Gimbal range	+/- 11°
Weight	7,748 lb
Service life	55 flights 27,000 sec
Total program hot-fire time	3,171 starts 1,095,677 sec

Image: NASA

JACOBS

Product ID: JPID-FY18-01508

SSME → RS-25 Adaptation



- Four RS-25 engines are used to power the core stage of SLS
- Initial flights will use RS-25 engines recovered from Space Shuttle program (RS-25 Adaptation program)
- Future flights will use the engines manufactured using cheaper and more affordable processes (RS-25 Restart Production)
- A hot-fire testing program was planned to test the engine performance over a range of operating conditions to demonstrate the capability to meet mission requirements
- Engine static fire testing is conducted on A1 test stand at NASA Stennis Space Center

JACOBS

System Requirements

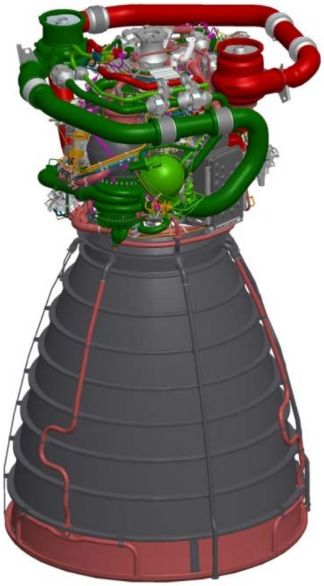
RS-25 requirements overview

Vacuum Thrust
-Rated = 470,000 lbf
-Precision = ±6000 lbf
-Closed-loop control

Minimum Vacuum Isp
451.3 s (at 109% rated thrust)

Mixture Ratio
-Nominal = 6.00
-Precision:
±1.7% (65% to 90% rated thrust)
±1% (90% to 109% rated thrust)
-Closed-loop control

Engine Gimbal = 8° circle



Engine Throttling
Steps 1% between 65% to 109% of rated thrust

Engine Mass = 8280 lbm

Engine Dimensions = 94" D X 167" L

Operational Life (Post delivery)
-6 starts, 2500 seconds (1st and 2nd SLS flight)
-3 starts, 1100 seconds (3rd and 4th SLS flight)

Engine Control system
-Electronic controller and software
-Reprogrammable

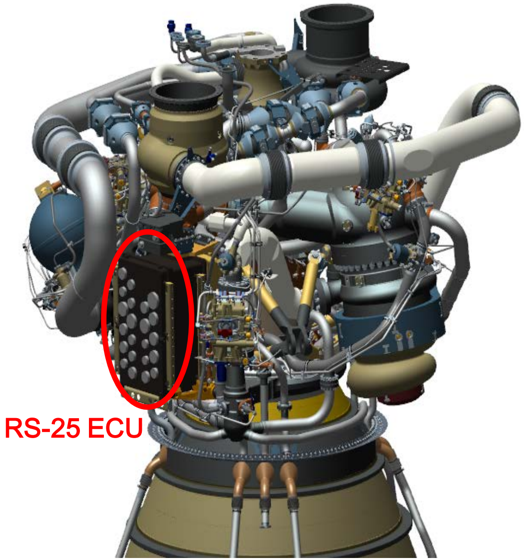
JACOBS

Product ID: JPID-FY18-01508

Controller Development

Controller Development

- In the RS-25 Engine Adaptation program, the only engine component that was upgraded was the Engine Controller (ECU)
- The Engine Control (EC) system is composed of ECU (hardware/software) and the new cabling/harness



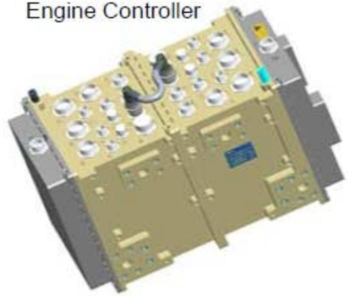
ECU Functions

- Receive and respond to commands from the vehicle.
- Provide closed-loop thrust and mixture ratio control of the engine during mainstage operation through position control of variable position propellant valves to the separate preburners.
- Manage engine state (i.e., start enable, start, mainstage, shutdown, etc.) transition and timing of effectors used during the different states. This includes the control of numerous purges and bleed flows.
- Continuously monitor engine health.
- Provide data and health status to the vehicle flight controllers.
- Provide electrical power to all engine control elements, sensors and effectors.

Controller Development

SSME
Engine Controller

RS-25
Engine Controller



J-2X
Engine Controller

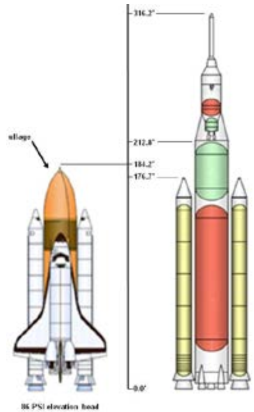
Test Acceptance Path	Test Purpose
Printed Wiring Assembly (PWA) Card Level Testing →	Screen Electronic, Electrical, and Electromagnetic (EEE) integrity and workmanship issues at board level
⇩ Acceptance Test Procedure →	Screen EEE integrity, workmanship, and board integration issues at assembly level
⇩ Post engine installation checkouts →	EC integration of Engine Hardware and Flight Software
⇩ Hot Fire Green Run →	Hot Fire Environment – EC Integration of Engine Hardware and Flight Software
⇩ If needed	

JACOBS

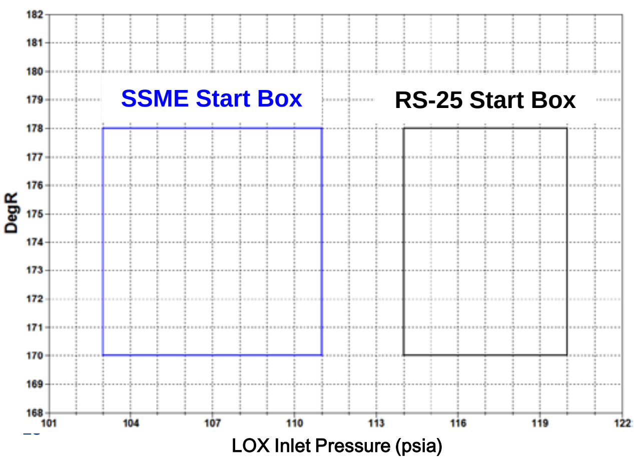
Product ID: JPID-FY18-01508

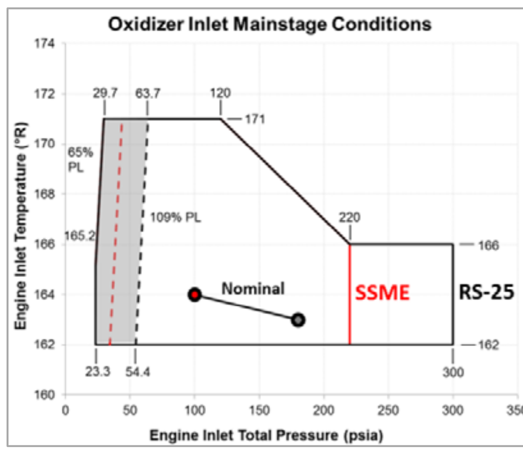
System DDT&E

RS-25 Changes: LOX Inlet Pressure



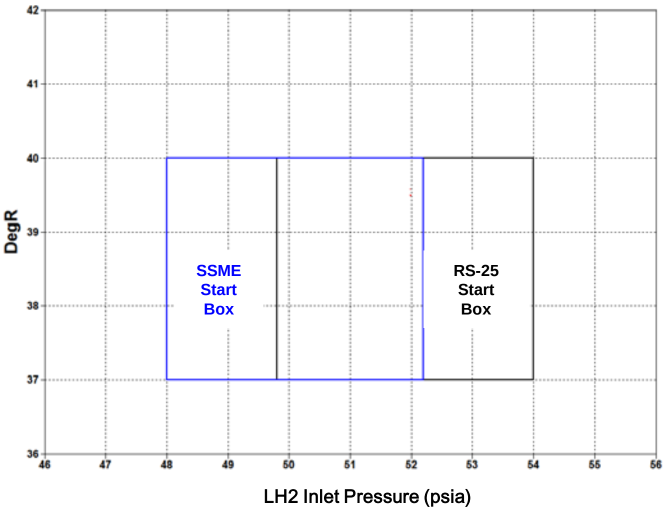
- Increased tank height
- Increased acceleration
- Changes in ullage schedule
- New start box
- New main stage envelope
- Beyond SSME start experience

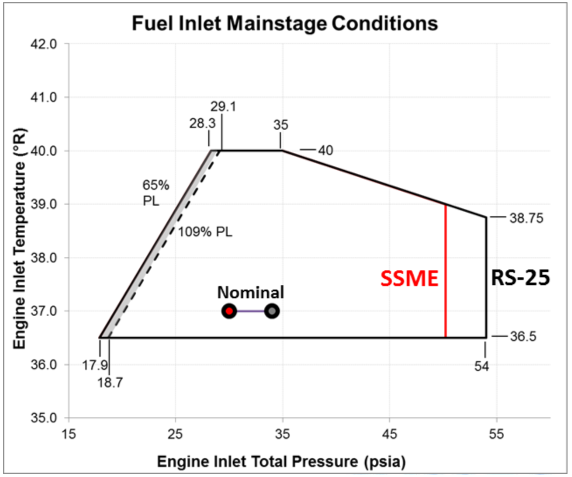




RS-25 Changes: Fuel Inlet Pressure

- Increased tank height
- Changes in ullage schedule
- Fuel tank pressurized to maintain gauge pressure
- Modified start box
- Main stage exposed to higher inlet pressure for extended period
- Beyond SSME start experience

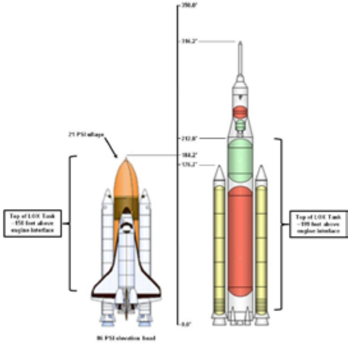


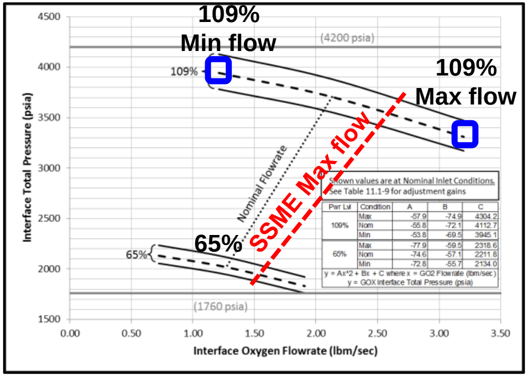


Product ID: JPID-FY18-01508

RS-25 Changes: GOX Tank Pressurization

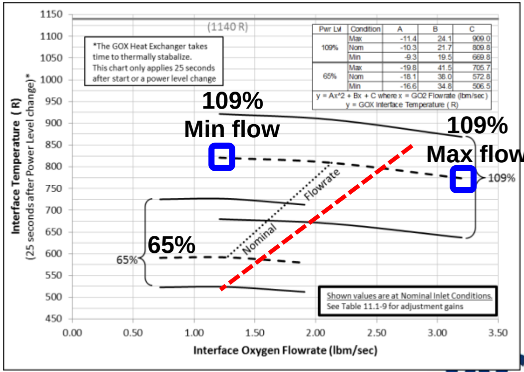
- Increased tank pressurization flow (repress) to maintain ullage pressure
- Valve material sensitive to GOX temperature
- Additional requirements as a function of power level and flowrate
  - Interface Pressure
  - Interface Temperature
- Test Max and Min repress flows at various power levels for a set duration during the mainstage and also during the start and shut down.





Pwr Lvl	Condition	A	B	C
109%	Max	-57.9	-74.9	4304.2
	Nom	-55.8	-72.1	4112.7
	Min	-53.8	-69.5	3945.1
65%	Max	-77.9	-59.5	2318.6
	Nom	-74.6	-57.1	2211.8
	Min	-72.8	-55.7	2134.0

y = Ax^2 + Bx + C where x = GO2 Flowrate (lbm/sec)
y = GOX Interface Total Pressure (psia)



Pwr Lvl	Condition	A	B	C
109%	Max	-11.4	24.1	909.0
	Nom	-10.3	21.7	809.8
	Min	-9.3	19.5	669.8
65%	Max	-19.8	41.5	705.7
	Nom	-18.1	38.0	572.8
	Min	-16.6	34.8	506.5

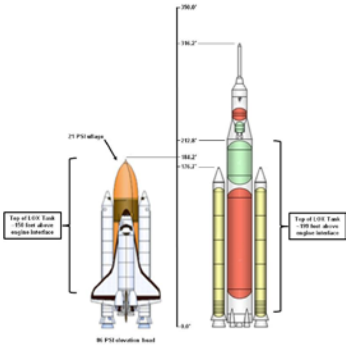
y = Ax^2 + Bx + C where x = GO2 Flowrate (lbm/sec)
y = GOX Interface Temperature (R)

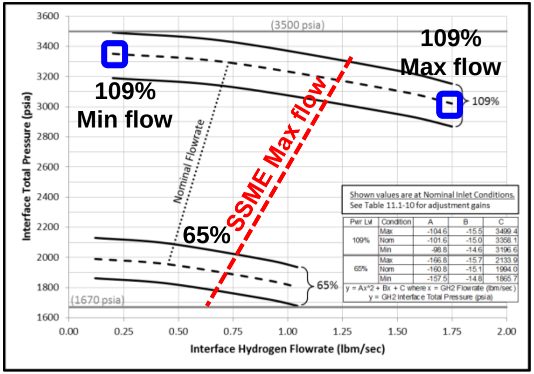
JACOBS

Product ID: JPID-FY18-01508

RS-25 Changes: Fuel Tank Pressurization

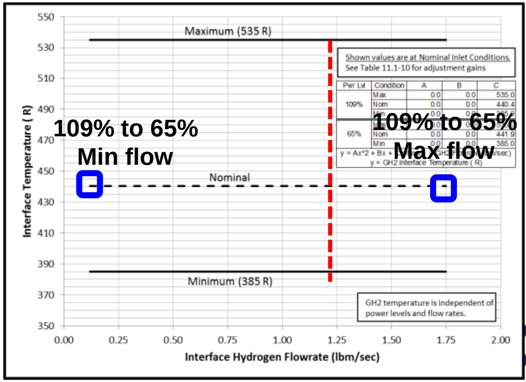
- Increased tank pressurization flow (repress) to maintain ullage pressure
- Core stage auxiliary power unit (CAPU) now driven by GH2 tap
  - Will power all hydraulics including thrust vector & valves
- Additional requirements as a function of power level and flowrate
  - Interface Pressure
  - Interface Temperature
- Test Max and Min repress flows at various power levels for a set duration during the mainstage and also during the start and shut down.





Pwr Lvl	Condition	A	B	C
109%	Max	-104.6	-15.5	3499.4
	Nom	-101.6	-15.0	3358.1
	Min	-98.8	-14.6	3196.6
65%	Max	-166.8	-15.7	2133.9
	Nom	-160.8	-15.1	1994.0
	Min	-157.5	-14.8	1865.7

y = Ax^2 + Bx + C where x = GH2 Flowrate (lbm/sec)
y = GH2 Interface Total Pressure (psia)

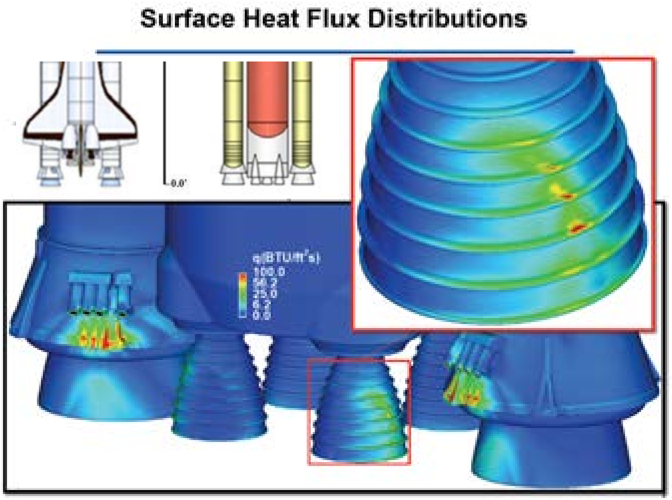


Pwr Lvl	Condition	A	B	C
109%	Max	0.0	0.0	535.0
	Nom	0.0	0.0	440.4
	Min	0.0	[illegible]	[illegible]
65%	Max	[illegible]	[illegible]	[illegible]
	Nom	0.0	0.0	441.9
	Min	0.0	0.0	385.0

y = GH2 Interface Temperature (R)

RS-25 Changes: Nozzle Heating

- Engine is now close to in-plane with Solid Rocket Boosters (SRBs) resulting in increased convective and radiant heating
- Additional heating due to plume recirculation and radiant heat
- GH2 dumped overboard is ignited to prevent free hydrogen buildup which will cause some more heating
- Test strip of nozzle ablative (Adhesion test)



Product ID: JPID-FY18-01508

RS-25 Adaptation Testing - Summary

- **Vehicle Changes & Engine Effects**
  - Thermal conditioning
  - Higher power level
  - Higher inlet pressures
  - Higher tank pressurization flows
  - Helium ingestion
  - Nozzle Heating
- **Controller Changes & Engine System**
  - Mixture ratio control
  - Throttle control
- **Adaptation Plan**
  - Green Run
  - Life Extension
  - DVR Verification Requirements
  - Development Objectives

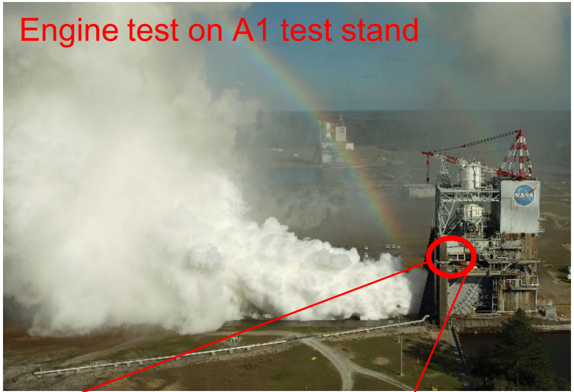
JACOBS

Product ID: JPID-FY18-01508

Engine System Testing

RS-25 Adaptation Test: A-1 Test Stand

- The A-1 test stand located in NASA's Stennis Space Center was chosen to conduct all the tests
- Capabilities
  - Maximum test article size 33 ft in diameter
  - 1.1 M-lb (vertical)
  - 0.7 M-lb (horizontal)
  - Supplied with cryogenic fluids
- LOX and LH_2 are supplied from cryogenic barges
- Propellant feed lines and other run lines were changed as per RS-25 requirements
- Thrust Measurement System (TMS) was updated
- LOX runline piping spools were electropolished ro remove any metal particles



RS-25 Engine mounted on the stand

JACOBS

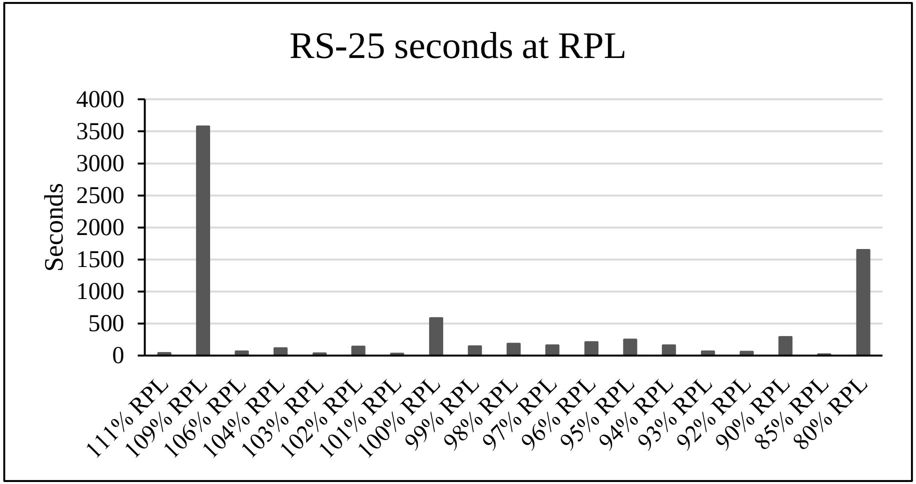
Product ID: JPID-FY18-01508

RS-25 Adaptation Test

- A total of 18 hot-fire tests were performed as part of the Adaptation test series between Jan 2015 – Jan 2018.

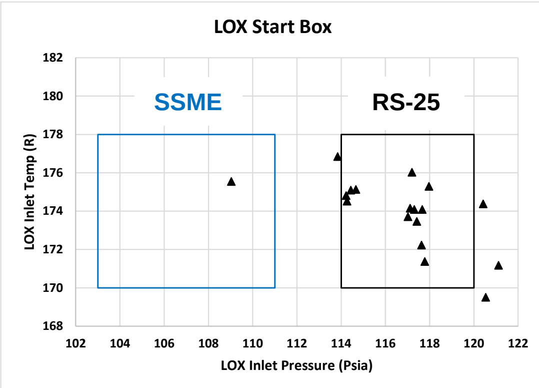
- Two of the tests were engine acceptance tests where flight engines were tested and tagged.

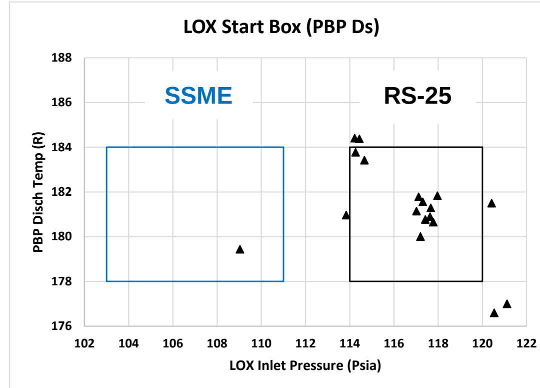
- Sixteen tests were performed on two development engines



Product ID: JPID-FY18-01508

RS-25 Adaptation Test

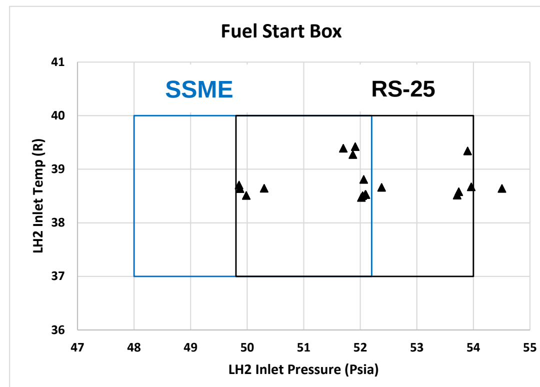




▲ RS-25 adaptation tests

- The first test in the series was a baseline of the engine performance at SSME start propellant inlet conditions

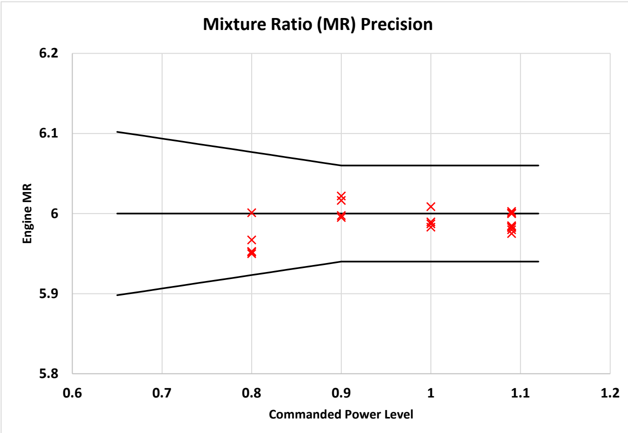
- Some tests were conducted at the corners of the start boxes to test the system to component hardware operating limits

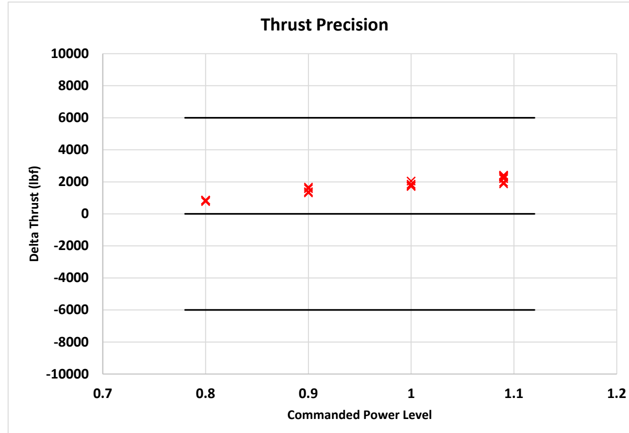


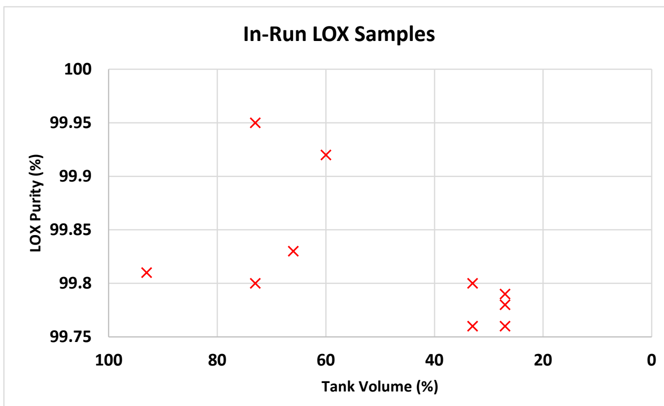
JACOBS

Product ID: JPID-FY18-01508

RS-25 Adaptation Test





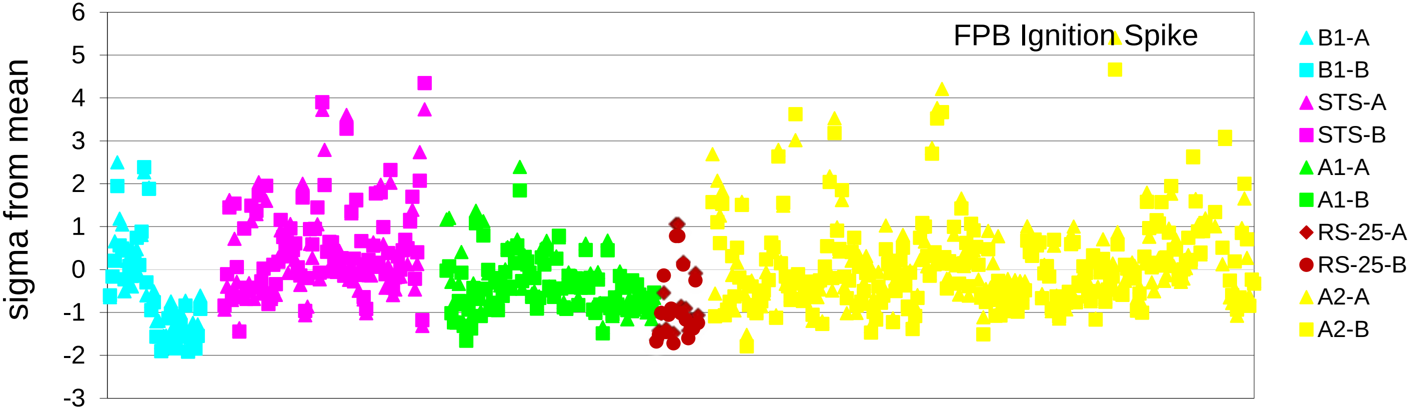


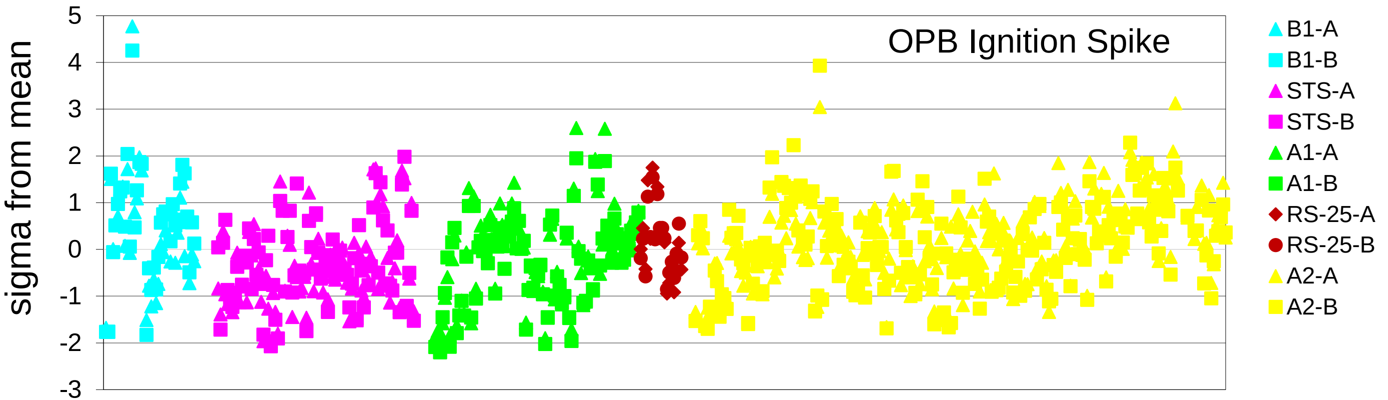
x RS-25 adaptation tests

JACOBS

Product ID: JPID-FY18-01508

RS-25 Adaptation Test





Summary

- RS-25 adaptation test series successfully demonstrated that the flight controllers meet the mission requirements

- All the other RS-25 requirements have been successfully tested

- Lessons learned during the test program will help the future tests in the RS-25 restart production program

Acknowledgements

The authors wish to thank the following those who made valuable suggestions and helped in completion of this package and the manuscript: Richard Ballard (XP20), Michael Nelson (ER22), John Butas (ER21), and Tim Duquette (ER21).