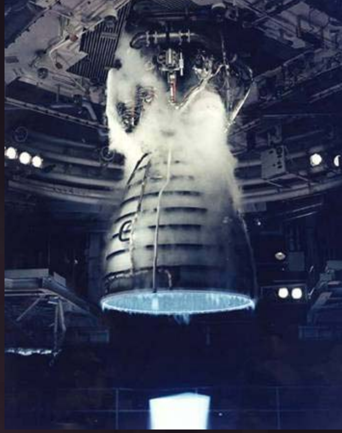
# 41st Joint Propulsion Conference and Exhibit



Tuscon, Arizona

July 13-14, 2005

**Sub-Topic:**
**Liquid Rocket Engine Testing**

***AIAA Short Course on Liquid Rocket Engines***


Dr. Shamim Rahman

NASA John C. Stennis Space Center, MS

# Section Outline



- Objectives and Motivation for Testing
  - Technology, RDT&E, Evolutionary
- Representative LRE Test Campaigns
  - Apollo, Shuttle, ELV Propulsion
- Overview of Test Facilities for Liquid Rocket Engines
  - Boost, Upper Stage (Sea-level and Altitude)
- Statistics (historical) of Liquid Rocket Engine Testing
  - LOX/LH, LOX/RP, Other development
- Test Project Enablers: Engineering Tools, Operations, Processes, Infrastructure

*Continued on Next Page ...*

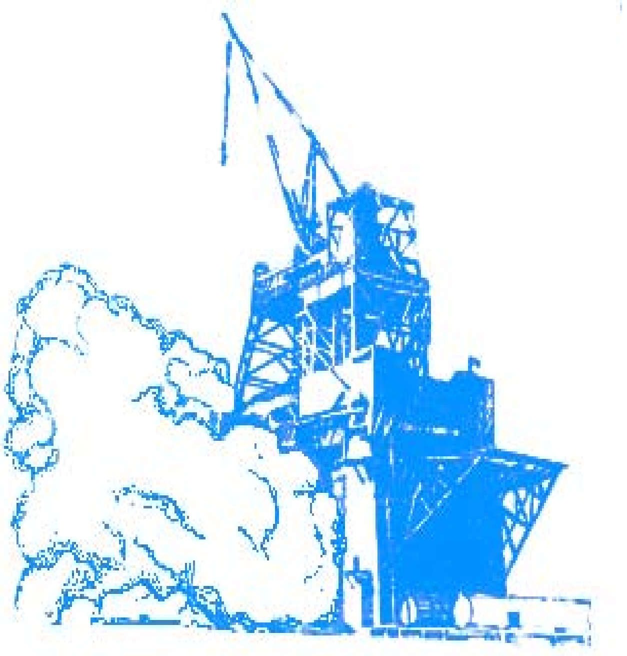
# Section Outline (cont.)



*Continued from Previous Page …*

- Non-NASA Test Capability
  - National Rocket Propulsion Test Alliance
  - Commercial Test Sites
  - University Test Sites
- Summary
- BACKUP MATERIAL

# *OBJECTIVES & MOTIVATION FOR LRE TESTING*



# Key Terms

- ***Development*** testing is required to achieve design maturity, demonstrate capability, and to reduce risk to the qualification program. Development tests are conducted, as required, to:
  - Validate new design concepts or the application of proven concepts and techniques to a new configuration,
  - Assist in the evolution of designs from the conceptual phase to the operational phase,
  - Validate design changes,
  - Reduce the risk involved in committing designs to the fabrication of qualification and flight hardware,
  - Develop and validate qualification and acceptance test procedures,
  - Investigate problems or concerns that arise after successful qualification,

  An objective of development testing is to identify problems early in their design evolution so that any required corrective actions can be taken prior to starting formal qualification testing.

- ***Qualification*** tests (also commonly known as *certification* tests) are conducted to:
  - Demonstrate that the design, manufacturing process, and acceptance program produce hardware/software that meet specification requirements with adequate margin to accommodate multiple rework and test cycles,
  - In addition, the qualification tests should validate the planned acceptance program, including test techniques, procedures, equipment, instrumentation, and software.

  Generally qualification follows completion of the development test program.

- ***Acceptance*** tests are conducted to demonstrate the acceptability of each deliverable item to meet performance specification and demonstrate error-free workmanship in manufacturing. Acceptance testing is intended to:
  - Stress screen items to precipitate incipient failures due to latent defects in parts, processes, materials, and workmanship,
  - Component acceptance testing at the bench level serves to reduce risk for engine acceptance testing, but it may not simulate the engine environments adequately.

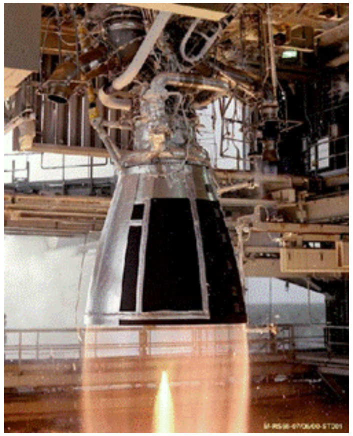
  Many components require engine hot fire to adequately reduce flight risk. (An engine LRU is a component that may be removed and replaced by a new unit, without requiring reacceptance test firing of the engine with the new unit. If the unit being replaced was included in an engine acceptance test firing as part of its acceptance test, then the replacement unit either should be subjected to such a test on an engine, or should undergo equivalent unit-level acceptance testing).

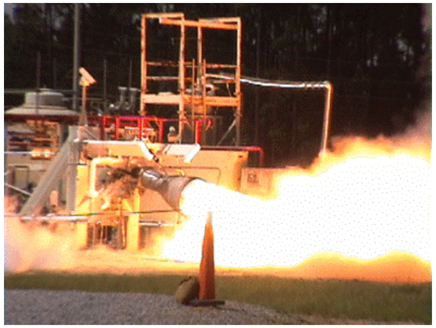
# Objectives of Liquid Propulsion Testing



*Some examples of each are listed*

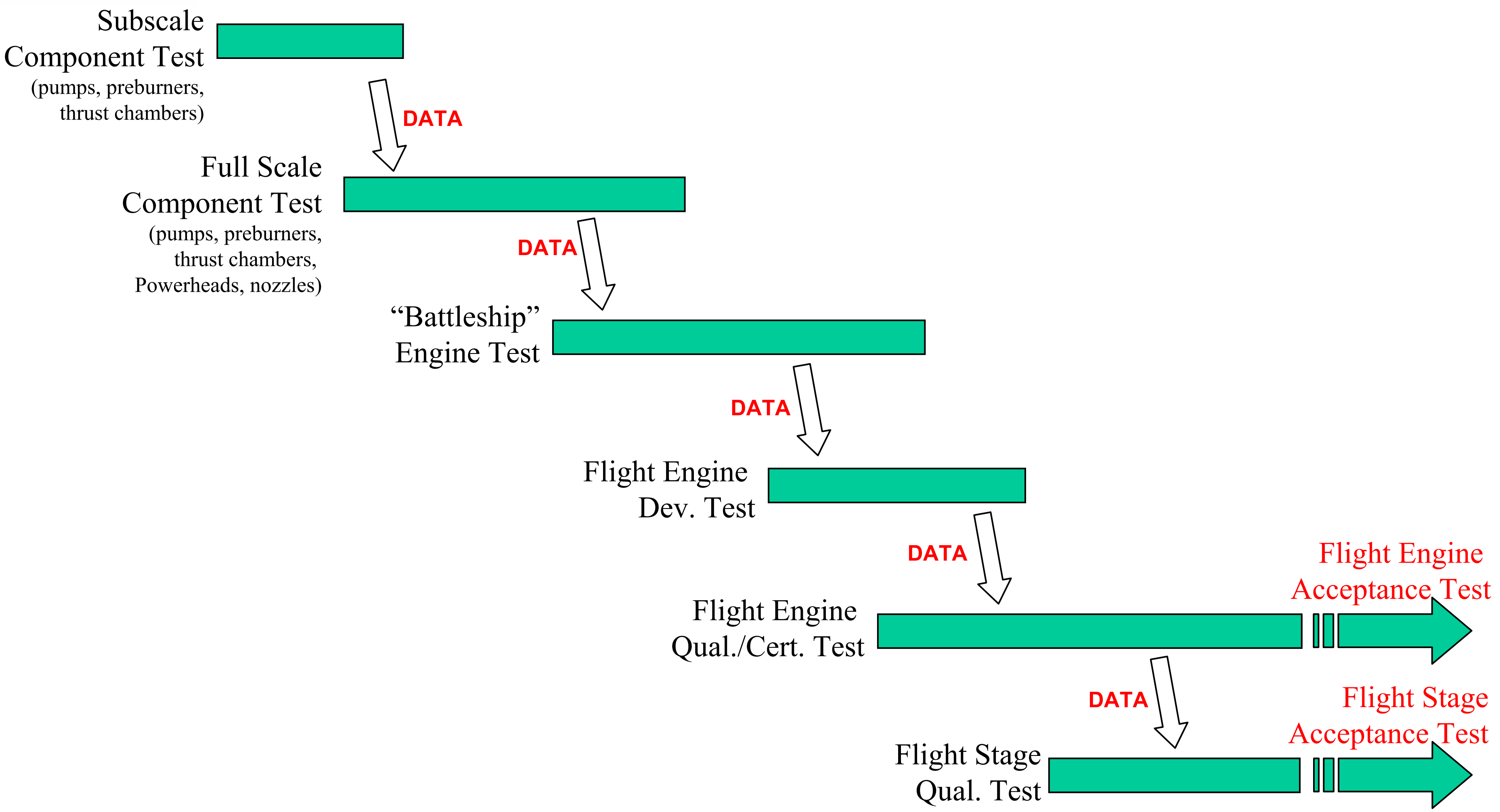
- Component Development
  - Combustion devices (turbomachinery, chambers, ignitors), e.g. RS-84
  - Advanced technology demonstrators
- Prototype Engine Development
  - J-2*S*, XRS-2200, RL-60, MB-60
- Flight Engine Qualification, Certification
  - J-2, F-1, SSME, RS-68, RL-10, etc.
- Flight Engine Acceptance
  - RS-68, SSME
- Major Engine Upgrades
  - SSME Block Upgrades
- Re-development and Re-Use Potential
  - LR-89 thrust chamber





# Typical Sequence of Testing



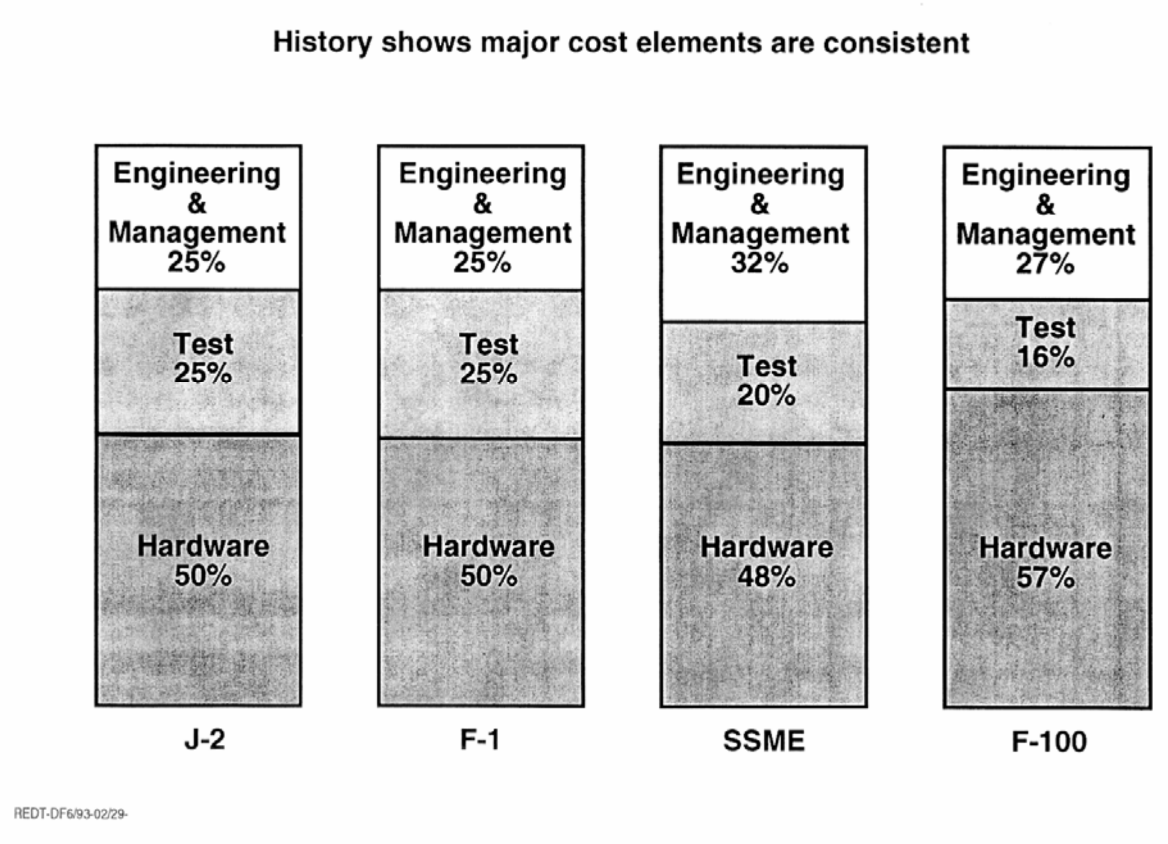



- An On-going process of risk reduction (components, engines, stages)

# Testing Cost / Total Cost for Propulsion



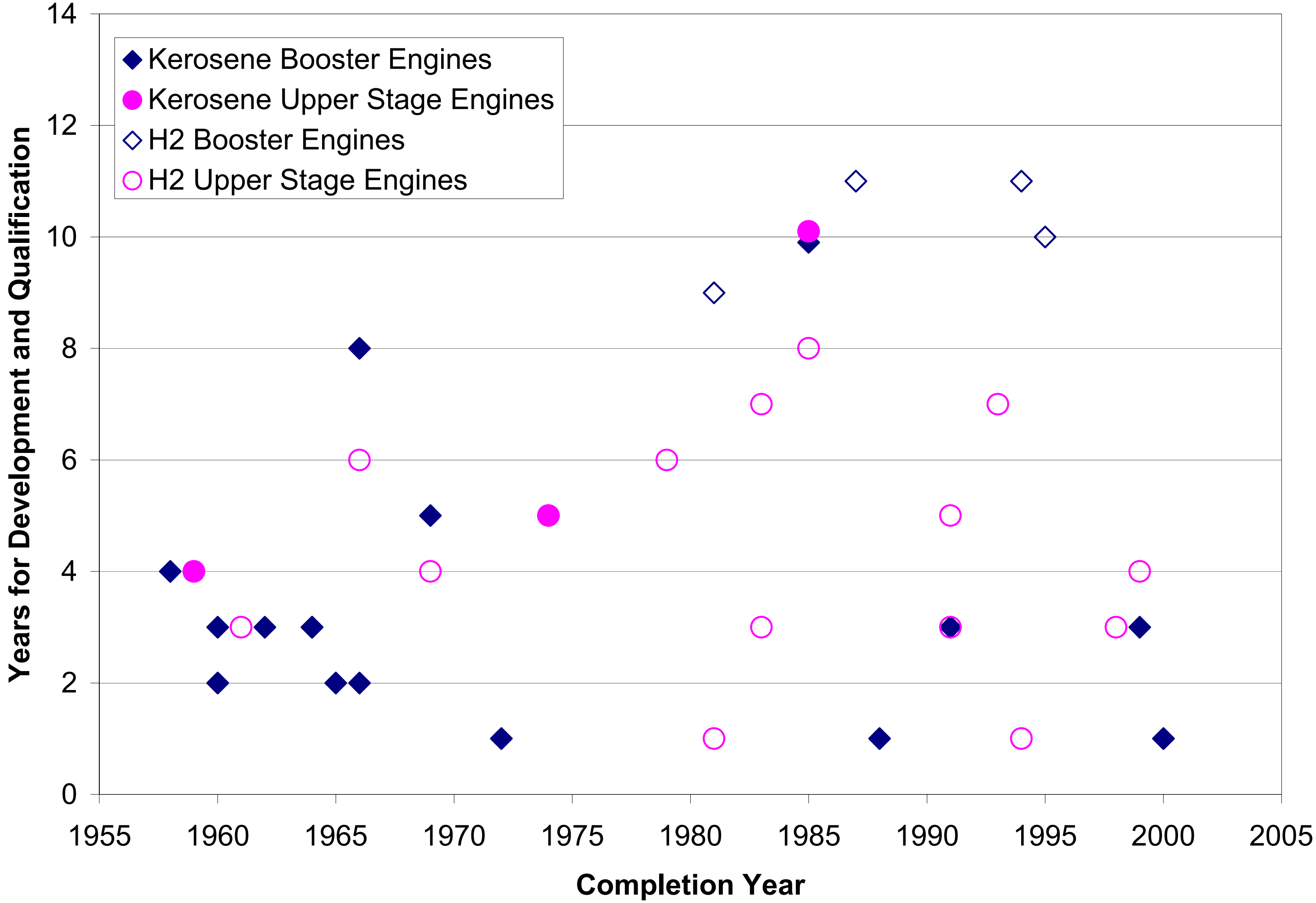
## Historical Full Scale Development Cost Distribution




George, D.; "Chemical Propulsion: How To Make It Low Cost," presented at Highly Reusable Space Transportation Meeting, 25-27 July 1995.

# Survey of LOX/RP and LOX/LH Engine Development Programs

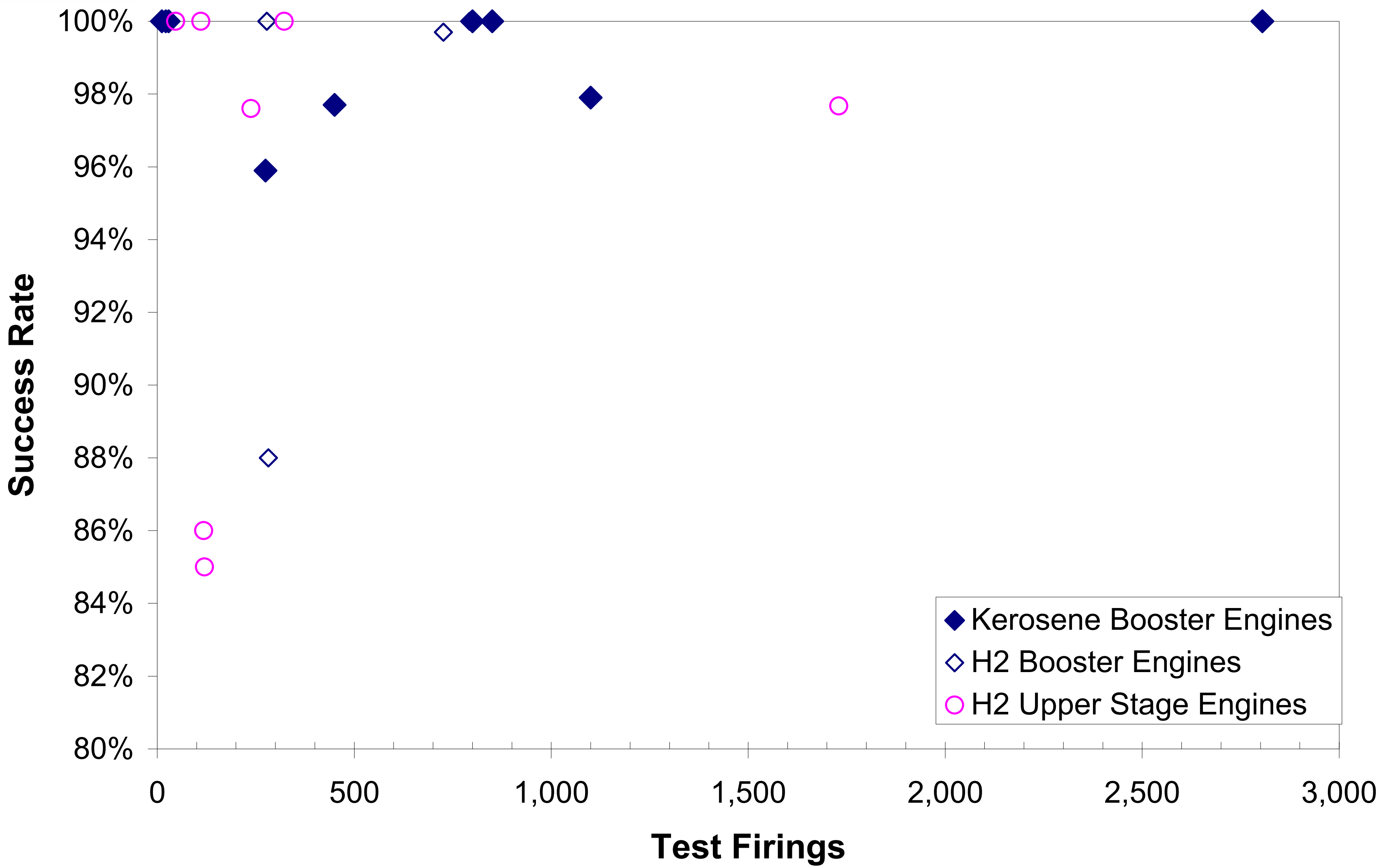





- Emdee, J., “A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines,” AIAA Paper No. 2001-0749.
- Emdee, J., “A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines,” AIAA Paper No. 2001-3985.

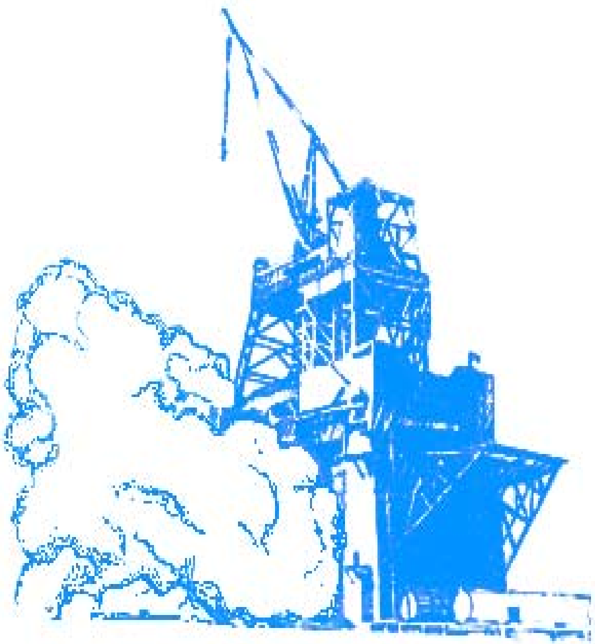
# Effect on Engine Flight Success Rate






- Emdee, J., "A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines," AIAA Paper No. 2001-0749.
- Emdee, J., "A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines," AIAA Paper No. 2001-3985.

# REPRESENTATIVE TEST CAMPAIGNS

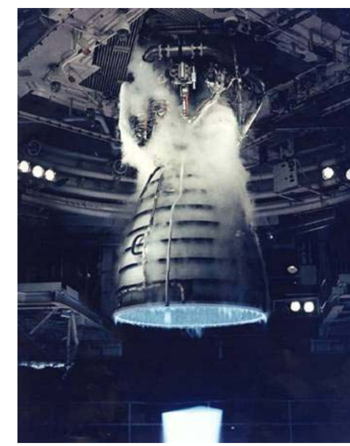


# Test Facility Challenges – *Components, Engines, Stages*



- Stage/Vehicle Testing
  - Complex
    - Self Contained
    - Transfer Systems
- Engine Testing
  - More Complexity
    - Engine Self Contained
    - Propellant Systems on Stand
    - Transfer Systems
- Component Testing
  - More Complexity
    - Facility Emulates Engine Parameters
    - High Pressures
    - High Flowrates
    - Extremely Fast Controls


Space Shuttle Vehicle (External Tank)



Space Shuttle Main Engine

Turbopump Component

# A Survey of Test Engine Test Campaigns



| | SSME (Boost) | F-1 (Boost) | RS-68 (Boost) | J-2 (U/S) | RL-10A-1 (U/S) | LMDE (Lander) |
|---|---|---|---|---|---|---|
| Thrust | 500 Klbf | 1.5 Mlbf | 700 Klbf | 250 Klbf | 15 Klbf | 10 Klbf |
| Hot-Fire Test Seconds Prior to First Flight | 110,000 s | 250,000 s | **11,000 s (i/w) | 120,000 s | 71,000 s | 149,000 s |
| Hot-Fire Test Seconds After First Flight | ~750,000 s* (& counting) | 30,000 s | 6,810 s | in-work (i/w) | Upgraded to RL-10A-3 | N/A |
| Hot-Fire Tests Prior to First Flight | 726 | 2805 | 188 | 1730 | 707 | 2809 |
| Years of Devt. | 9 | 8 | 5 - 6 | 6 | 3 | 5 |
| Missions Flown | 113 | ~15 | 3 | ~15 | i/w | 6 (Apollo 11,12,14-17) |
| Vehicle | Shuttle | Saturn V | Delta IV | Saturn V | Various | Saturn V |

*SSME Flight Seconds (~150,000 s) not counted
**RS-68 Pre-flight Seconds (in-work): ~19500 s total (~11000 s at SSC)

For many of the above:
testing was performed at a variety of locations


- Emdee, J., "A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines," AIAA Paper No. 2001-0749.
- Emdee, J., "A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines," AIAA Paper No. 2001-3985.
- Elverum, G. et al., "The Descent Engine for the Lunar Module," AIAA Paper No. 67-521.

# Testing to Enhance Reliability (LOX/LH)



## Booster Engines

| Designation | Time from Program Start to Qualification | Engine Life (firings / secs) | Burn Time (secs) | Feasibility | | | Development including stage firings | | | Qualification including stage firings | | | Total Development and Qualification including stage firings | | | Flight Success Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Engines | Firings | Seconds | Engines | Firings | Seconds | Engines | Firings | Seconds | Engines | Firings | Seconds | |
| LE-7 | 11 years ('83–'94) | - / 1720 | 350 | 2 | - | - | 9 | - | - | 5 | - | - | 14 | 282 | 15,639 | 88.0% |
| RD-0120 | 11 years ('76-'87) | 4 / 2000 | 460 | - | - | - | - | - | - | 3 | - | - | 90 | 793 | 163,000 | 100.0% |
| SSME† | 9 years ('72-'81) | 55 / 27,000 | 520 | 0 | 0 | 0 | 16+ | 627 | 77,135 | 4+ | 99 | 33,118 | 20+ | 726 | 110,253 | 99.7% |
| Vulcain | 10 years ('85-'95) | 20 / 6000 | 575 | 0 | 0 | 0 | 12+ | - | - | 2 | - | - | 14+ | 278 | 87,000 | 100.0% |

† SSME includes production up to 1st flight

## Upper Stage Engines

| Designation | Time from Program Start to Qualification | Engine Life (firings / secs) | Burn Time (secs) | Feasibility | | | Development including stage firings | | | Qualification including stage firings | | | Total Development and Qualification including stage firings | | | Flight Success Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Engines | Firings | Seconds | Engines | Firings | Seconds | Engines | Firings | Seconds | Engines | Firings | Seconds | |
| HM7A | 6 yrs ('73-'79) | - | 570 | - | - | - | - | - | - | - | - | - | 11 | - | 25,000 | 90.0% |
| HM7B | 3 yrs ('80-'83) | - | 745 | - | - | - | - | - | - | - | - | - | 10 | - | - | 96.6% |
| J-2 | 6 yrs ('60-'66) | 30 / 3750 | 450 | - | - | - | 36 | 1,700 | 116,000 | 2 | 30 | 3,807 | 38 | 1,730 | 120,000 | 97.7% |
| J-2S* | 4 yrs ('65-'69) | 30 / 3750 | 450 | 1 | - | 10,756 | 6 | 273 | 30,858 | Development only | | | Development only | | | N/A |
| LE-5 | 8 yrs ('77-'85) | - | 600 | 3 | 54 | 2,587 | 5 | 188 | 13,414 | 3 | 134 | 14,292 | 8 | 322 | 27,706 | 100.0% |
| LE-5A | 5 yrs ('86-'91) | 14 / 2920 | 535 | 0 | 0 | 0 | 2 | 66 | 6,918 | 2 | 52 | 9,238 | 4 | 118 | 16,156 | 86.0% |
| LE-5B | 4 yrs ('95-'99) | 16 / 2236 | 534 | 1 | 8 | 237 | 1 | 23 | 1,077 | 4 | 79 | 11,963 | 5 | 102 | 13,040 | N/A |
| RL10A-1 | 3 yrs ('58-'61) | - | 380 | - | - | - | >230 | - | - | - | - | - | >230 | 707 | 71,036 | N/A |
| RL10A-3-3A | 1 yr ('80-'81) | 23 / 5800 | 600 | 0 | 0 | 0 | 4+ | 214 | 18,881 | 1 | 24 | 5,864 | 5+ | 238 | 24,745 | 97.6% |
| RL10A-4 | 3 yrs ('88-'91) | 27 / 4000 | 400 | 3+ | 51 | 8,321 | 2+ | 73 | 15,055 | 1 | 38 | 5,265 | 3+ | 111 | 20,320 | 100.0% |
| RL10A-4-1 | 1 yr ('94) | 28 / 3480 | 400 | 0 | 0 | 0 | 1 | 5 | 2,068 | 1 | 42 | 3,683 | 2 | 47 | 5,751 | 100.0% |
| RL10B-2 | 3 yrs ('95-'98) | 15 / 3500 | 700 | 1 | 119 | 1,701 | 3+ | 125 | 11,605 | 1 | 30 | 4,044 | 4 | 155 | 15,649 | 50.0% |
| YF-73 | 7 yrs ('76-'83) | - | 800 | - | - | - | - | - | - | - | - | - | - | 120 | 30,000 | 85.0% |
| YF-75 | 7 yrs ('86-'93) | - | 500 | - | - | - | - | - | - | - | - | - | - | - | 28,000 | 100.0% |

* J-2S did not enter qualification due to program cancellation. Data included for comparative purposes only

- Emdee, J., "A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines," AIAA Paper No. 2001-0749.

# Testing to Enhance Reliability (LOX/RP)



## Booster Engines

| Designation | Time from Program Start to Qualification | Engine Life (firings / secs) | Nominal Burn Time (secs) | Feasibility | | | Development including stage firings | | | Qualification including stage firings | | | Total Development and Qualification including stage firings | | | Flight Success Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Engines | Firings | Seconds | Engines | Firings | Seconds | Engines | Firings | Seconds | Engines | Firings | Seconds | |
| F-1 | 8 yrs ('59-'66) | 20 / 2250 | 165 | - | - | - | - | - | - | 2 | 34 | >2255 | 56 | 2805† | 252,958† | 100.0% |
| H-1 165K | 2 yrs ('58-'60) | - | 165 | - | - | - | - | - | - | - | - | - | 17 | 85 | - | 100.0% |
| H-1 188K | 3 yrs ('60-'62) | - | 165 | - | - | - | - | - | - | - | - | - | 27 | 1,100 | - | 97.9% |
| H-1 200K | 2 yrs ('63-'65) | - | 165 | - | - | - | - | - | - | - | - | - | 48 | 1,700 | - | N/A |
| H-1 205K | 2 yrs ('65-'66) | - | 165 | - | - | - | - | - | - | - | - | - | 16 | 800 | - | 100.0% |
| LR87-AJ-1 | 4 yrs ('55-'58) | - | 138 | - | - | - | - | - | - | 1 | 46 | 3,579 | - | - | - | - |
| MA-3 Booster | 3 yrs ('58-'60 | - | - | - | - | - | - | - | - | 3 | 44 | - | - | - | - | 98.2% |
| MA-3 Sustainer | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 96.4% |
| MA-5 Booster | 3 yrs ('61-'64) | - | 174 | - | - | - | - | - | - | - | - | - | - | - | - | 98.7% |
| MA-5 Sustainer | 3 yrs ('61-'64) | | 266 | - | - | - | - | - | - | - | - | - | - | - | - | 98.7% |
| MA-5A Booster | 3 yr ('88-'91) | - | 170 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 29 | 748 | 1 | 29 | 748 | 100.0% |
| MA-5A Sustainer | 3 yr ('88-'91) | | 289 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 12 | 716 | 1 | 12 | 716 | 100.0% |
| NK-15/NK-15B | 5 yrs ('64-'69) | 1 / 110 | 110 | - | - | - | - | - | - | - | - | - | 199 | 450 | 40,200 | 97.7% |
| NK-33 / NK-43 | 5 yrs ('69 - '74) | 3 / 365 | 110 | - | - | - | - | - | - | 9 | 39 | 4,875 | 101 | 350 | 61,651 | N/A |
| RD-171 | 10 yrs ('75-'85) | - | 150 | - | 346 | 19,685 | - | - | - | - | - | - | ~80 | ~275 | ~25,000 | 95.9% |
| RD-180 (Atlas III) | 3 yrs ('96-'99) | - | 186 | - | - | - | 8+ | 70 | 10,956 | 4+ | 25 | 4,618 | 11+ | 95 | 15,574 | 100.0% |
| RD-180 (Atlas V) | 1 yr ('99-'00) | - | 230 | - | - | - | 3+ | 19 | 3,420 | 1 | 5 | 1,024 | 4+ | 24 | 4,444 | N/A |
| RS-27 | 1 yr ('72) | - | 265 | - | - | - | - | - | - | - | - | - | - | - | - | 100.0% |
| RS-27A | 1 yr ('88) | - | 265 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 22 | - | 1 | 22 | - | 100.0% |

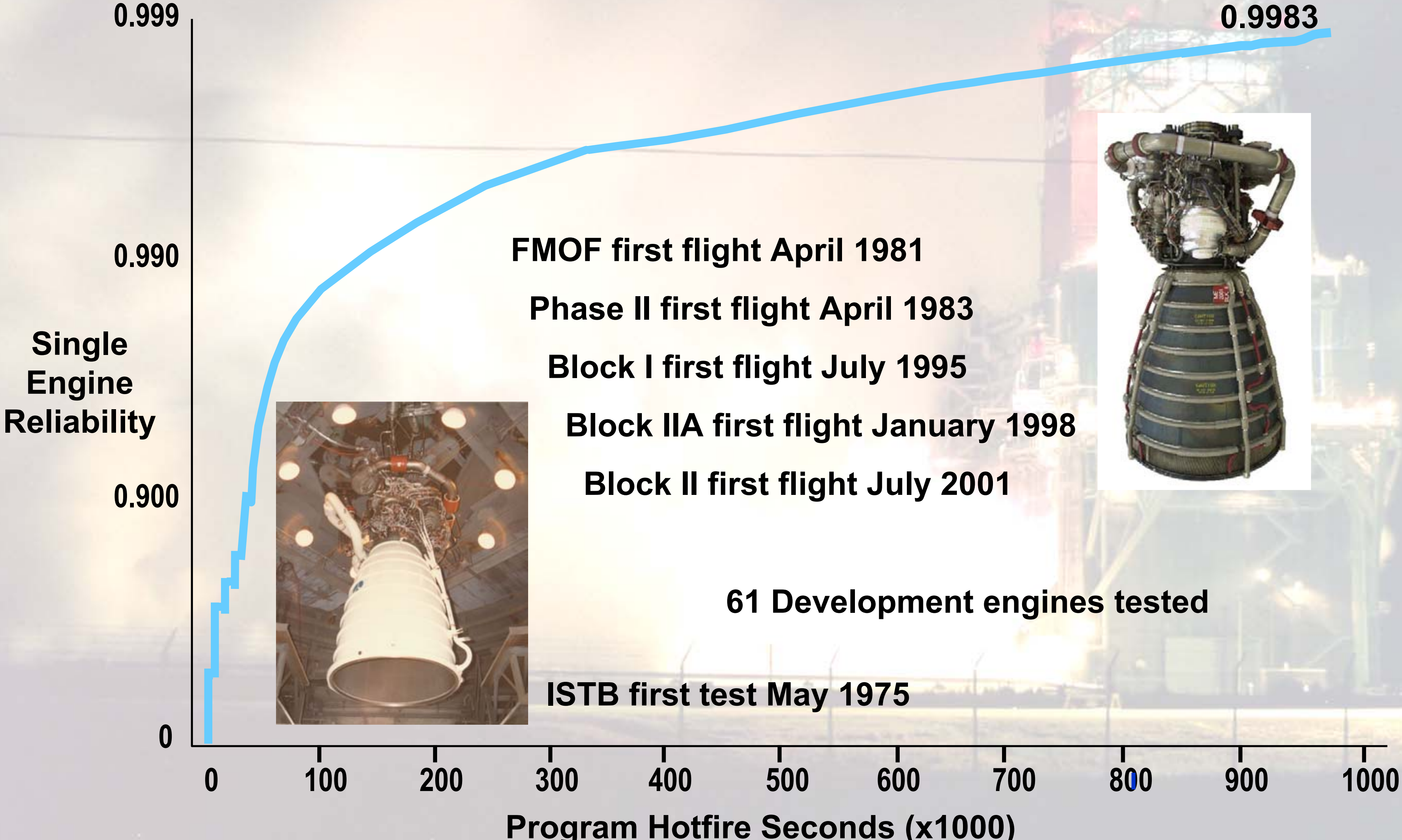
† = includes production due to lack of further information

## Upper Stage Engines

| Designation | Time from Program Start to Qualification | Engine Life (firings / secs) | Burn Time (secs) | Feasibility | | | Development including stage firings | | | Qualification including stage firings | | | Total Development and Qualification including stage firings | | | Flight Success Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Engines | Firings | Seconds | Engines | Firings | Seconds | Engines | Firings | Seconds | Engines | Firings | Seconds | |
| LR91-AJ-1 | 4 yrs ('55-'59) | - | 225 | - | - | - | - | - | - | 1 | 39 | 2,933 | - | - | - | - |
| NK-43 | 5 yrs ('69 - '74) | 3 / 365 | | - | - | - | - | - | - | - | - | - | 5 | 13 | 969 | - |
| RD-120 | 10 yrs ('75-'85) | - | 315 | - | - | - | - | - | - | - | - | - | - | - | - | 94.9% |

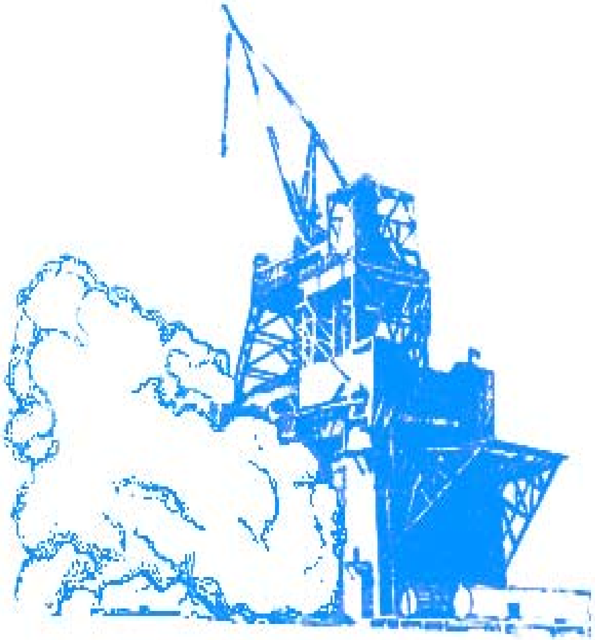
• Emdee, J., "A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines," AIAA Paper No. 2001-3985.

# Test Demonstrated Reliability



# OVERVIEW OF TEST FACILITIES FOR LIQUID PROPULSION TESTING

## (representative capabilities)



# Rocket Propulsion Test Sites



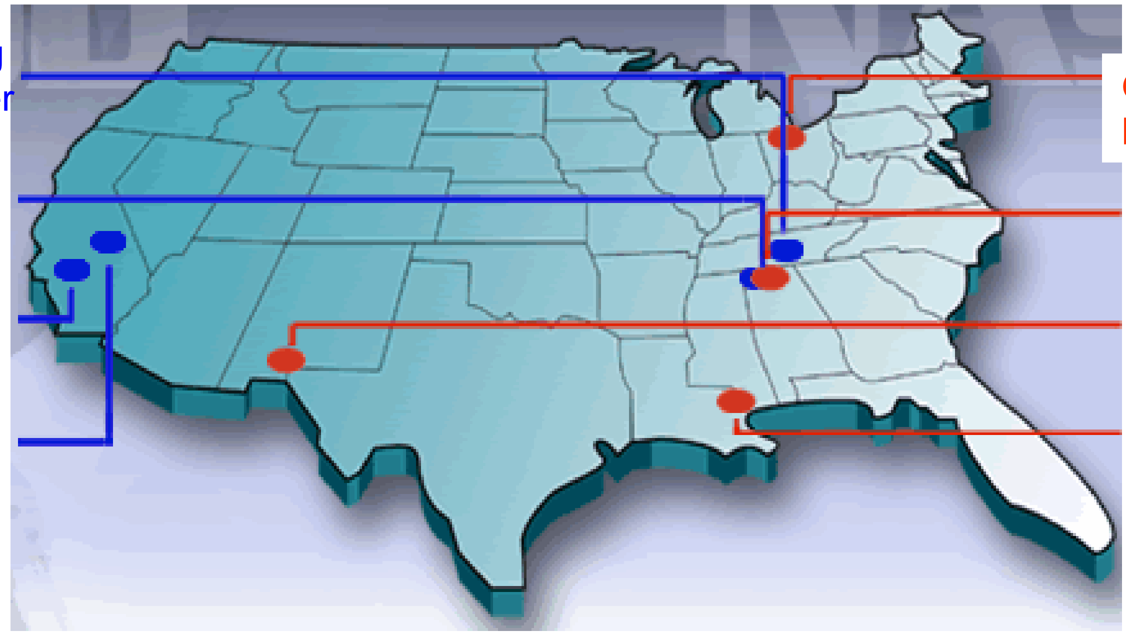
**DoD Sites**

Arnold Engineering
Development Center

Redstone Arsenal

Edwards AFB,
AFRL

Naval Warfare,
China Lake



**NASA Sites**

Glenn Research Center
Plum Brook Station

Marshall Space
Flight Center

White Sands
Test Facility

Stennis Space Center

https://rockettest.ssc.nasa.gov

# Test Capability Figures of Merit

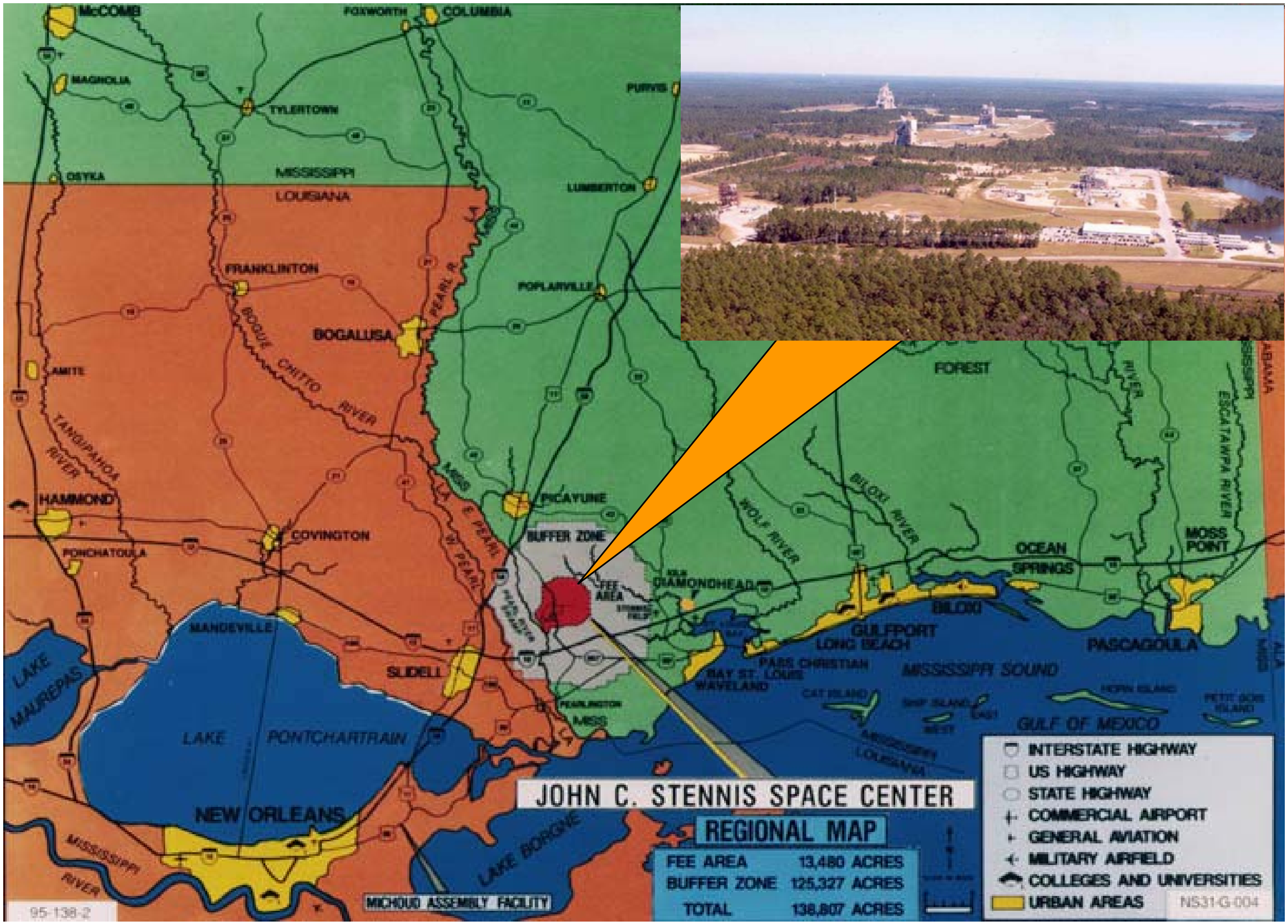


- Component Testing Capability
  - Thrust Scale, Propellants, Pressure, Duration
- Engine Testing
  - Thrust Scale, Propellants, Duration (& Vac if needed)
- Stage Testing
  - Thrust Scale, Propellants, Pressure

Pressure ➔ ultra-low (vac demo) and ultra-high (for components dev)
Duration ➔ extended duration capability sufficient to run mission profile
Propellants ➔ cryo, or non-cryo, hypergol, storables, etc.
Thrust Scale ➔ appropriate thrust level infrastructure for test article size/thrust

# SSC and Surrounding Buffer Zone





# Stennis Space Center Test Facilities

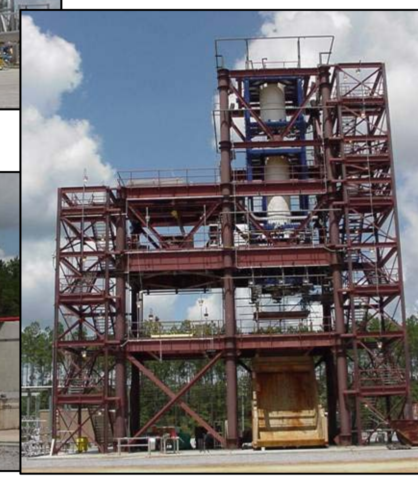


**A-1 … Large Scale Devt. & Cert … A-2**

**E-1 Stand**

**High Press, Full Scale**

**(Battleship, Proto h/w)**



**E-2**

**High Press**

**Mid-Scale**

**& Subscale**

**B-1/B-2 … Full Scale Devt. & Cert**

**E-3**

**High Press**

**Small-Scale**

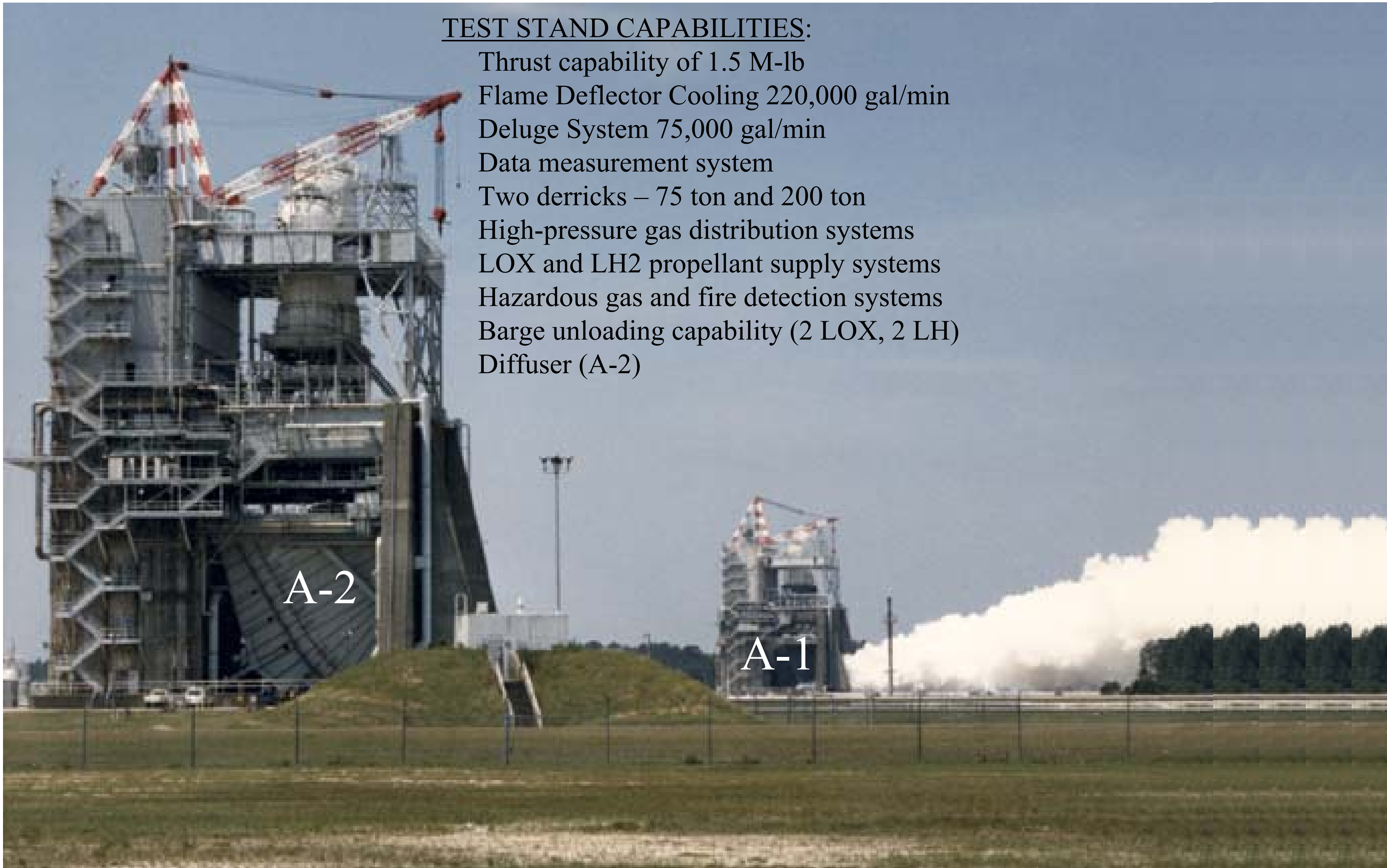
**Subscale**

# Stage & Engine Testing – SSC A Complex



<u>TEST STAND CAPABILITIES</u>:

- Thrust capability of 1.5 M-lb
- Flame Deflector Cooling 220,000 gal/min
- Deluge System 75,000 gal/min
- Data measurement system
- Two derricks – 75 ton and 200 ton
- High-pressure gas distribution systems
- LOX and LH2 propellant supply systems
- Hazardous gas and fire detection systems
- Barge unloading capability (2 LOX, 2 LH)
- Diffuser (A-2)



# Space Shuttle Main Engine Test

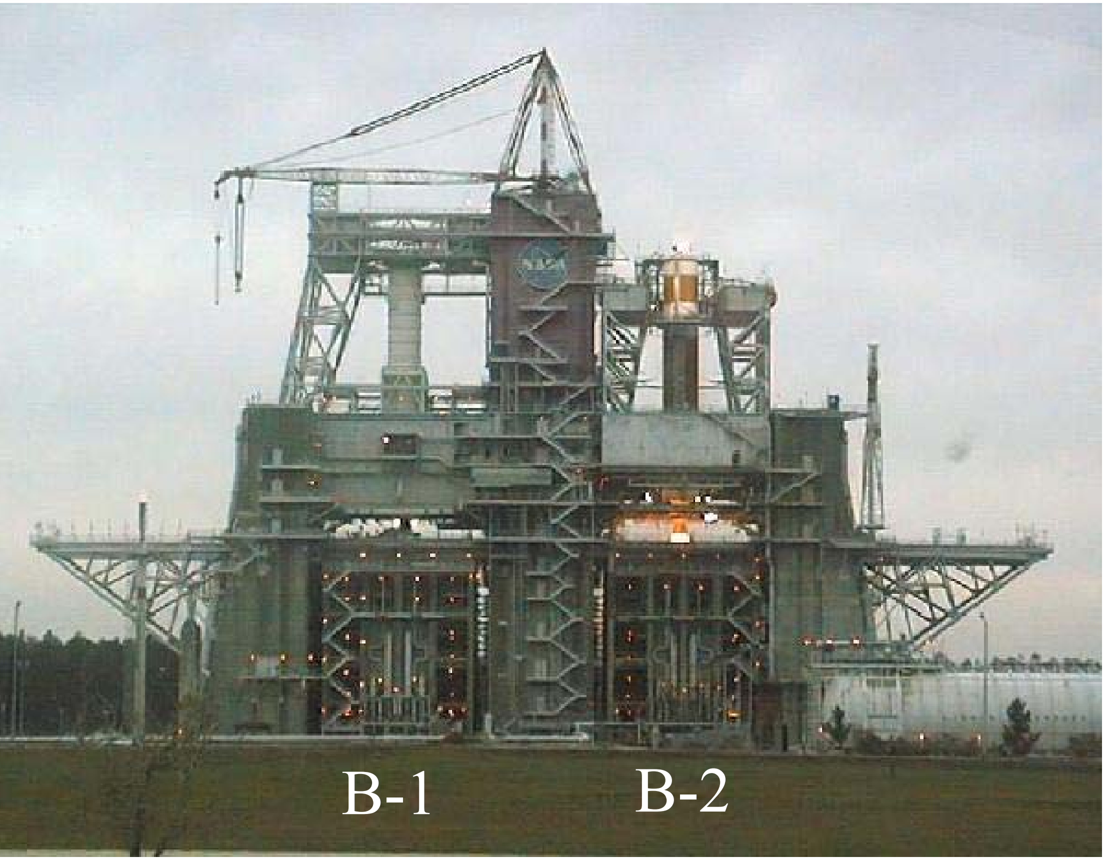


SSC A-1 Test Stand

Space Shuttle Engine

# Stage and Engine Testing – SSC B Complex

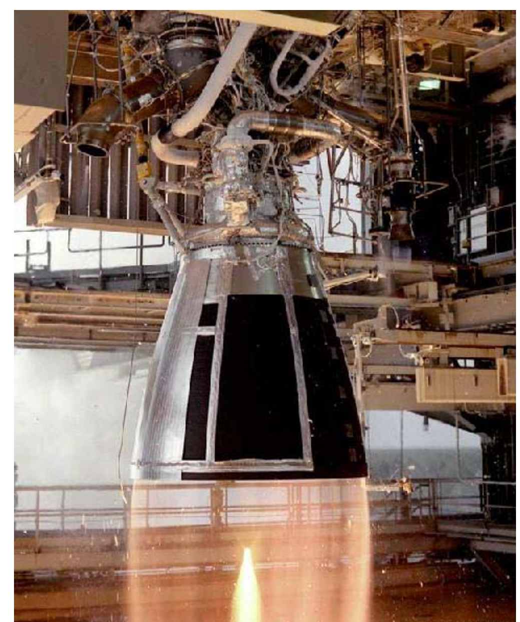





B-2 Test of Delta IV Common Booster Core

TEST STAND CAPABILITIES:

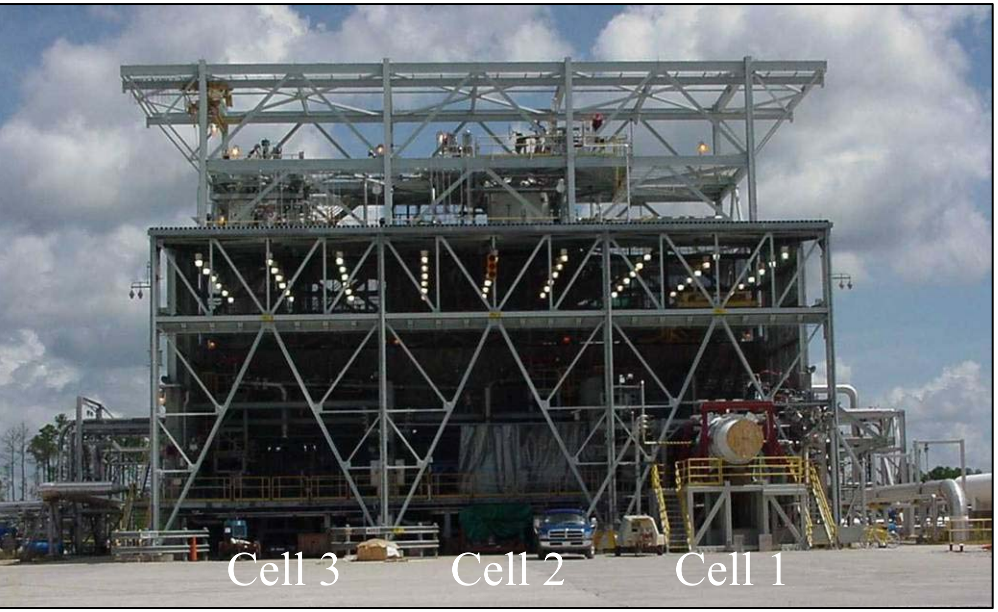
- Thrust capability of 13 M-lb
- Flame Deflector Cooling 330,000 gal/min
- Deluge System 123,000 gal/min
- Data measurement system
- Two derricks – 175 ton and 200 ton
- High-pressure gas distribution systems
- LOX and LH2 propellant supply systems
- Hazardous gas and fire detection systems
- Barge unloading capability (3 LOX, 3 LH)



B-1 Test of Delta IV RS-68

# Component and Engine Testing - SSC E-1 Test Stand






- E1 Cell 1
  - Primarily Designed for Pressure-Fed $LO_2/LH_2$/RP & Hybrid-Based Test Articles
  - Thrust Loads up to 750K $lb_f$ (horizontal)
- E1 Cell 2
  - Designed for $LH_2$ Turbopump & Preburner Assembly Testing
  - Thrust Loads up to 60K $lb_f$
- E1 Cell 3
  - Designed for $LO_2$Turbopump, Preburner Assembly Testing & LOX/LH Engine Testing
  - Thrust Loads up to 750K $lb_f$

<u>General Pressure Capabilities</u>

- $LO_2/LH_2$ ~ 8,500 psi
- RP ~ 8500 psi (Ready 1/06)
- GN/GH ~ 15,000 psi
- Ghe ~ 10,000 psi

# Mid-Scale Component/Engine Testing - SSC E-2



- E2 Cell 1
  - Primarily Designed for Pressure-Fed $LO_2$/RP1 Based Test Articles
  - Thrust Loads up to 100K $lb_f$ (horizontal)
  - $LO_2$/RP1 ~ 8500 psia
  - GN/GH ~ 15000 psia
  - Hot GH (6000 psia/1300 F)

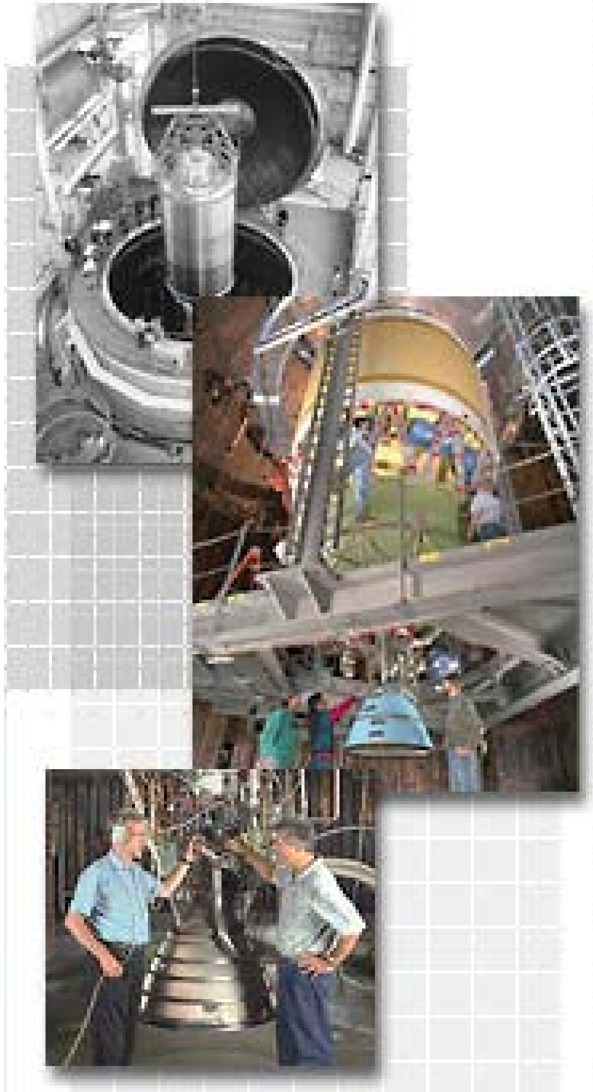
- E2 Cell 2
  - Designed for $LO_2$ /H2O2/RP1 Engine/Stage Test Articles
  - Loads up to 150K $lb_f$

## Spacecraft Propulsion Research Facility **(Plum Brook Station B-2)**

B-2 is a one-of-a-kind facility that tests full-scale upper-stage launch vehicles and rocket engines under simulated high-altitude conditions.
(e.g. Delta LV Upper Stage – LOX/LH)

Purpose: To test an engine or vehicle that is exposed for indefinite periods to low ambient pressures, low background temperatures, and dynamic solar heating simulating the environment hardware encounters during orbital or interplanetary travel.

- certification and baseline tests of unique flight hardware
- capability for long duration space environment soaking
- spacecraft subsystem and full system integration testing



# Altitude Simulation (cont.)

*Rocket Engine Firing Inside Vacuum Test Cell*

## White Sands Test Facility

- Eight engine/system test stands (5 vacuum cells)
- Long-duration high-altitude simulation
  - −SSME OMS, RCS
- Hypergolic (Hydrazines, NTO) and cryogenic liquid rocket systems
  - −Small to medium thrust levels

For details see: https://rockettest.ssc.nasa.gov


*Propulsion Test Area 400*

*Altitude Simulation System Operation for Rocket Engine Tests*

# Advanced Propulsion Test Capability



## Test Stand 115, 116
## **(Marshall Space Flight Center)**

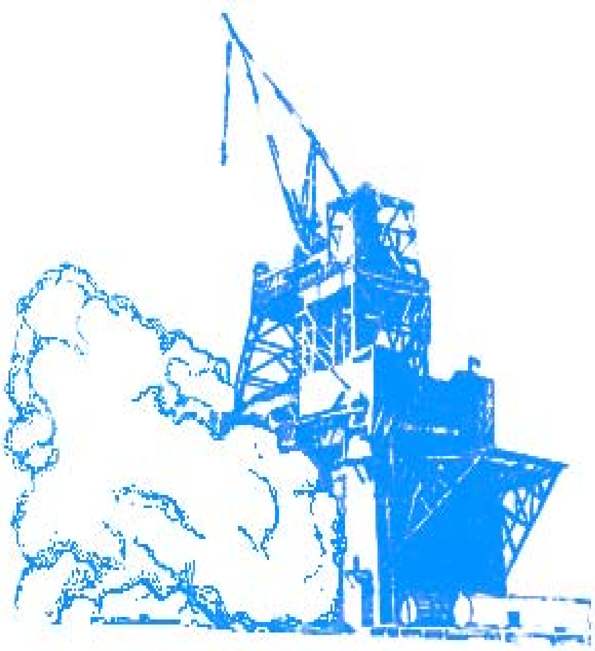
**TF 115**

- Ambient Test Capability
- Propellants: GH2, LH2, LOX, LCH4 & RP-1
- Maximum Thrust - 4 K lbf
- The compact size of the facility makes it ideal for testing subscale components.

**TF 116**

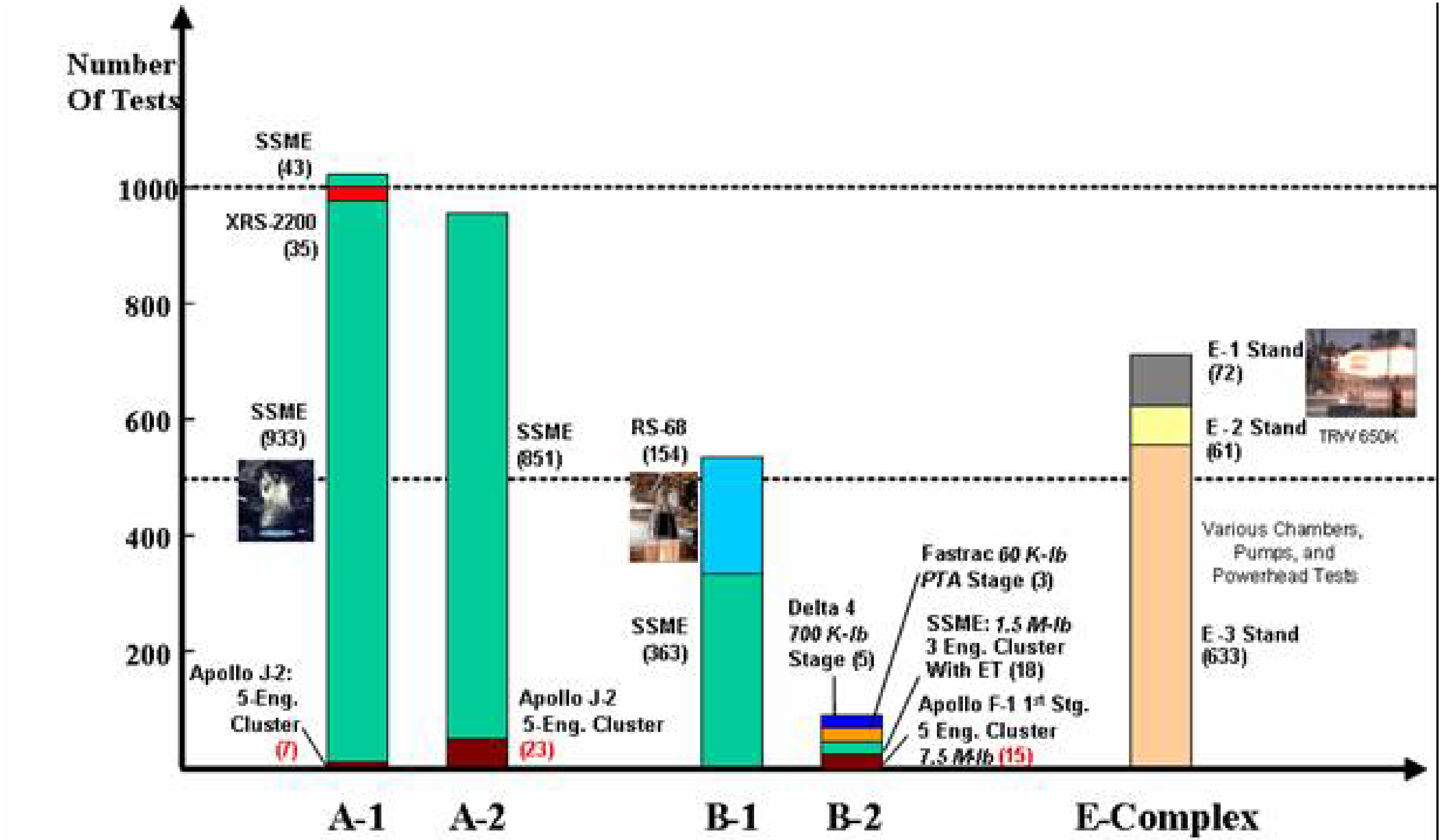
- Multiple Position Facility
- Ambient Test Capability
- Designed to test High Pressure Combustion Devices, Engines/System, Cryogenic Propellant Systems

# STATISTICS (HISTORICAL) OF LRE TESTING



# SSC Testing History (1966 – 2004)

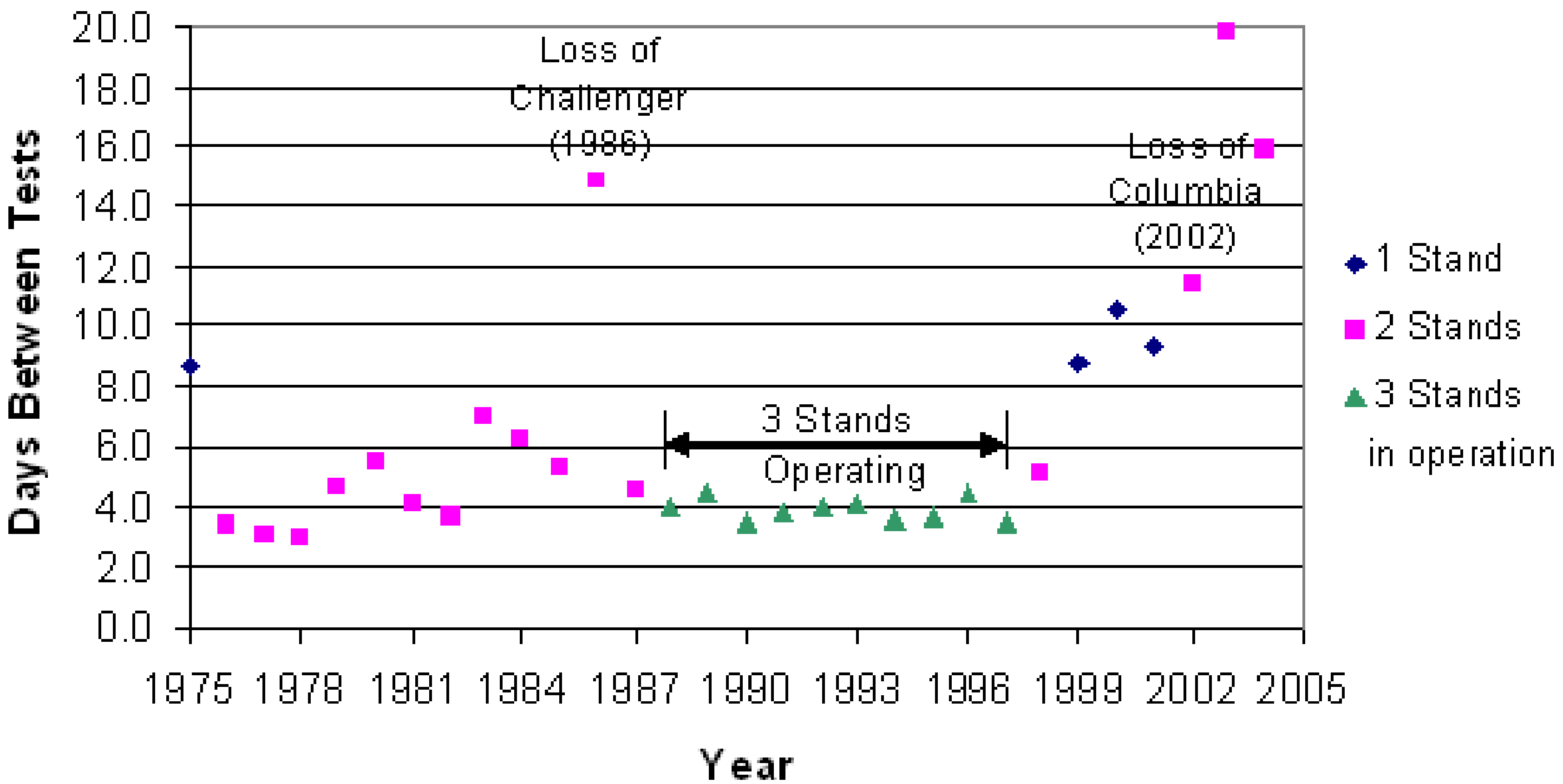





Ref: Kirchner, C., Morgan, J., and Rahman, S., “SSC Rocket Propulsion Testing Major Statistics,” SSC Internal Memo, 2005.

# SSC Test Rate for SSME (1976 – 2004)






Ref: Kirchner, C., Morgan, J., and Rahman, S., "SSC Rocket Propulsion Testing Major Statistics," SSC Internal Memo, 2005.

# Overview of US Engine Test Campaigns



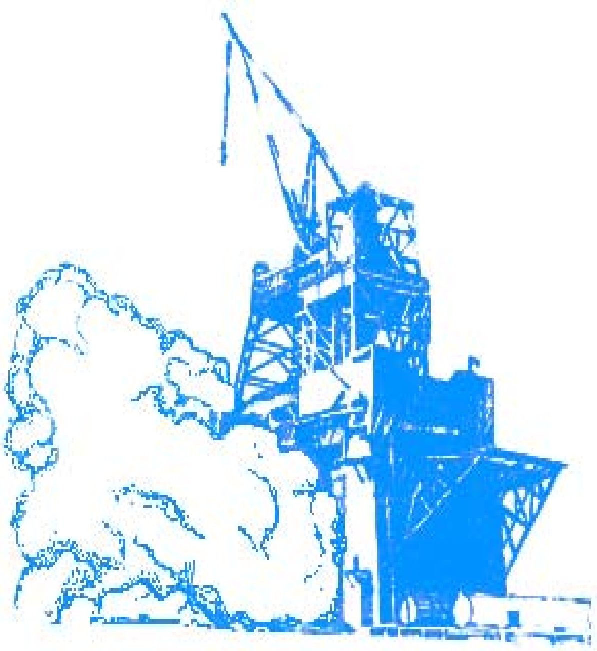
| | SSME (Boost) | F-1 (Boost) | RS-68 (Boost) | J-2 (U/S) | RL-10A-1 (U/S) | LMDE (Lander) |
|---|---|---|---|---|---|---|
| Thrust | 500 Klbf | 1.5 Mlbf | 700 Klbf | 250 Klbf | 15 Klbf | 10 Klbf |
| Hot-Fire Test Seconds Prior to First Flight | 110,000 s | 250,000 s | **11,000 s (i/w) | 120,000 s | 71,000 s | 149,000 s |
| Hot-Fire Test Seconds After First Flight | ~750,000 s* (& counting) | 30,000 s | 6,810 s | in-work (i/w) | Upgraded to RL-10A-3 | N/A |
| Hot-Fire Tests Prior to First Flight | 726 | 2805 | 188 | 1730 | 707 | 2809 |
| Years of Devt. | 9 | 8 | 5 - 6 | 6 | 3 | 5 |
| Missions Flown | 113 | ~15 | 3 | ~15 | i/w | 6 (Apollo 11,12,14-17) |
| Vehicle | Shuttle | Saturn V | Delta IV | Saturn V | Various | Saturn V |

***SSME Flight Seconds (~150,000 s) not counted**
****RS-68 Pre-flight Seconds (in-work): ~19500 s total (~11000 s at SSC)**

**For many of the above:**
**testing was performed at a variety of locations**


- Emdee, J., “A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines,” AIAA Paper No. 2001-0749.
- Emdee, J., “A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines,” AIAA Paper No. 2001-3985.
- Elverum, G. et al., “The Descent Engine for the Lunar Module,” AIAA Paper No. 67-521.

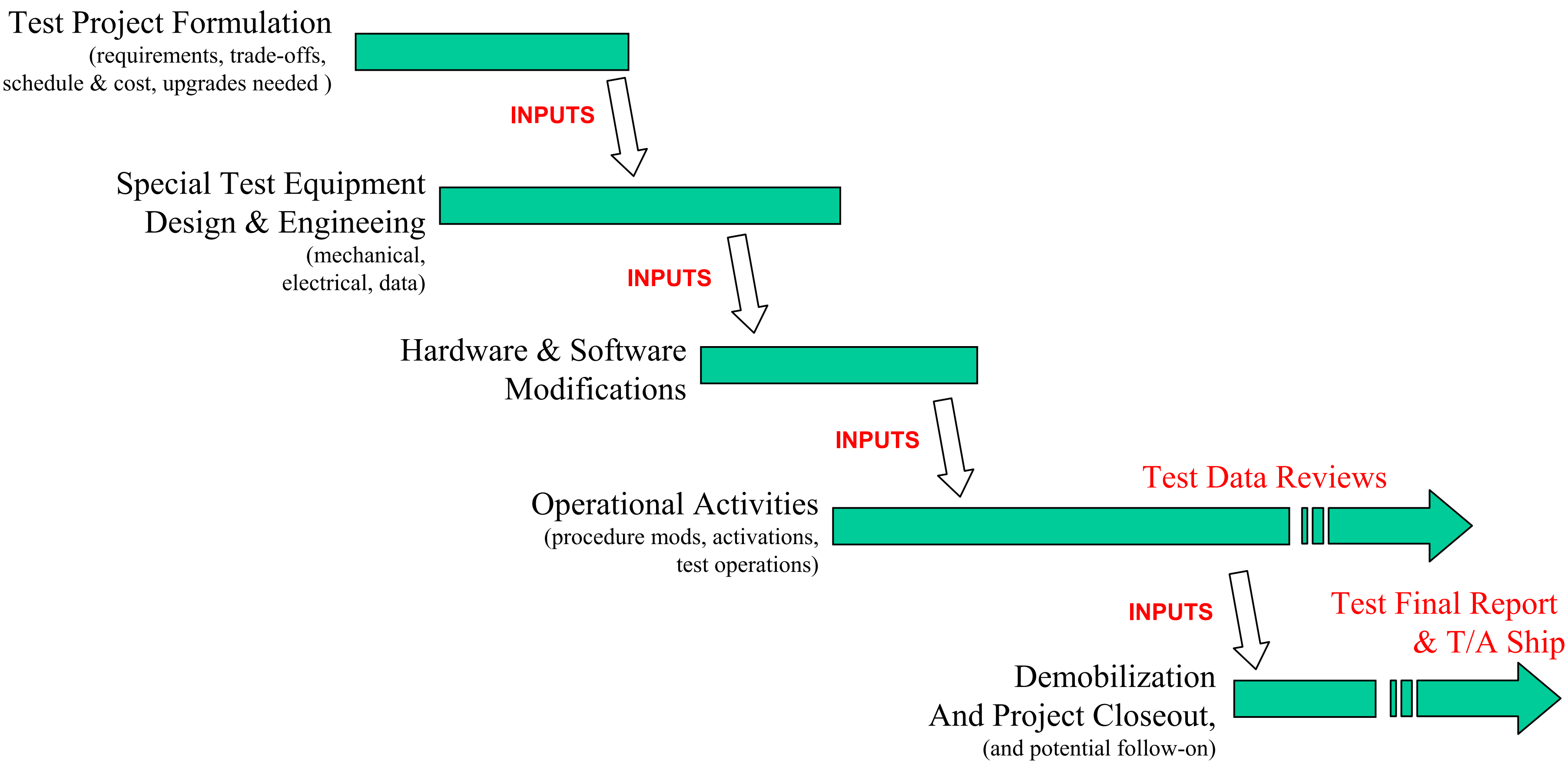
# TEST PROJECT ENABLERS
## - Engineering Tools, Operations, Processes, Infrastructure -



# Test Project Process



- Life cycle of a typical test project



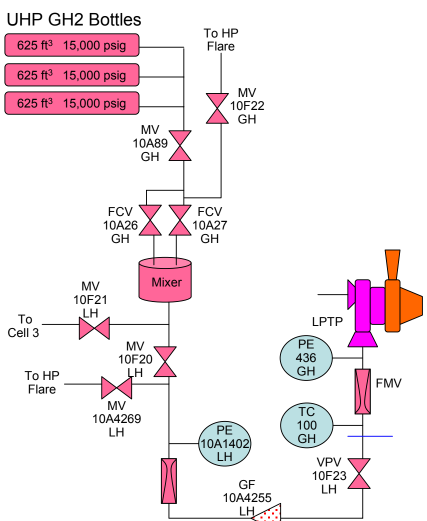
# Test Facility/Project Modeling and Analysis



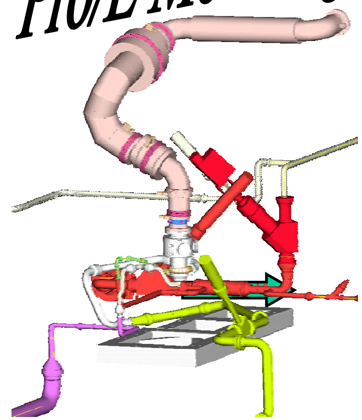
## *-- Propellant System Thermodynamic Modeling and Test Simulation --*

**SSC's integrated systems and operations performance modeling capability substantially improves understanding and knowledge of test systems performance and translates to improved test facility design, activation and test operations**

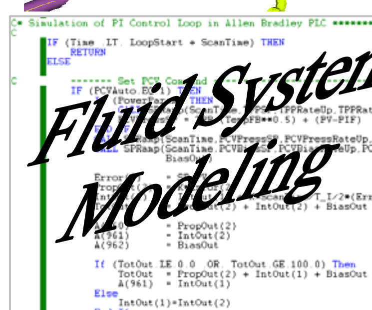

### Schematic Development



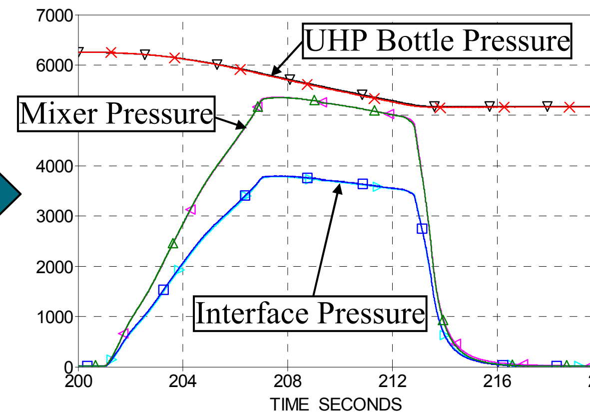

### Pro/E Modeling



### Fluid System Modeling



### Test Data vs Model Assessment



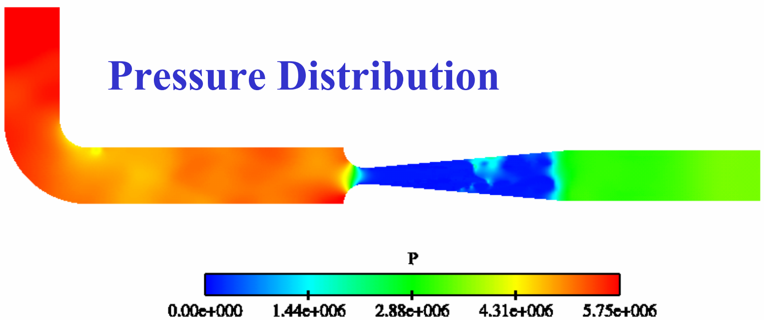

**GH2 Activation Test #1**
**June 29, 2004**

# CFD Flow Modeling Applications

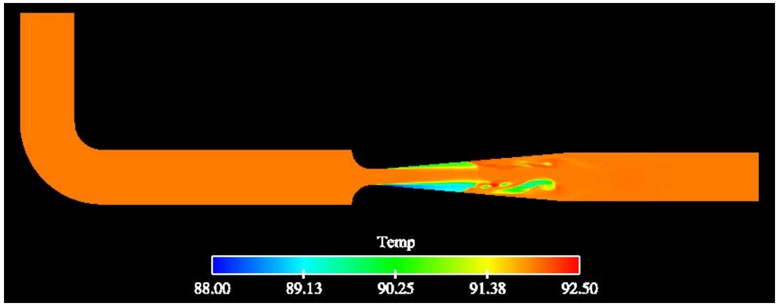


## Cavitating Venturi with Upstream Bend

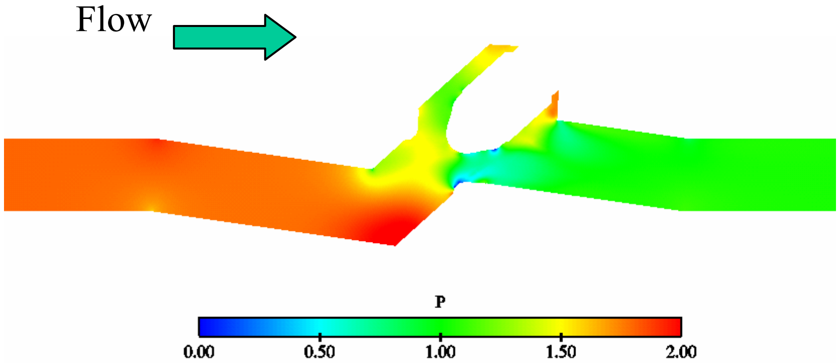
Pressure Distribution




Temperature Distribution




## Large Cryogenic High Pressure Valve




Also analyzed:
- Run Lines
- Run Tanks
- Pressure Regulators
- Rocket Plumes (*T, P, v, dB*)

# “Movie” of Run Tank CFD



MOVIE HERE

# State of the Art Test Stand Software



- Configuration Management
  - Automated Electronic Process
  - Test Site Drawings
  - Future – Project Requirements, Component Specs

- Data Acquisition and Controls Lab
  - Off-Line Testing
    - Test Software
    - Electrical Hardware

***Data Acquisition and Control Systems Lab (DACS Lab)***

# State of the Art Test Stand Hardware



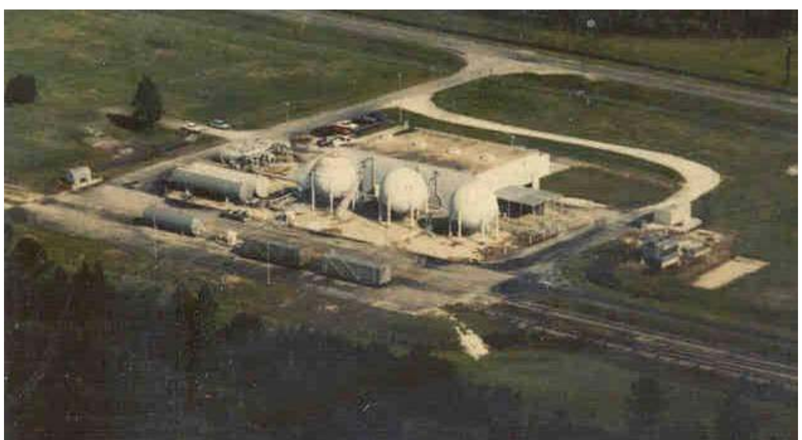
- Cooperative Agreement Procurements
  - Large, High Pressure Cryogenic Valves
  - Quick Responding, High Pressure RTD’s

# Test Support Infrastructure



Cryogenic Propellant Storage Facility (SSC)
Six (6) 100,000 Gallons LOX Barges
Three (3) 240,000 Gallons LH Barges

High Pressure Industrial Water (HPIW at SSC)
330,000 gpm



High Pressure Gas Facility (HPGF at SSC)
(GN, GHe, GH, Air)

Additional Support

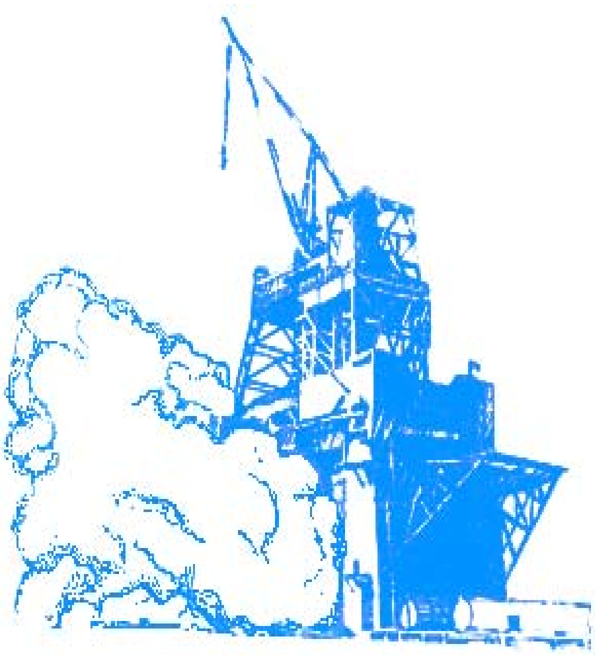
- Laboratories
  - •Environmental
  - •Gas and Material Analysis
  - •Measurement Standards and Calibration
- Shops
- Utilities

# Test Technology Advancements



- Advanced Sensors and Measurement Systems
  - Smart Sensor testbed, and integrated sensor suites
  - Integrated System Health Management testbed
- Advanced Data Acquisition and Controls
  - Closed loop fast feedback controls
  - System simulation integrated with Facility Controls
- Mechanical Components and Systems
  - Comprehensive modeling and simulation from Propellant tank to Test Article
  - Computational fluid dynamics solutions to complex internal flows (tanks, valves)
  - High performance test stand valves (15000 psi working pressures, rapid actuation)
- Plume Effects Prediction and Monitoring
  - Non-intrusive diagnostics (species, acoustics, thermal)
  - CFD analysis of plume effects with Benchmarked Codes

# NON-NASA TEST CAPABILITY
# - DOD, Commercial, University -



# Rocket Propulsion Test Sites



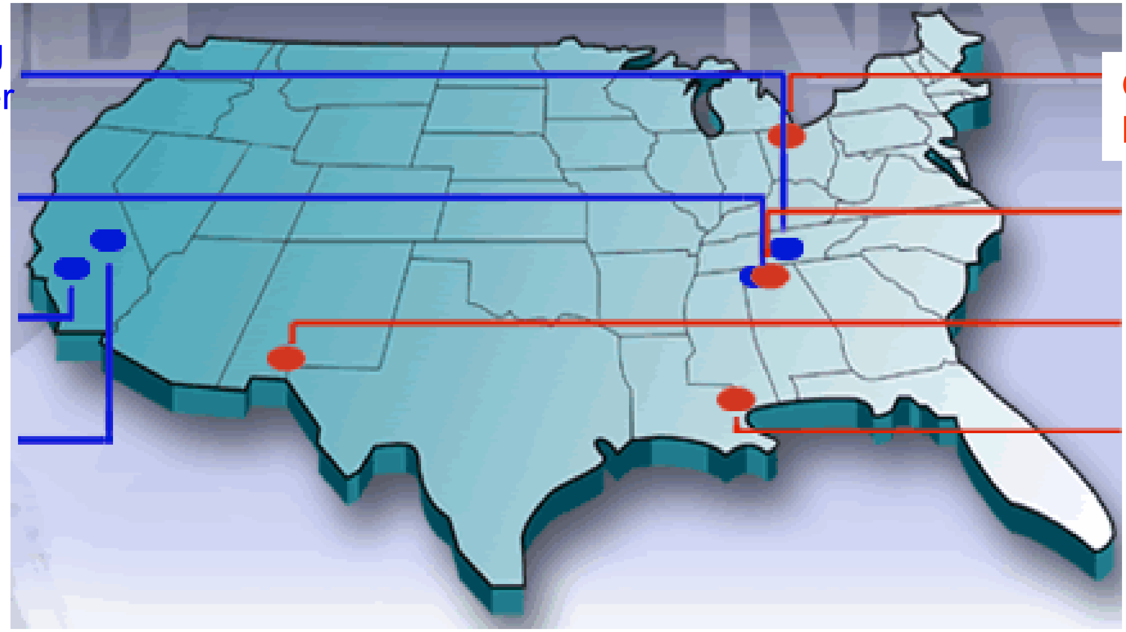
**DoD Sites**

Arnold Engineering Development Center

Redstone Arsenal

Edwards AFB, AFRL

Naval Warfare, China Lake



NASA Sites

Glenn Research Center Plum Brook Station

Marshall Space Flight Center

White Sands Test Facility

Stennis Space Center

https://rockettest.ssc.nasa.gov

# DOD LRE Test Capabilities



- Significant World Class Assets for Liquid Rocket Propulsion
  - Air Force Research Lab (AFRL, a.k.a. “rocket lab”), in CA.
    - Sea-Level Stands 2-A (components), and 1-D (engines)
  - Arnold Engineering Development Center (AEDC), in TN.
    - Altitude Simulation Stand J-4 (engines)

# Commercial LRE Test Capabilities



- Pratt & Whitney at West Palm Beach, FL.
  - Test stands E-6 and E-8
  - Conducted testing of SSME advance turbopump, and upper stage engine
- Northrup Grumman (was TRW) at San Juan Capistrano, CA.
  - Several test stands
  - Conducted testing of Lunar Lander in 1960s
- Rocketdyne at Santa Susanna Field Lab in CA.
  - RS-27 engine test to be retired with fleet; future of stands TBD
- Aerojet at Sacramento, CA.
  - Several test stands
  - Titan core liquid propulsion to be retired with fleet; future is TBD
- Other commercial entities
  - SpaceX corp. in TX; currently testing the Falcon launcher LRE's

# University Test Capability



Constellation University Institutes Program

- REAP = Rocket Engine Advancement Program
- Significant Test Capabilities
  - Penn State, Purdue, UAH, for liquid rocket engine technology
  - SOA for Plume Diagnostics, and Computational Modeling

**Rocket Engine Advancement Program Institute**

| Alabama-Huntsville | Purdue | Penn State | Auburn | Tuskegee |
|---|---|---|---|---|

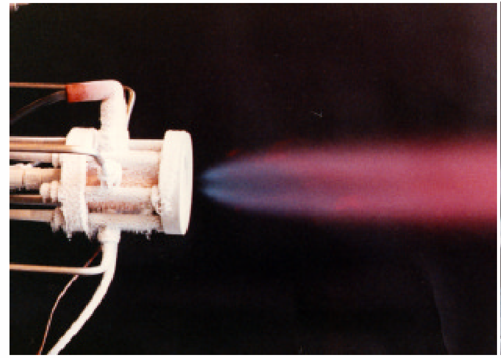
# Penn State University



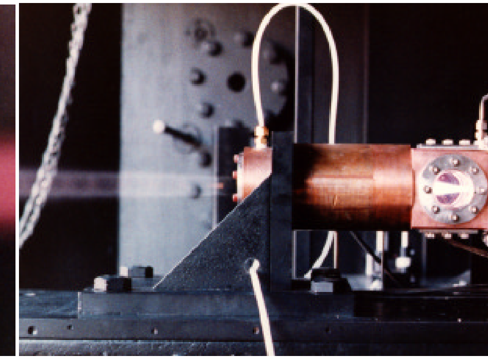
## PROPULSION ENGINEERING RESEARCH CENTER

POC: Prof. Bob Santoro and Dr. Sibtosh Pal
(Dept. of Mechanical Engineering)
- CRYOGENIC COMBUSTION LAB

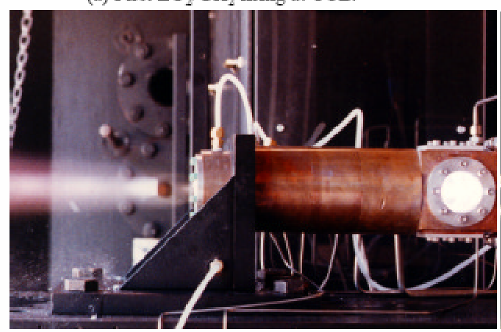
Representative LRE Injector Studies
Performance & Mixing
Combustion Stability
Heat Transfer
Non-Intrusive Diagnostics



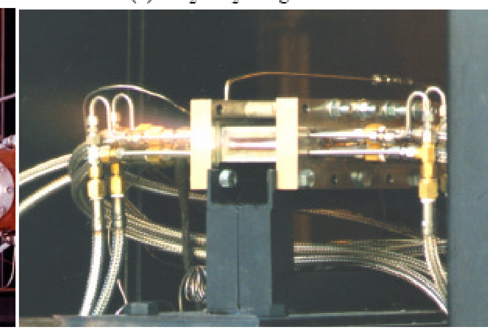
(a) First $LO_2/GH_2$ firing at CCL.



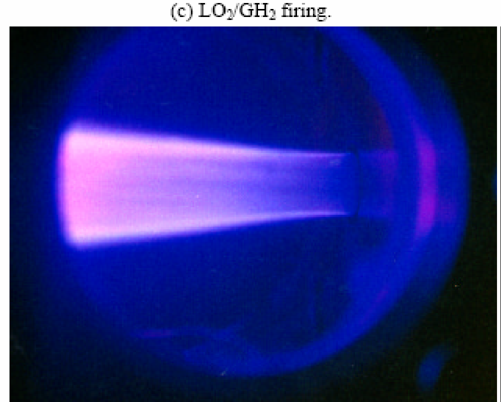
(b) $GO_2/GH_2$ firing.



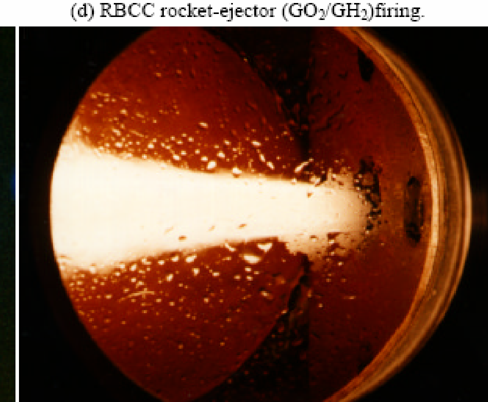
(c) $LO_2/GH_2$ firing.



(d) RBCC rocket-ejector ($GO_2/GH_2$)firing.



(e) UV closeup for $GO_2$/RP-1/$GH_2$ firing..



(f) Injector closeup for $GO_2$/RP-1/$GH_2$ firing.

# Penn State "PERC" (cont.)



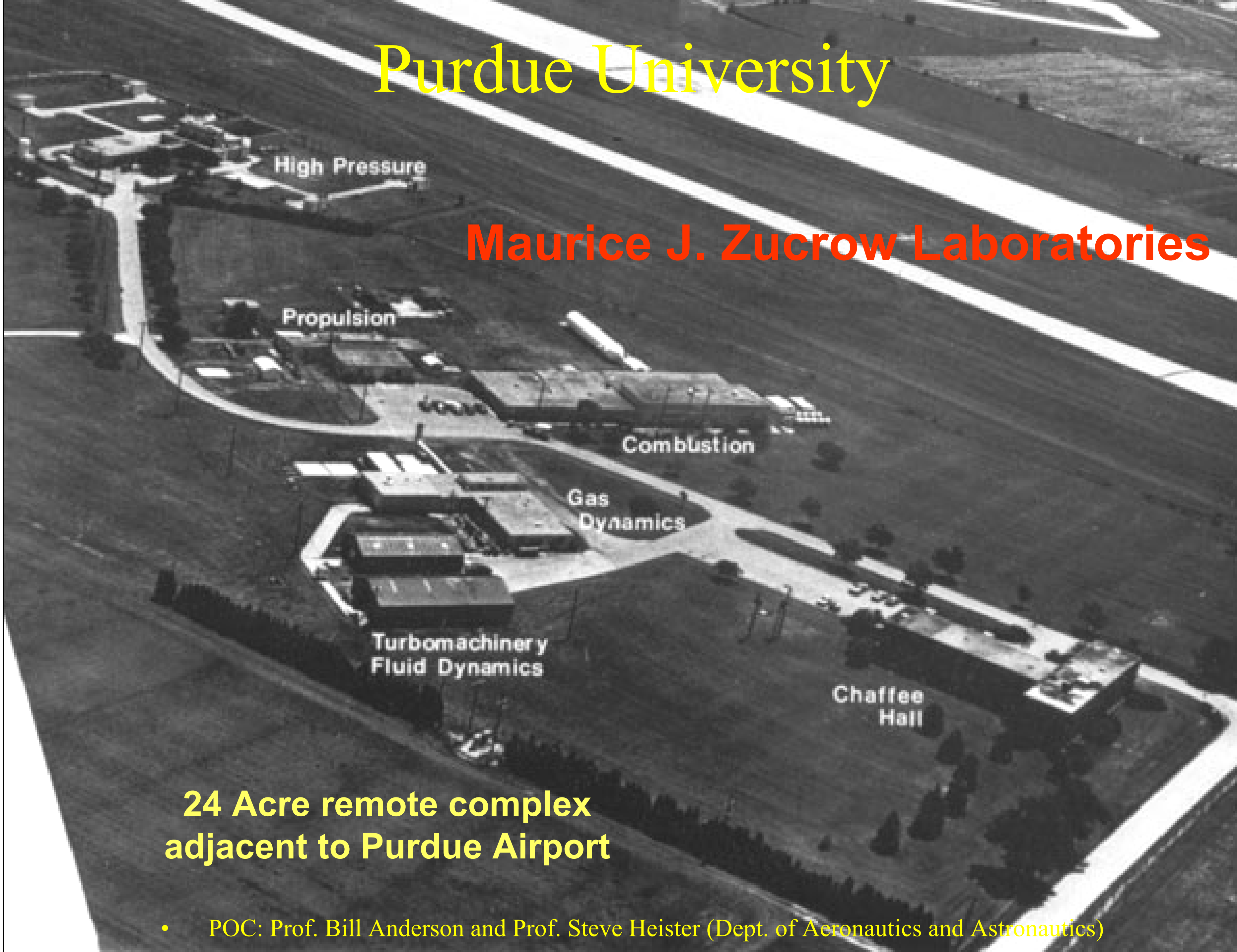
## PROPULSION ENGINEERING RESEARCH CENTER

(cf. Santoro et al., AIAA Paper No.2001-0748)

| System | Diagnostic | Measurements |
|---|---|---|
| 2 component PDPA system | drop size and velocity | • measuring LOX, methanol and RP-1 drops under hot-fire conditions. |
| 2-component LDV system | 2 -component velocity | • characterizing velocity field for $GO_2/GH_2$ combusting flowfield for shear coaxial element. |
| Raman system (Nd:Yag laser/Flash pumped dye laser + ICCD camera) | species measurements | • measuring $H_2$, $O_2$ and $H_2O$ species for various injectors ($GO_2/GH_2$ propellants) at pressures up to 1000 psia.<br>• measuring $H_2$, $O_2$, $N_2$ and $H_2O$ species in RBCC rocket-ejector environment |
| Planar Laser Induced Fluorescence System (Nd: Yag laser + Dye laser + frequency doubler + ICCD camera) | OH- radical measurements | • marking combustion zone for shear layers. |
| Laser Induced Incandescence | soot | • soot concentration measurements in hydrocarbon fuel flames at pressures up to 150 psia. |
| High speed cinematography | dynamic event capture @ 8000 fps | • atomization and combustion phenomena. |
| Schlieren photography | density gradient visualization | • reacting shear layer, two-phase flow injection, super-critical injection. |

# Purdue University

## Maurice J. Zucrow Laboratories




**24 Acre remote complex adjacent to Purdue Airport**

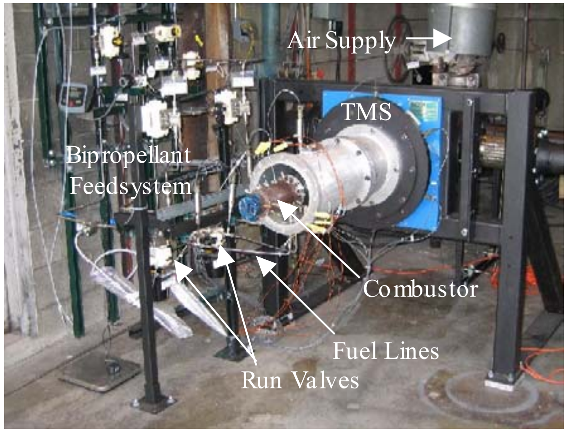
- POC: Prof. Bill Anderson and Prof. Steve Heister (Dept. of Aeronautics and Astronautics)

# Purdue “Zucrow Lab” (cont.)



Component Test & Validation

Test & Evalution




Assembly & Installation

# SUMMARY



- Comprehensive Liquid Rocket Engine testing is essential to risk reduction for Space Flight
- Test capability represents significant national investments in expertise and infrastructure
- Historical experience underpins current test capabilities
- Test facilities continually seek proactive alignment with national space development goals and objectives including government and commercial sectors

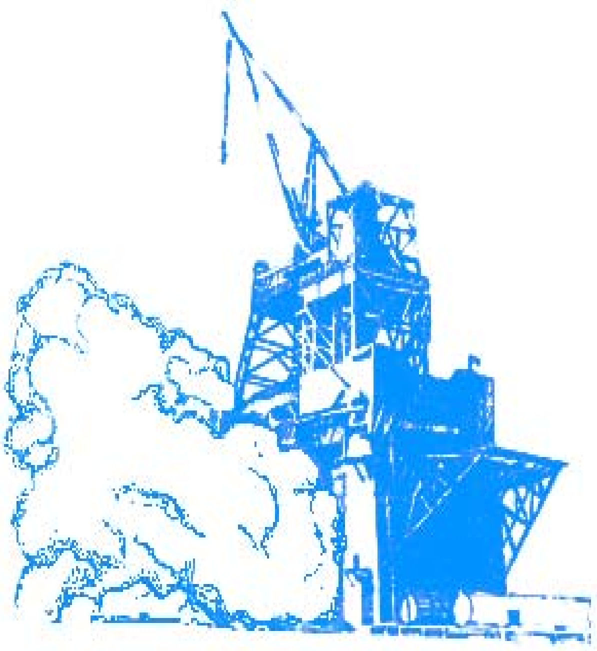
# Test What You Fly


B-2 Test Stand
Stennis Space Center
(Delta 4 Stage installation)

Ref: RS-68 Presentation
(Rocketdyne web-site)

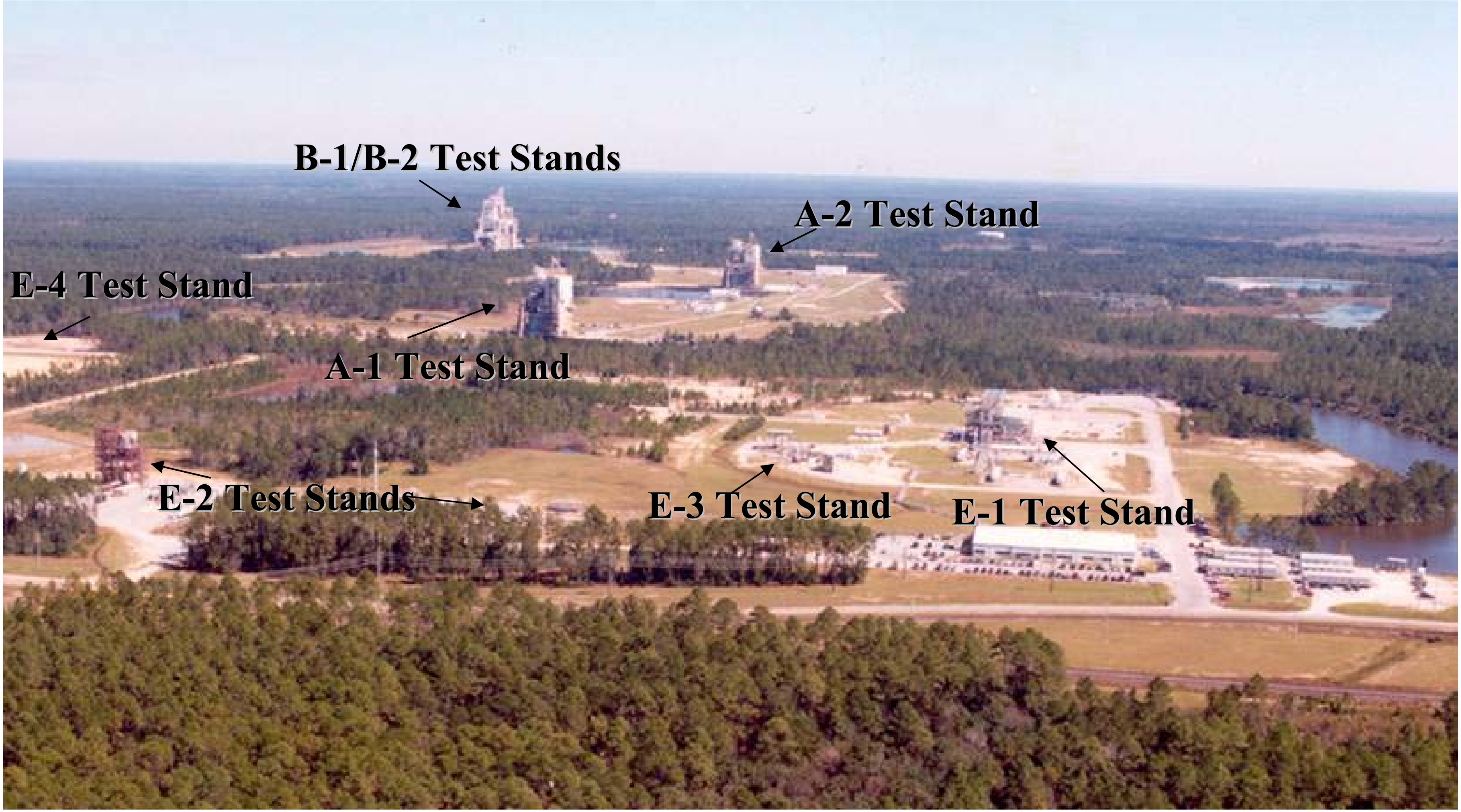
# BACKUP SLIDES





# SSC Test Stand Layout





# E-Complex History



- Late 1980s/Early 1990's
  - -DoD/NASA Advanced Launch System and National Launch System
  - -National Aerospace Plane

- Construction Starts
  - -E-1 1989
  - -E-2 1991
  - -E-3 1995
- First Test
  - -E-1 1999
  - -E-2 1994
  - -E-3 1995

# SSC E-1 Test Stand Projects



**250 Klbf Hybrid … 4 tests**
**(1999, 2001)**

**TRW 650K TCA … 15 tests**
**Hot-Fire**
**(Summer 2000)**

**IPD (250K-scale) LOX Pump**
**Cold-Flow**
**(Fall 2002)**

**IPD Ox Rich Preb … 9 tests**
**Hot Fire**
**(Sep - Oct 2002)**

**IPD LOX Pump … 12 tests**
**Hot Fire**
**(Mar - May 2003)**

**IPD LH Pump … 6 tests**
**Cold-Flow**
**(May - Nov 2004)**

**Subscale Ox-Rich Preb … 15 tests**
**(RS-76: Nov 98 – Jan 99)**
**(RS-84: Fall 2003)**

**240 Klbf Aerospike … 17 tests**
**(1999-2001)**

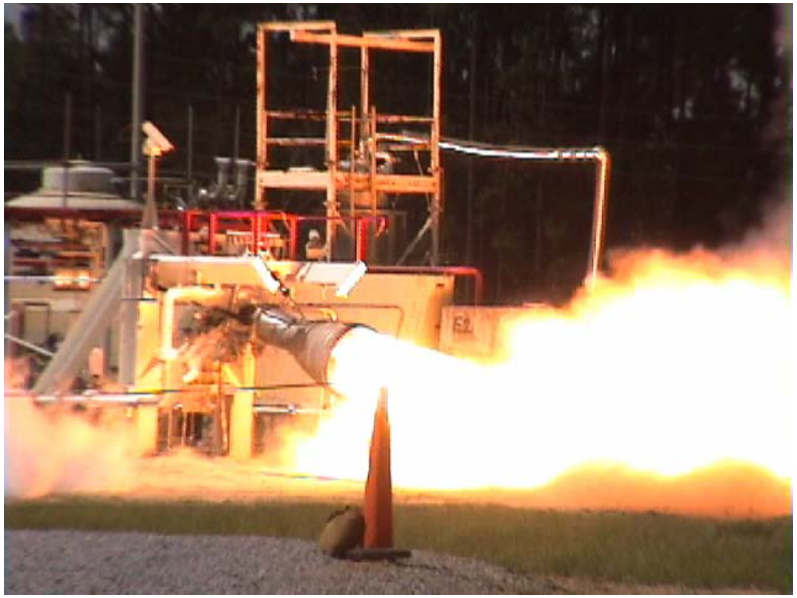
**RTF SSME Accep (8-19-04)**

**IPD Eng. Install (10-15-04)**

# SSC E-2 Test Stand



E-2 Cell 1 Test of RS-84 LOX Rich Preburner



E-2 Cell 1 Test of LR-89 LOX/RP Thrust Chamber

# SSC E-3 Test Stand Capabilities



- E3 Test Stand Capabilities
  - Primarily Designed for Rocket Engine Component & Sub-Scale Engine Development
  - Comprised of Two (2) Test Cells
- E3 Cell 1
  - Horizontal Test Cell
  - Propellants: $LO_2$, GOX, JP-8, $GH_2$
  - Support Gasses: $LN_2$, $GN_2$, GHe
  - Thrust Loads up to 60K $lb_f$
- E3 Cell 2
  - Vertical Test Cell
  - Propellants: $LO_2$, $H_2O_2$, JP-8
  - Support Gasses: $LN_2$, $GN_2$, GHe
  - Thrust Loads up to 25K $lb_f$

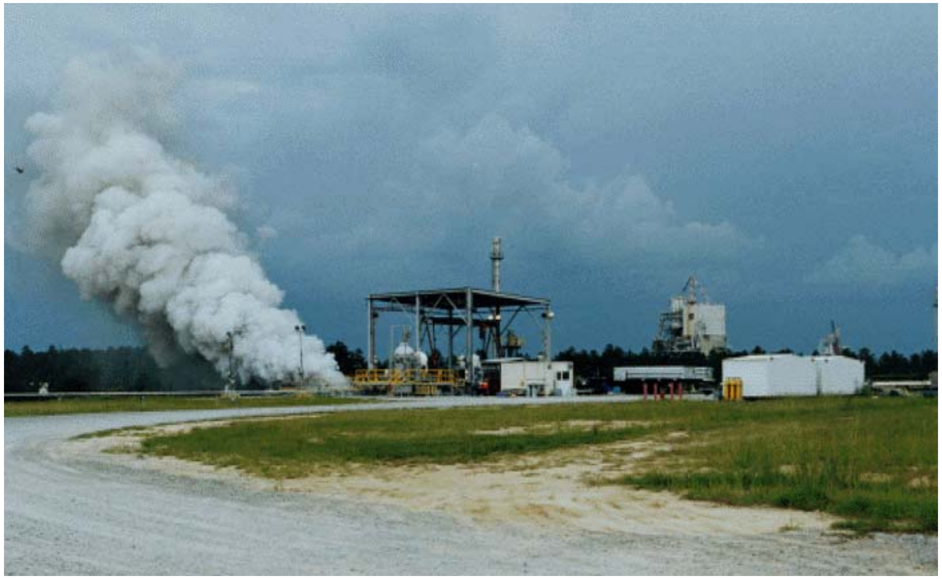

Cell 1


Cell 2

# SSC E-3 Test Stand Projects



## Hydrogen Peroxide Programs (50% to 98%)



- Tested Several H2O2 Test Articles
  - Boeing AR2-3
  - OSC Upper Stage Flight Experiment
  - Pratt & Whitney Catalyst Bed