41st Joint Propulsion Conference and Exhibit

Tuscon, Arizona

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Sub-Topic:
Liquid Rocket Engine Testing

AIAA Short Course on Liquid Rocket Engines

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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

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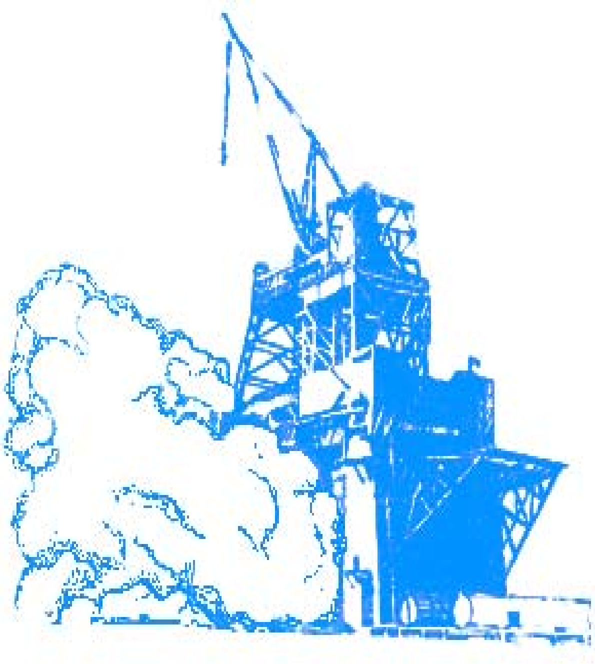
Section Outline (cont.)

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.

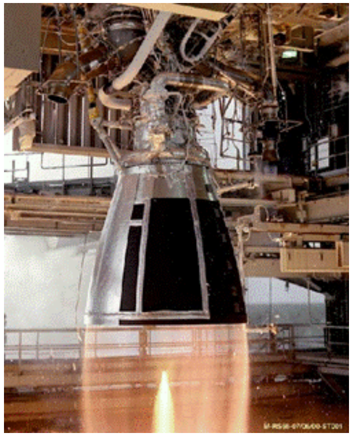
- ***Acceptance*** tests are conducted to demonstrate the acceptability of each deliverable item to meet performance specification and demonstrate error-free workmanship in manufacturing. Acceptance testing is intended to:
  - Stress screen items to precipitate incipient failures due to latent defects 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.

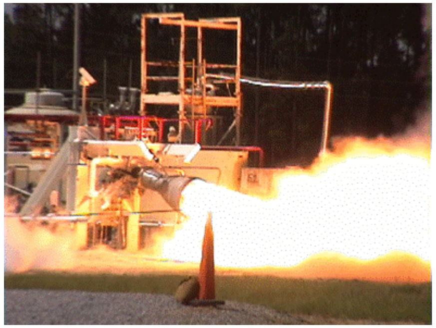
  Many components require engine hot fire to adequately reduce flight risk. (An engine LRU is a component that may be removed and replaced by a new unit, without requiring reacceptance test firing of the engine with the new unit. If the unit being replaced was included in an engine acceptance test firing 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

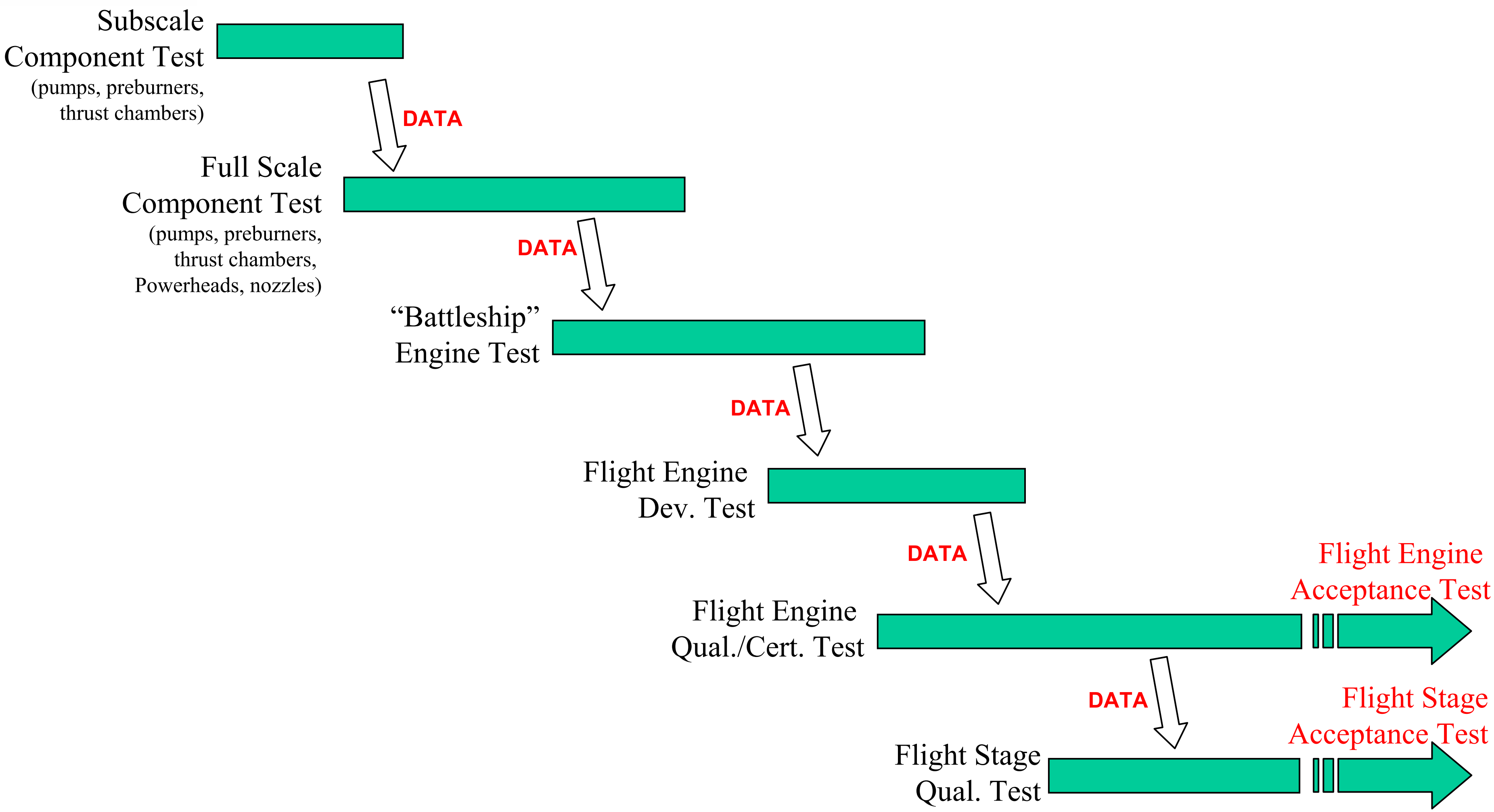
Some examples of each are listed

- 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





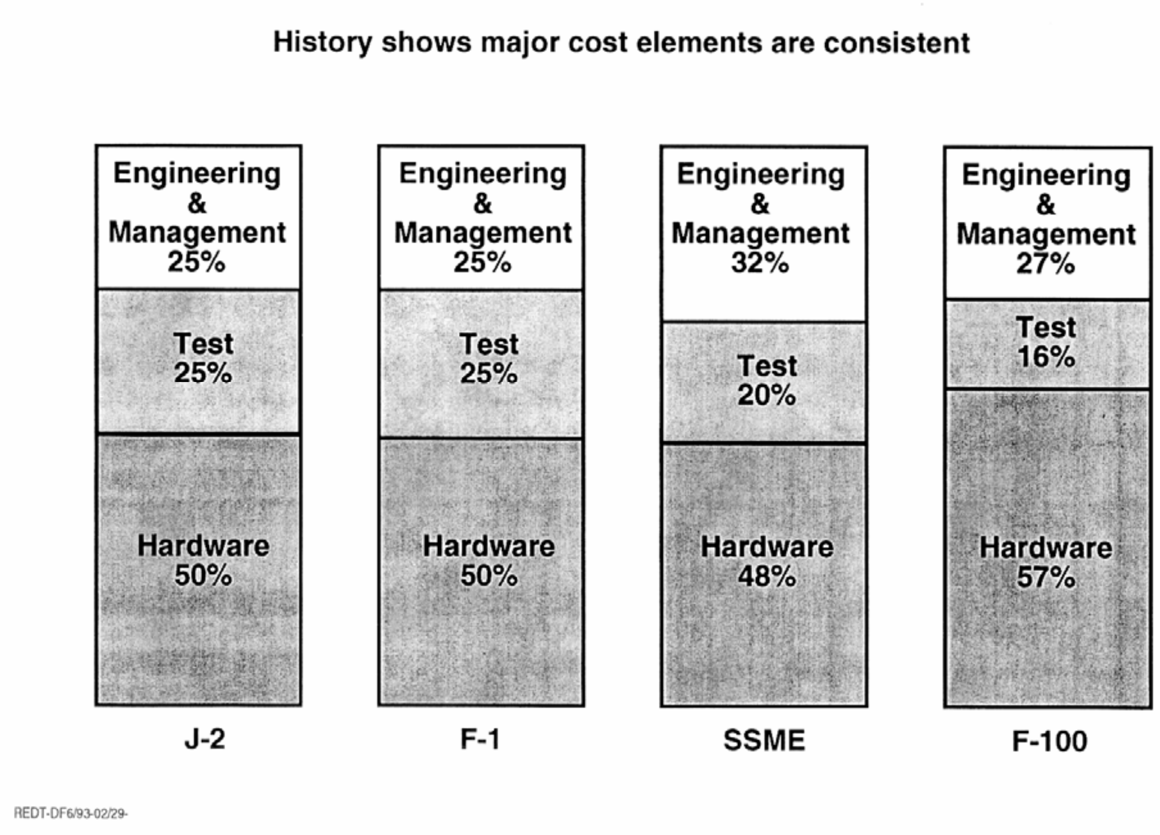
Typical Sequence of Testing



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

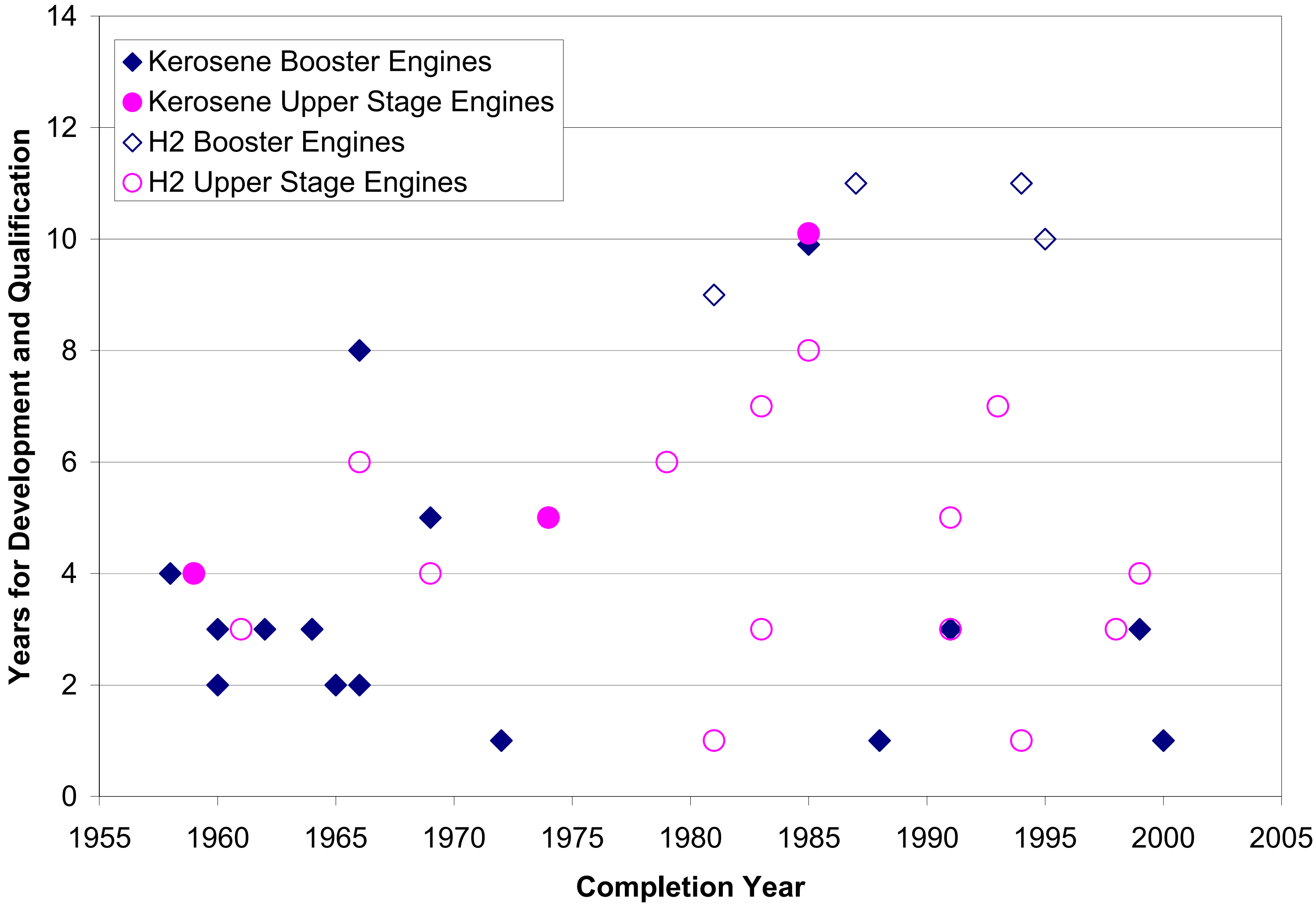
Testing Cost / Total Cost for Propulsion

Historical Full Scale Development Cost Distribution



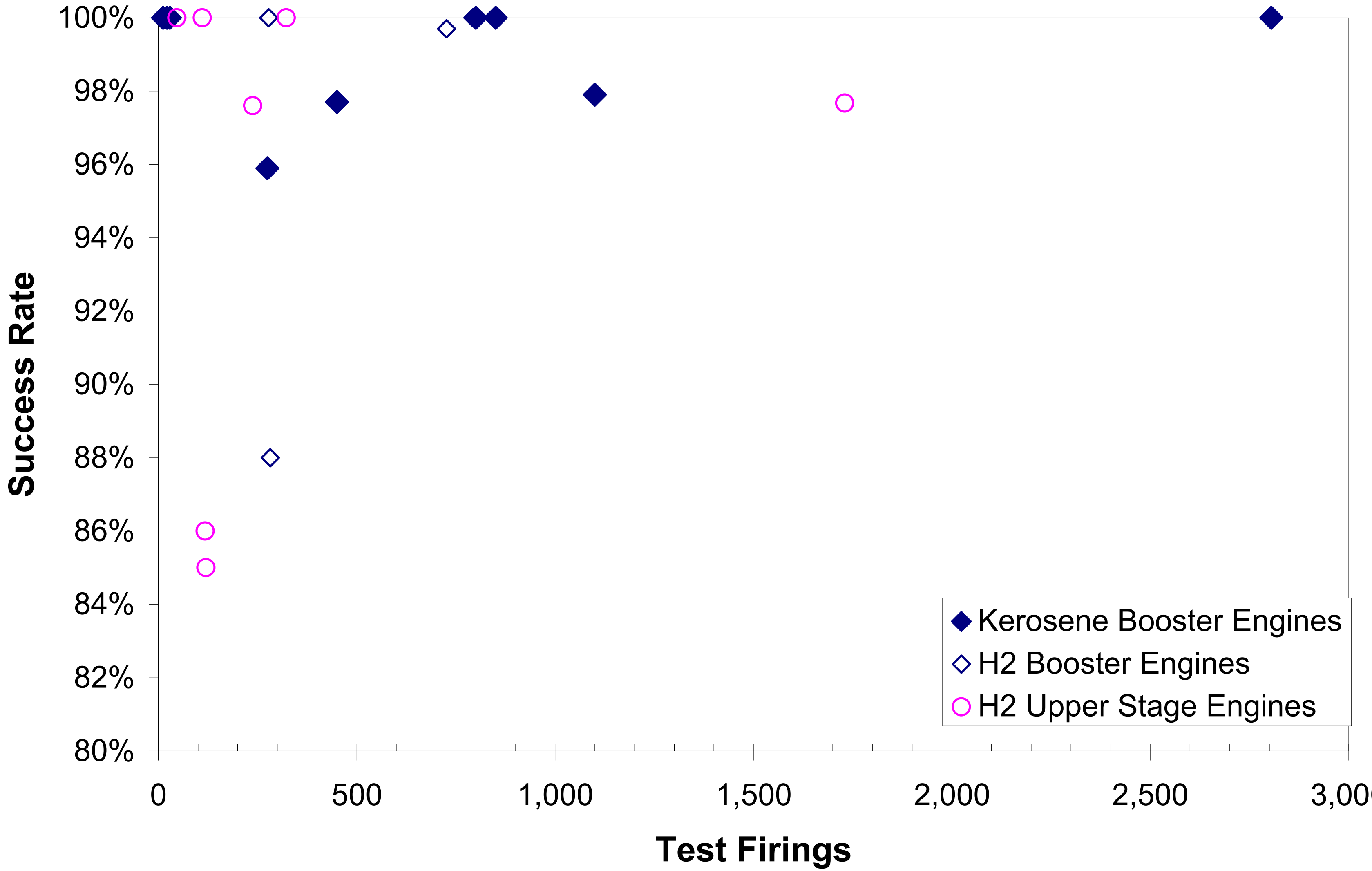
George, D.; "Chemical Propulsion: How To Make It Low Cost," presented at Highly Reusable Space Transportation Meeting, 25-27 July 1995.

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.
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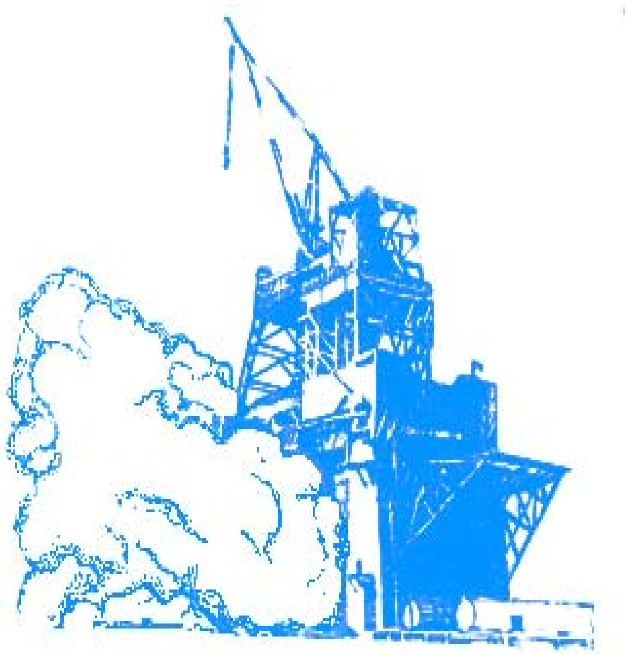
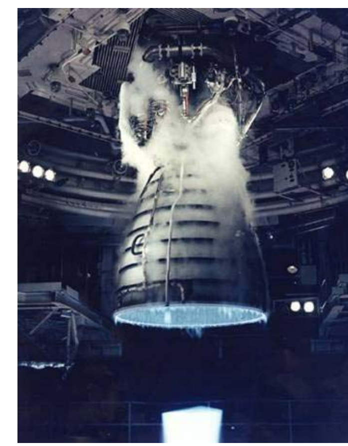
REPRESENTATIVE TEST CAMPAIGNS



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%

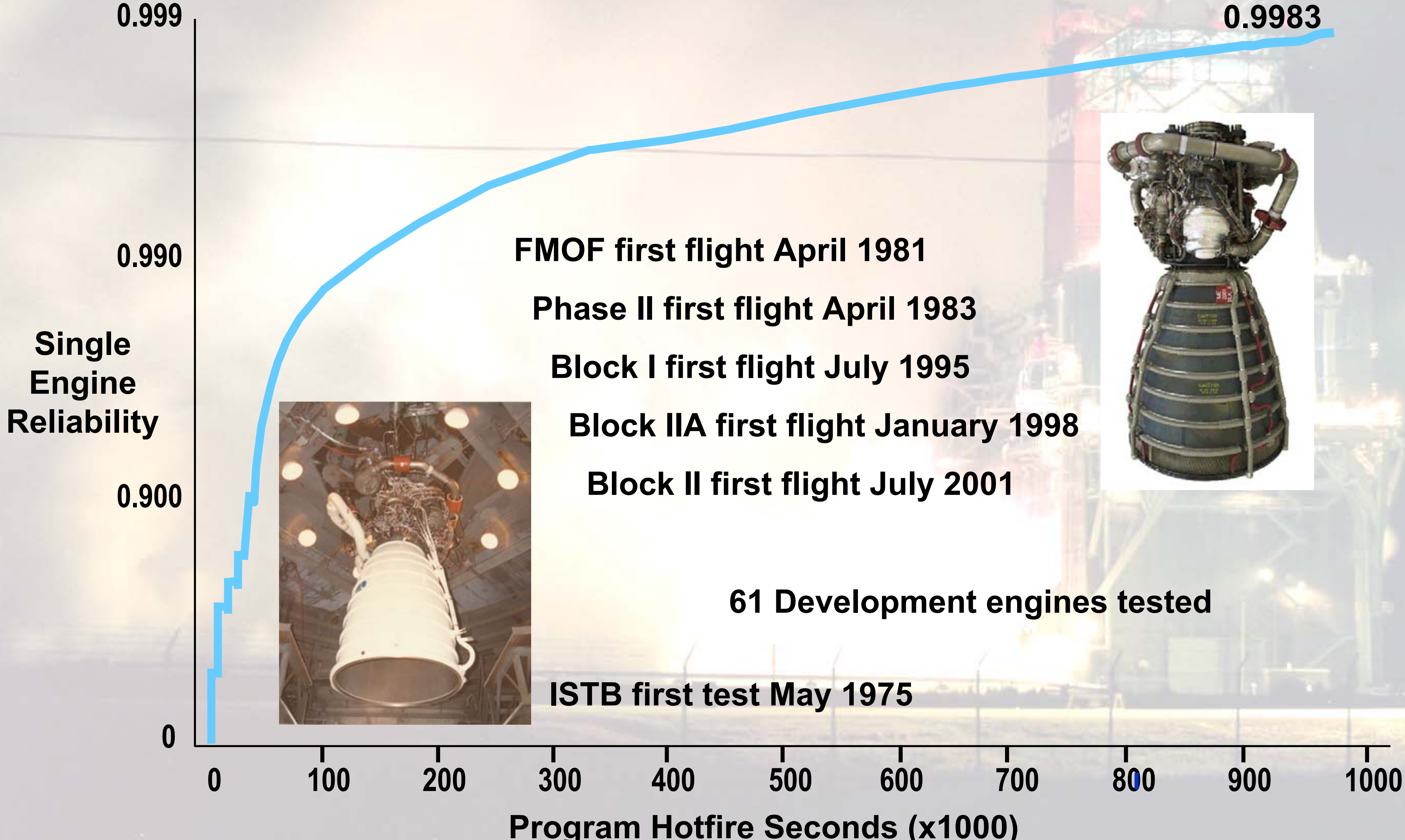
† = includes production due to lack of further information

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%

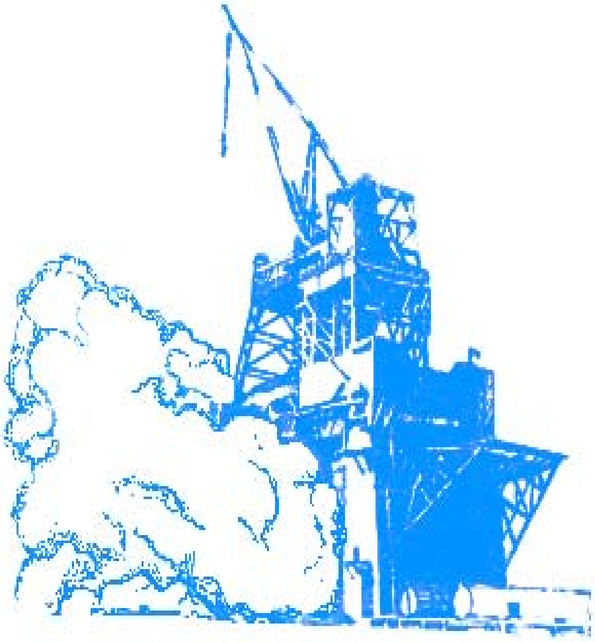
- Emdee, J., "A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines," AIAA Paper No. 2001-3985.

Test Demonstrated Reliability

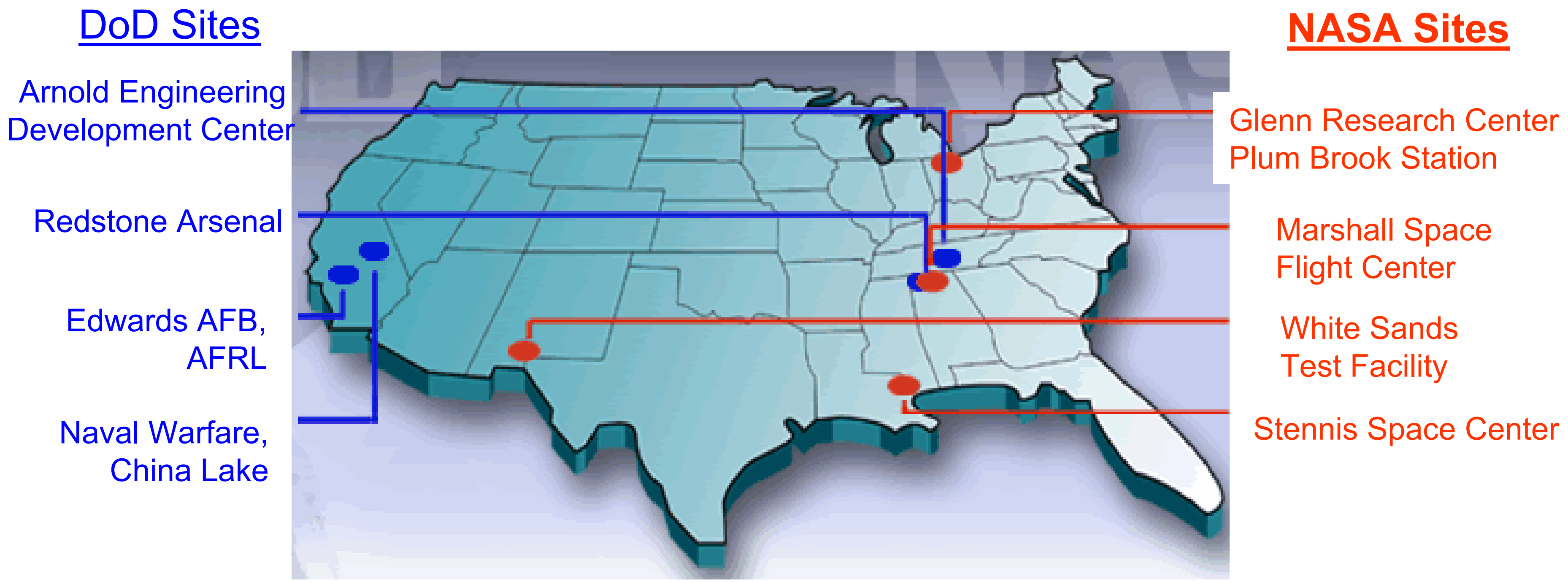


OVERVIEW OF TEST FACILITIES FOR LIQUID PROPULSION TESTING

(representative capabilities)



Rocket Propulsion Test Sites



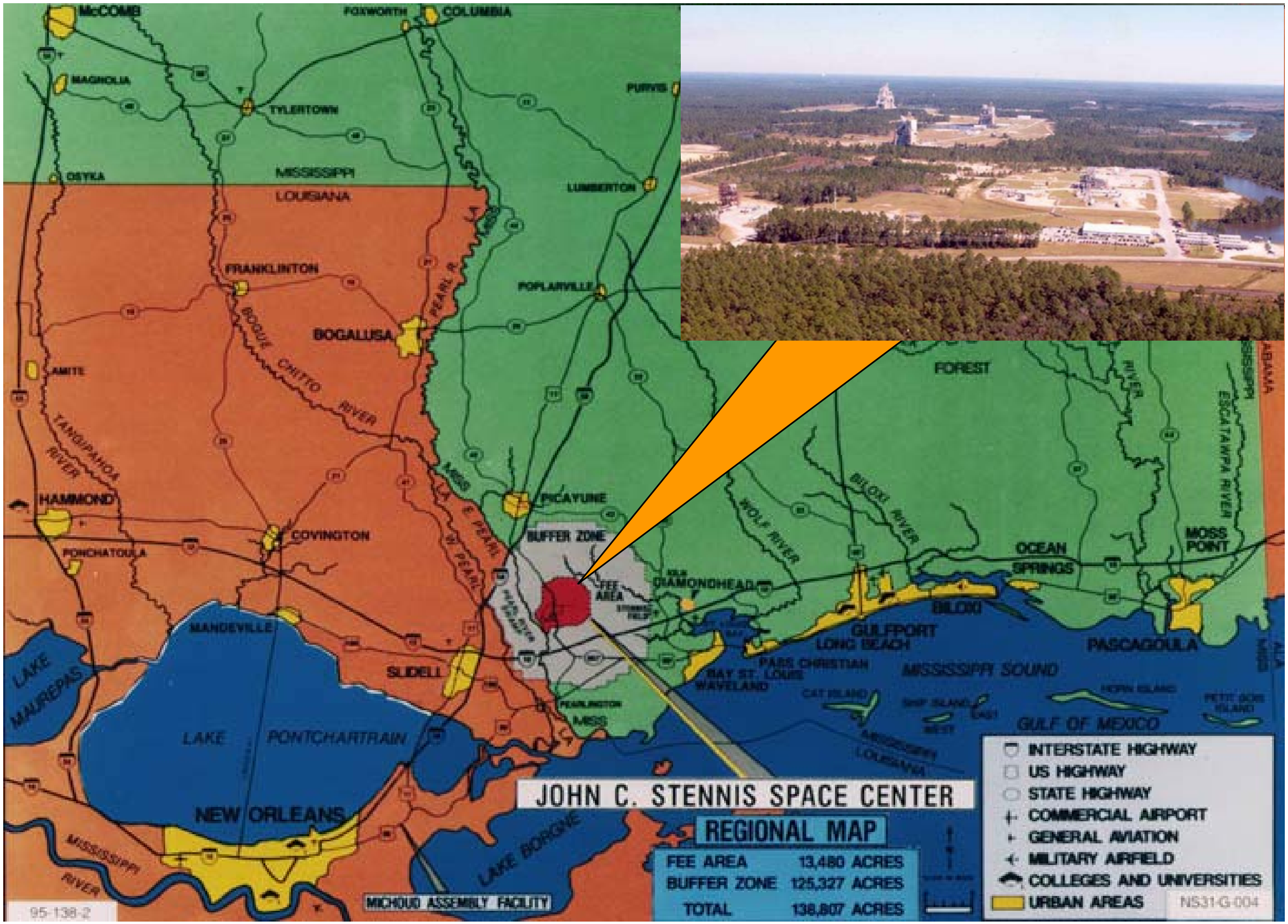
https://rockettest.ssc.nasa.gov

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

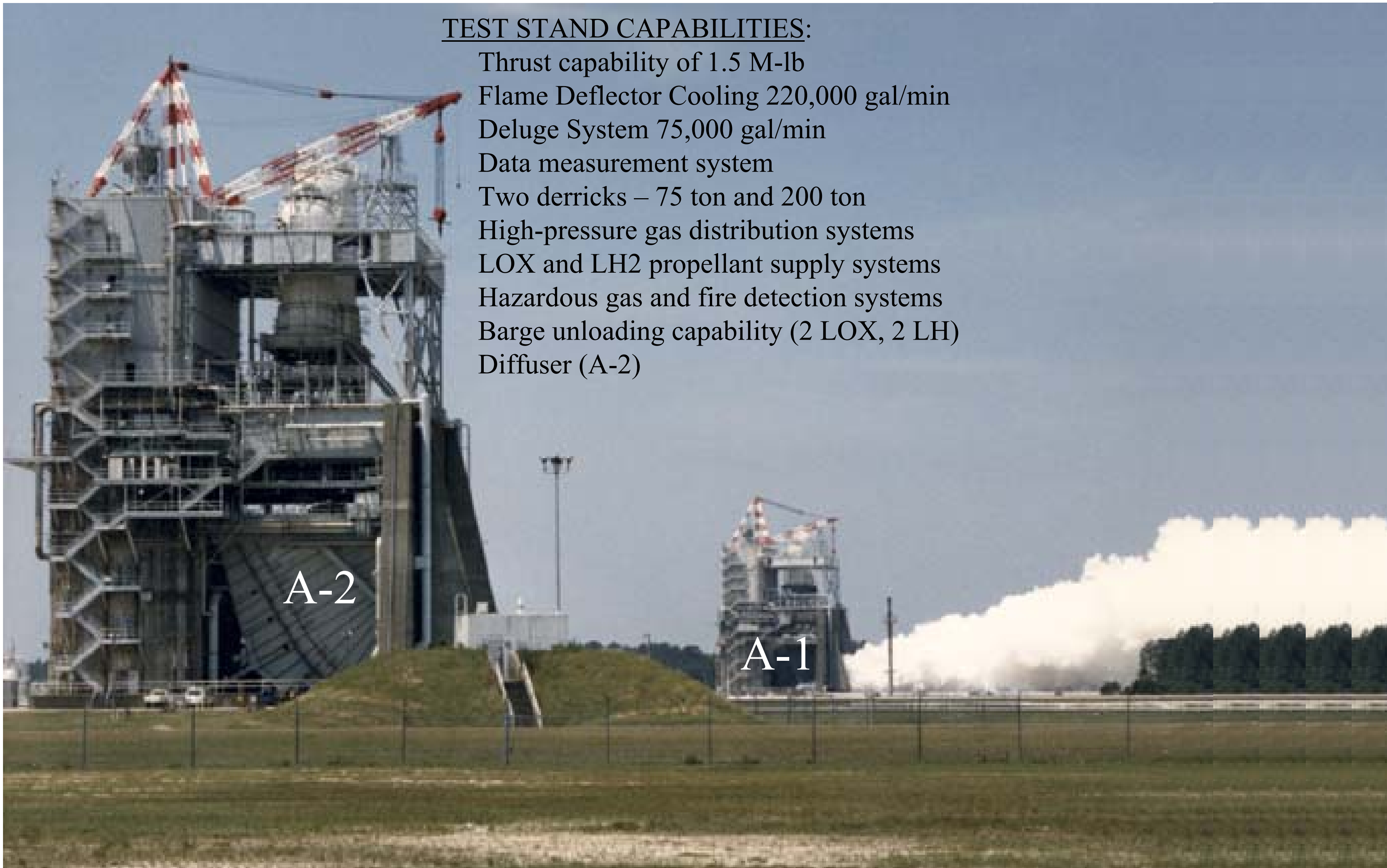
Small-Scale

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)

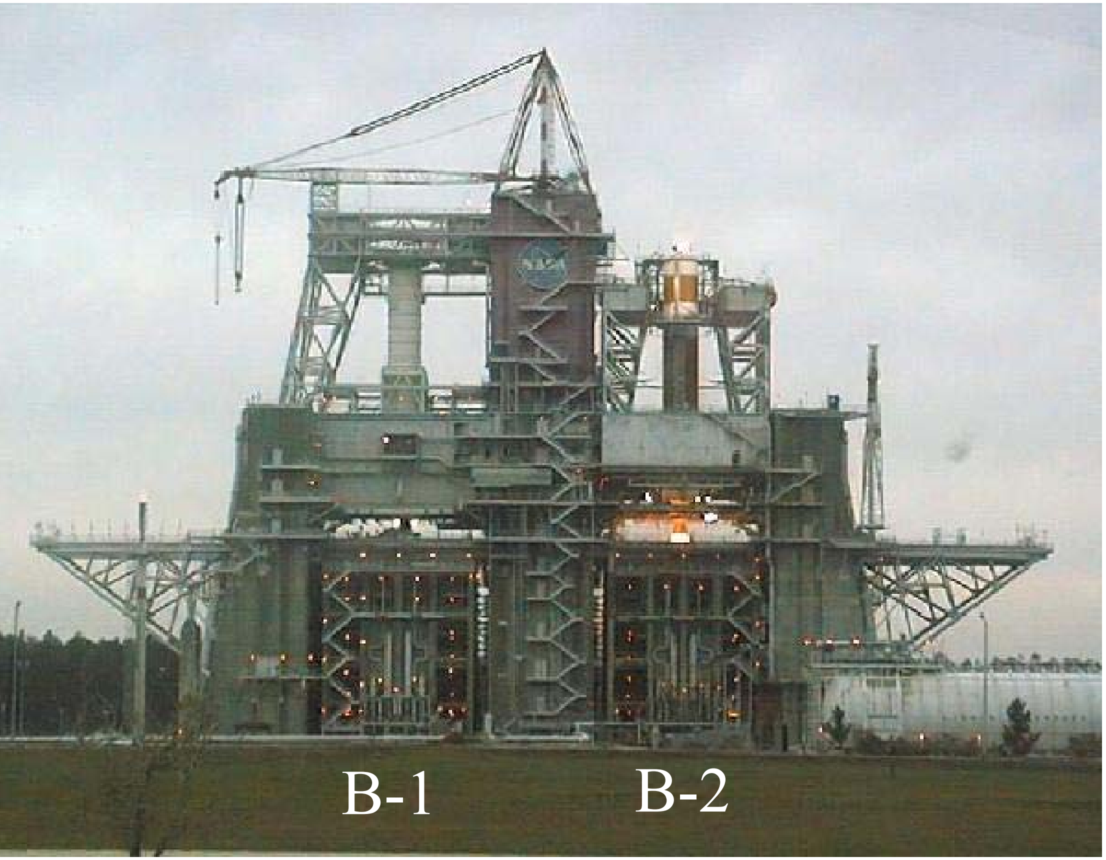


Space Shuttle Main Engine Test

SSC A-1 Test Stand

Space Shuttle Engine

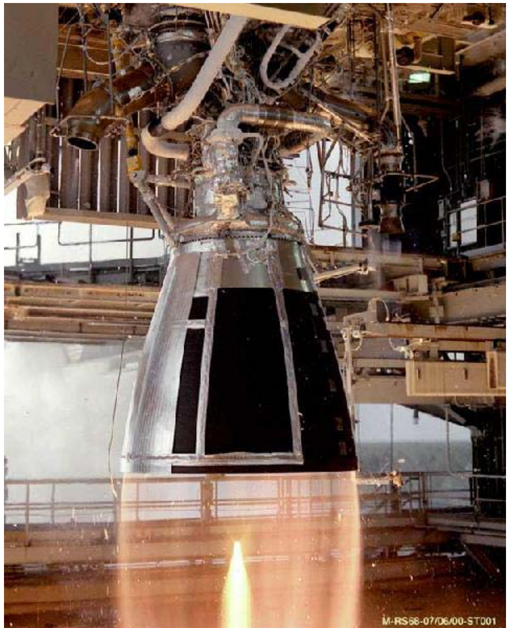
Stage and Engine Testing – SSC B Complex



B-2 Test of Delta IV Common Booster Core

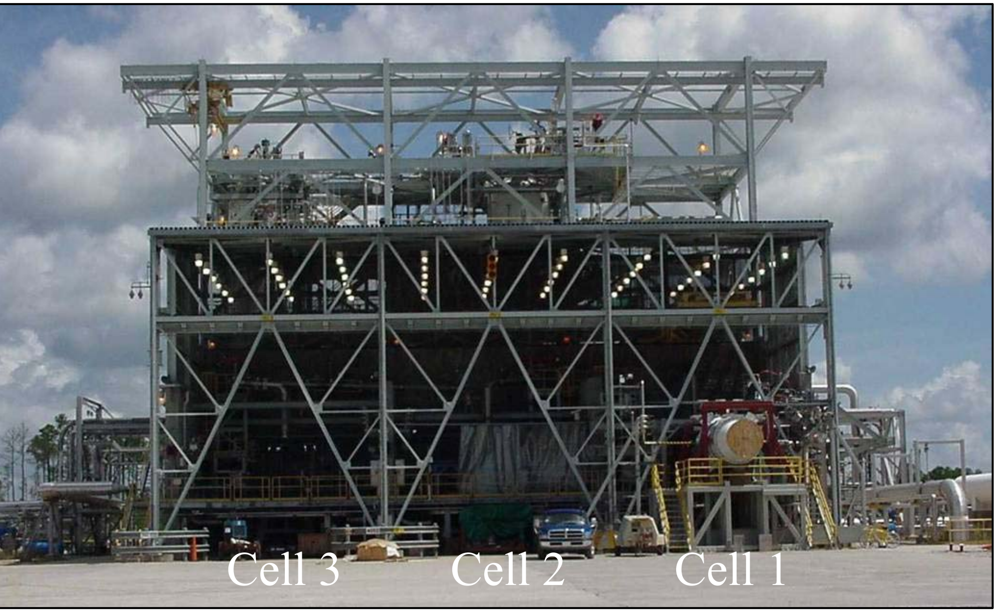
<u>TEST STAND CAPABILITIES</u>:

- 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_2Turbopump, 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

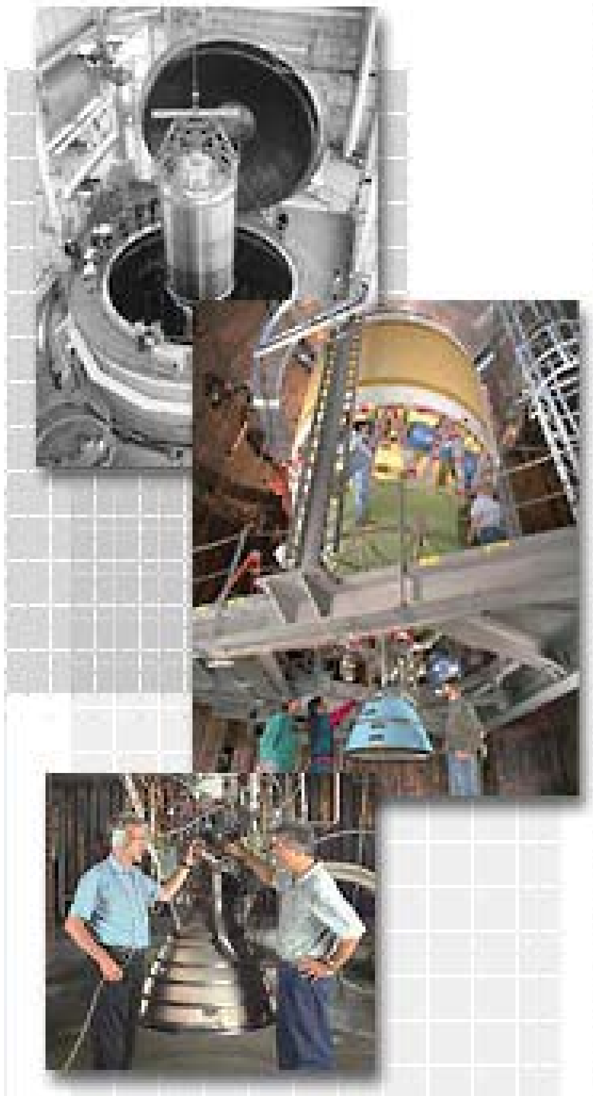
- E2 Cell 1
  - Primarily Designed for Pressure-Fed LO_2/RP1 Based Test Articles
  - Thrust Loads up to 100K lb_f (horizontal)
  - LO_2/RP1 ~ 8500 psia
  - GN/GH ~ 15000 psia
  - Hot GH (6000 psia/1300 F)
- E2 Cell 2
  - Designed for LO_2 /H2O2/RP1 Engine/Stage Test Articles
  - Loads up to 150K lb_f

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)

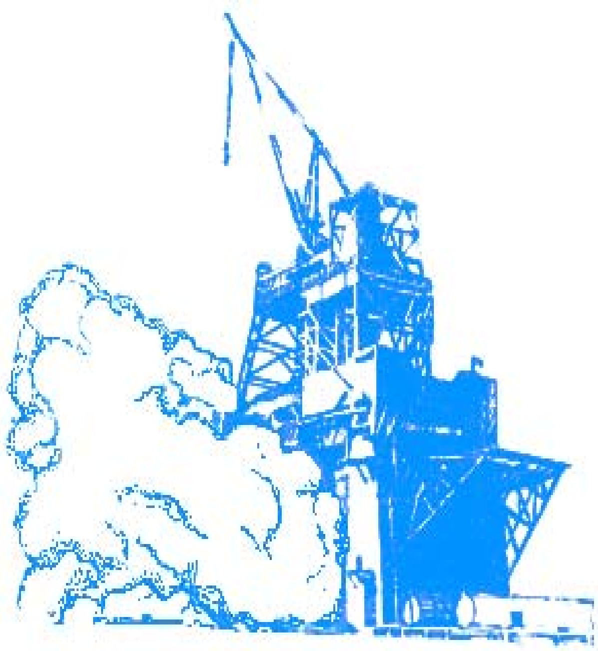
TF 115

- 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.

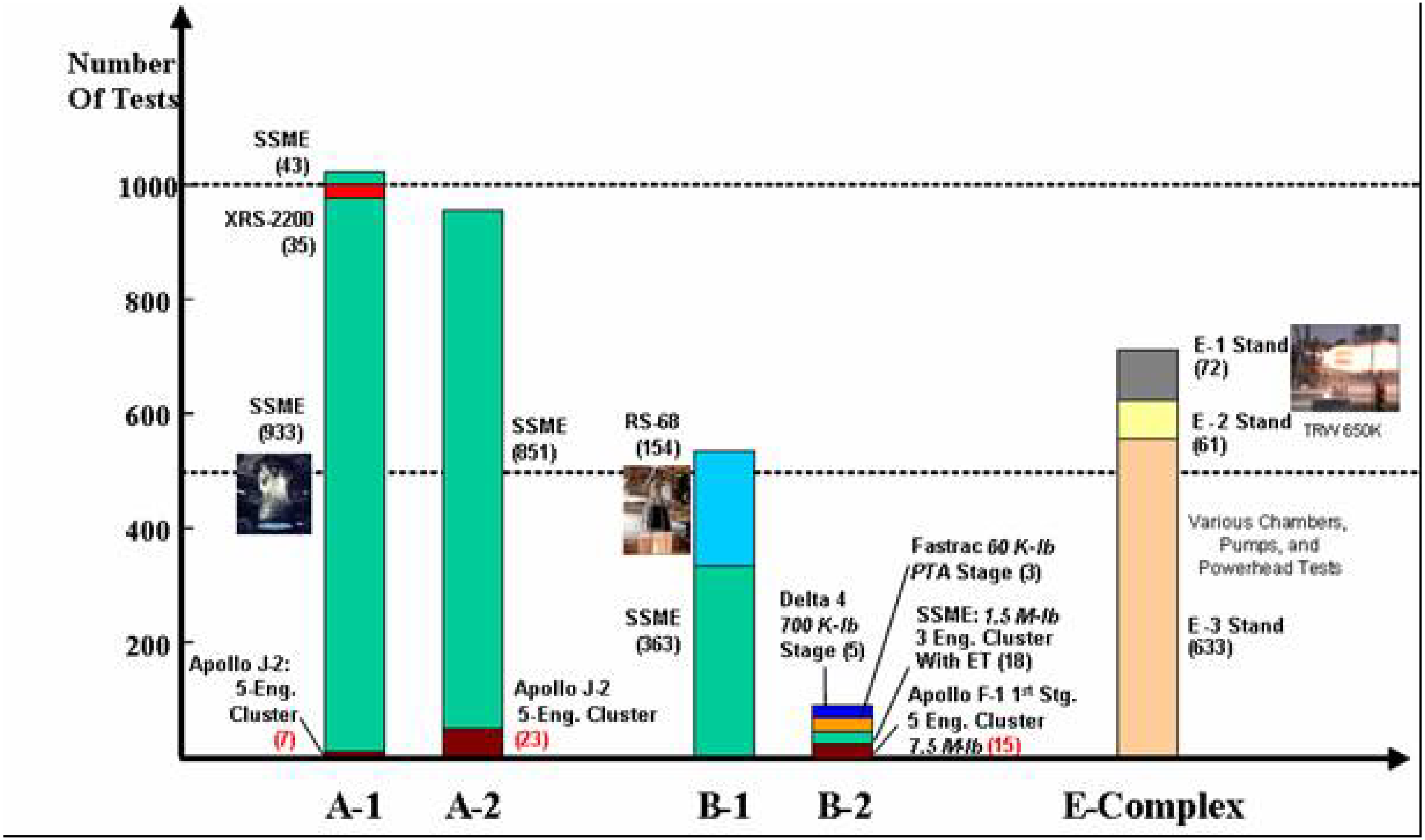
TF 116

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

STATISTICS (HISTORICAL) OF LRE TESTING

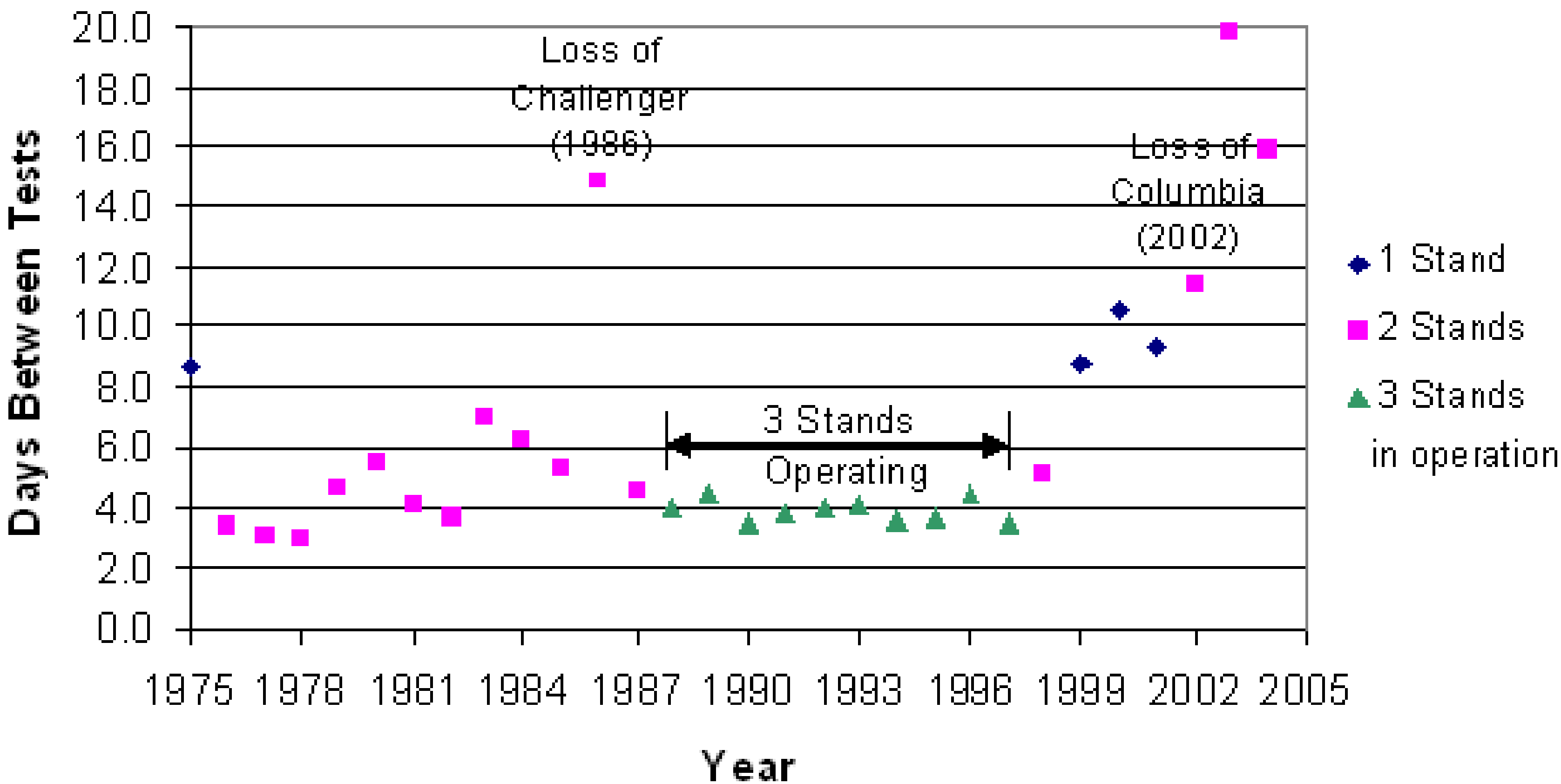


SSC Testing History (1966 – 2004)



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

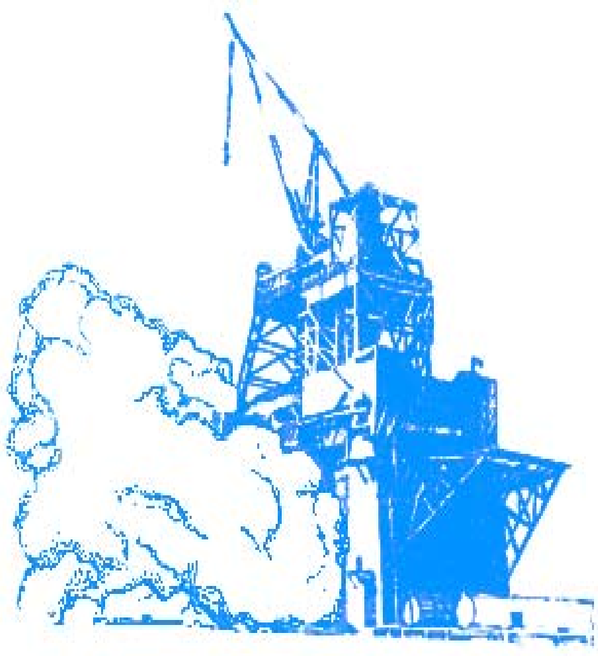
	SSME (Boost)	F-1 (Boost)	RS-68 (Boost)	J-2 (U/S)	RL-10A-1 (U/S)	LMDE (Lander)
Thrust	500 Klbf	1.5 Mlbf	700 Klbf	250 Klbf	15 Klbf	10 Klbf
Hot-Fire Test Seconds Prior to First Flight	110,000 s	250,000 s	**11,000 s (i/w)	120,000 s	71,000 s	149,000 s
Hot-Fire Test Seconds After First Flight	~750,000 s* (& 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

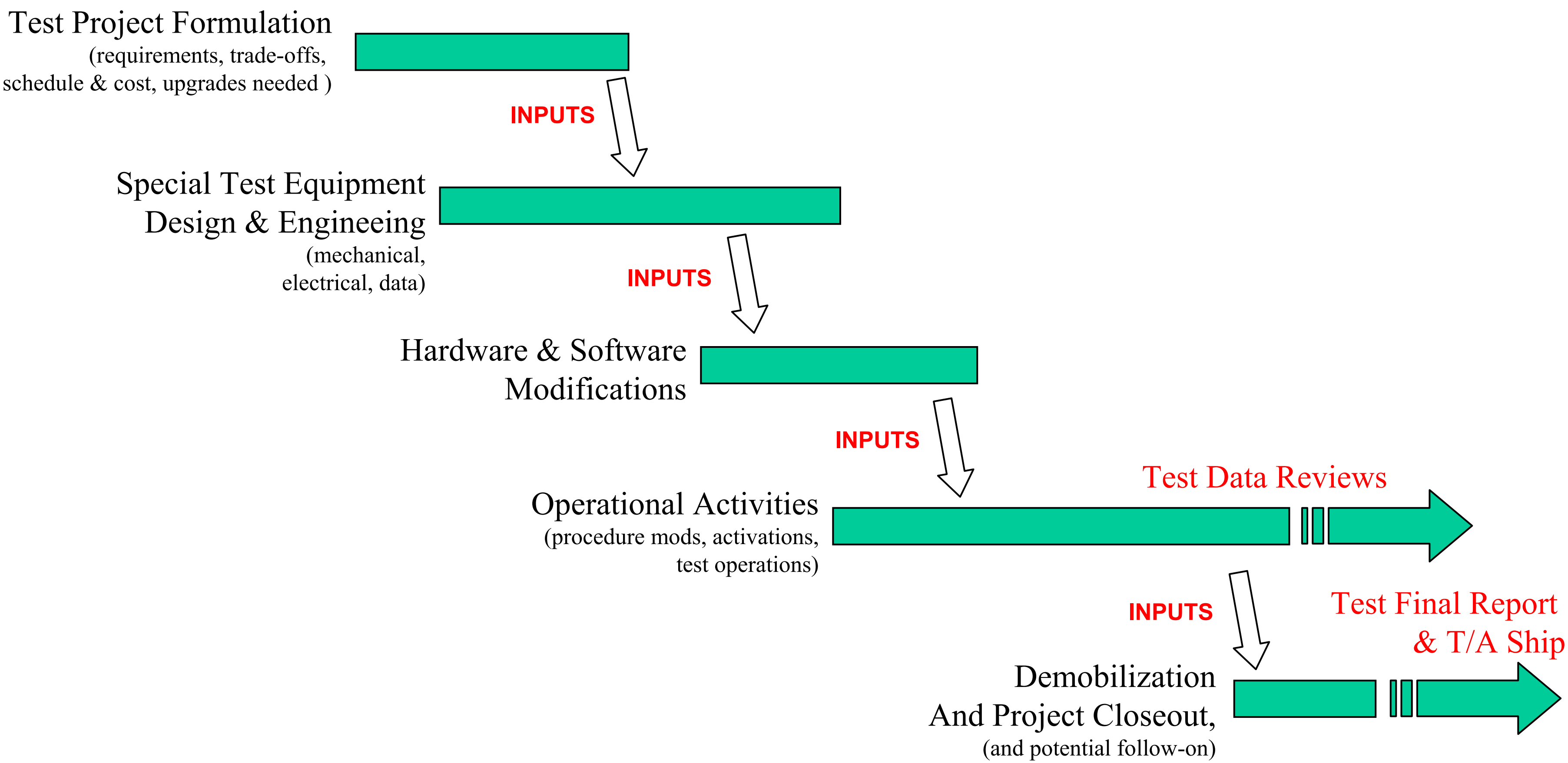
- Emdee, J., "A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines," AIAA Paper No. 2001-0749.
- Emdee, J., "A Survey of Development Test Programs for LOX/Kerosene Liquid Rocket Engines," AIAA Paper No. 2001-3985.
- Elverum, G. et al., "The Descent Engine for the Lunar Module," AIAA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

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



Test Project Process

- Life cycle of a typical test project

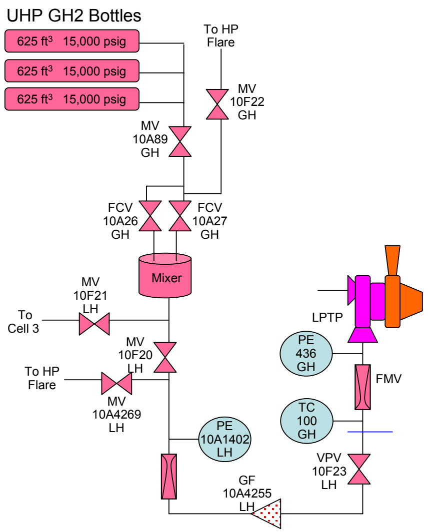


Test Facility/Project Modeling and Analysis

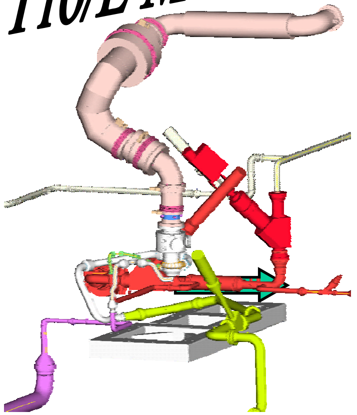
-- Propellant System Thermodynamic Modeling and Test Simulation --

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

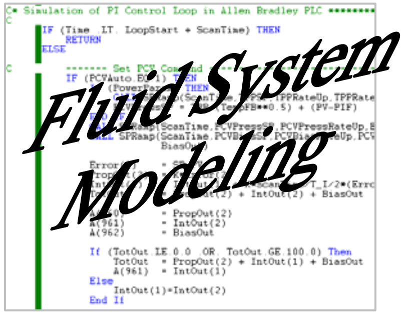
Schematic Development



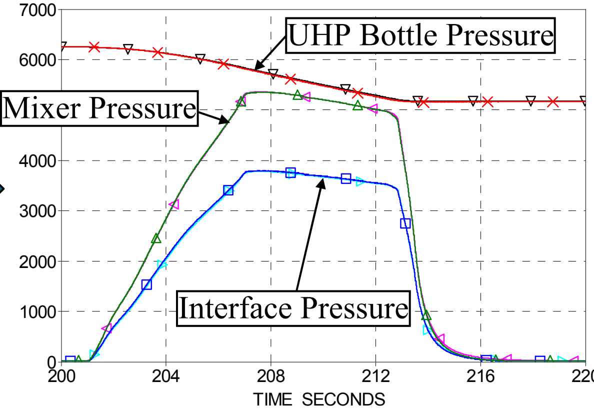
Pro/E Modeling



Fluid System Modeling



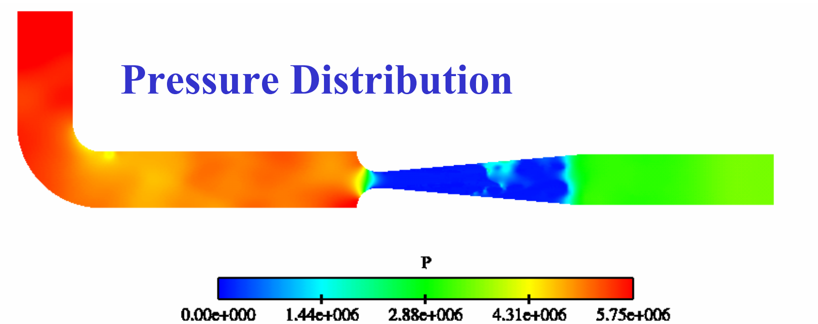
Test Data vs Model Assessment



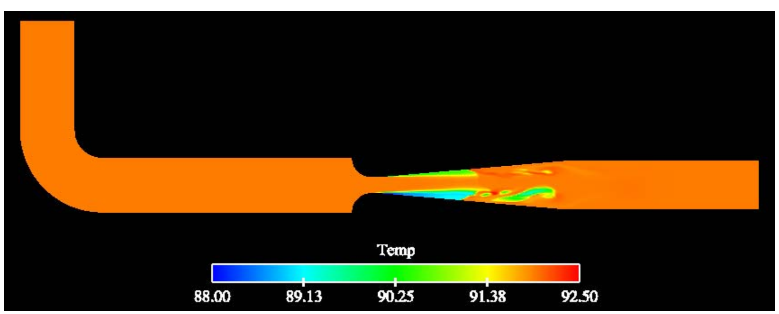
GH2 Activation Test #1
June 29, 2004

CFD Flow Modeling Applications

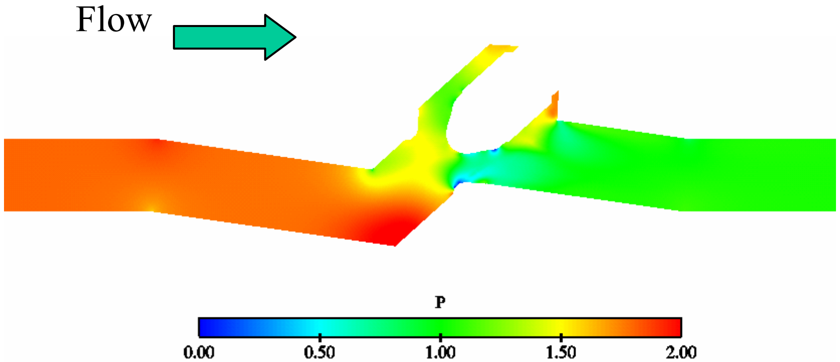
Cavitating Venturi with Upstream Bend



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)

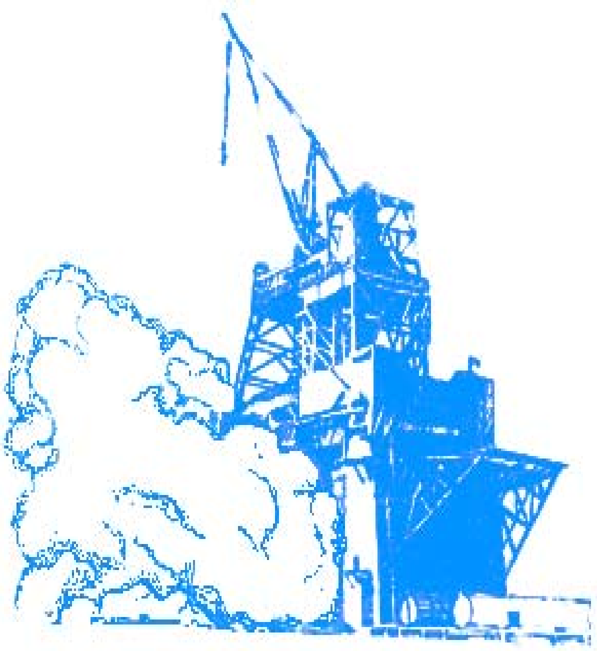
Additional Support

- 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

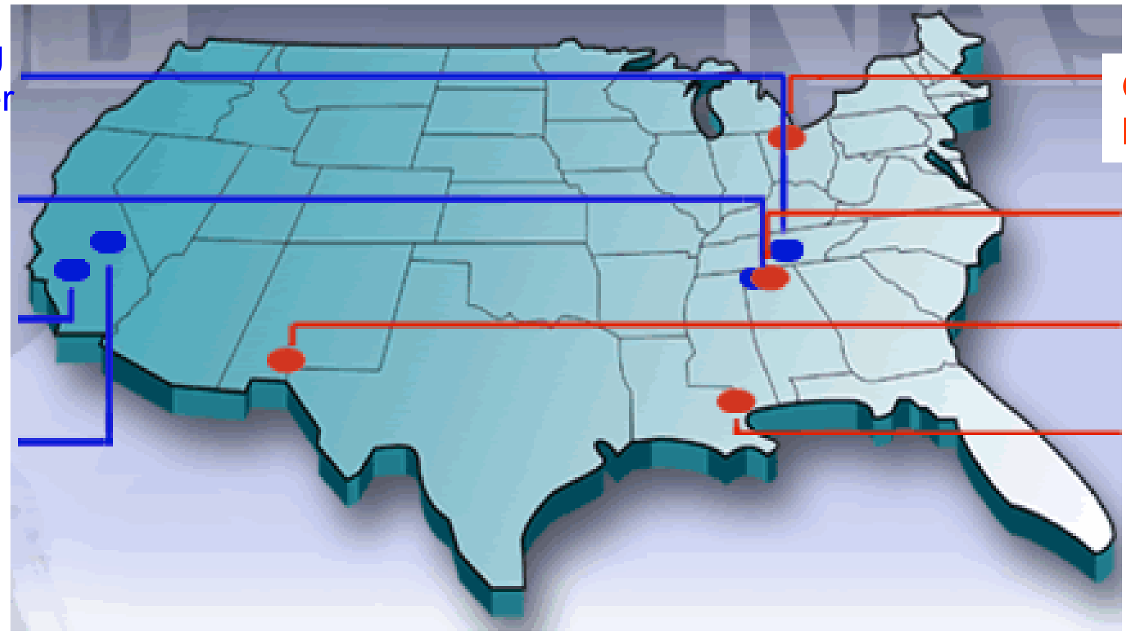
DoD Sites

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

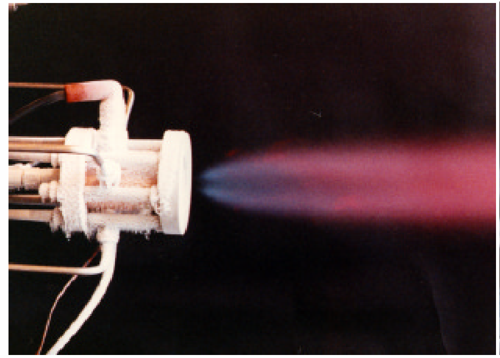
Rocket Engine Advancement Program Institute

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

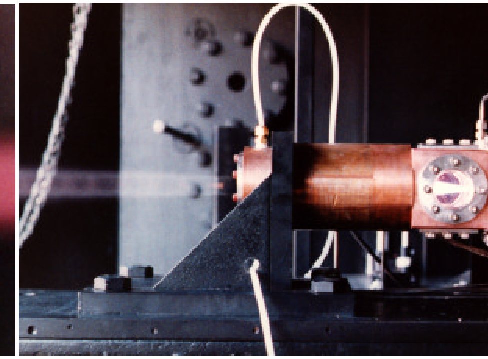
PROPULSION ENGINEERING RESEARCH CENTER

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

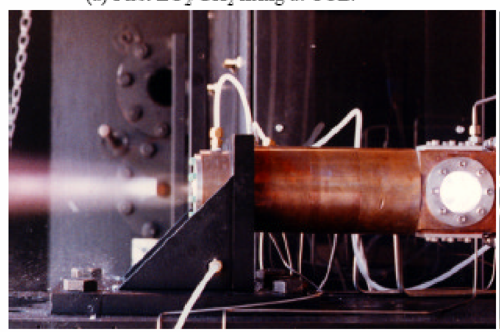
Representative LRE Injector Studies
Performance & Mixing
Combustion Stability
Heat Transfer
Non-Intrusive Diagnostics



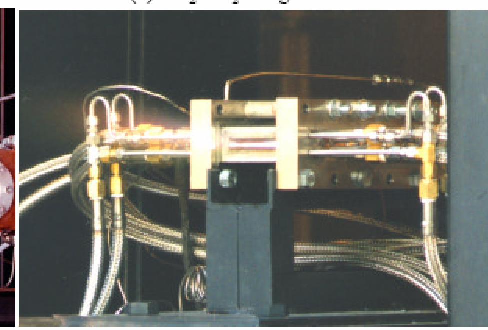
(a) First LO_2/GH_2 firing at CCL.



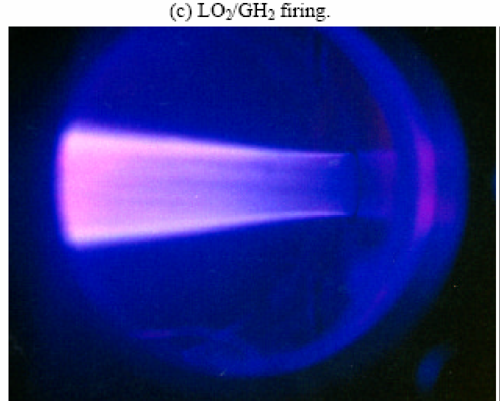
(b) GO_2/GH_2 firing.



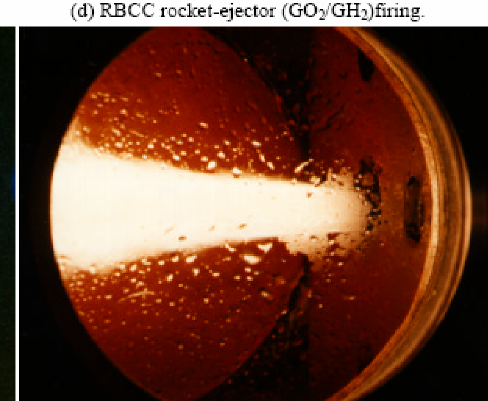
(c) LO_2/GH_2 firing.



(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.)

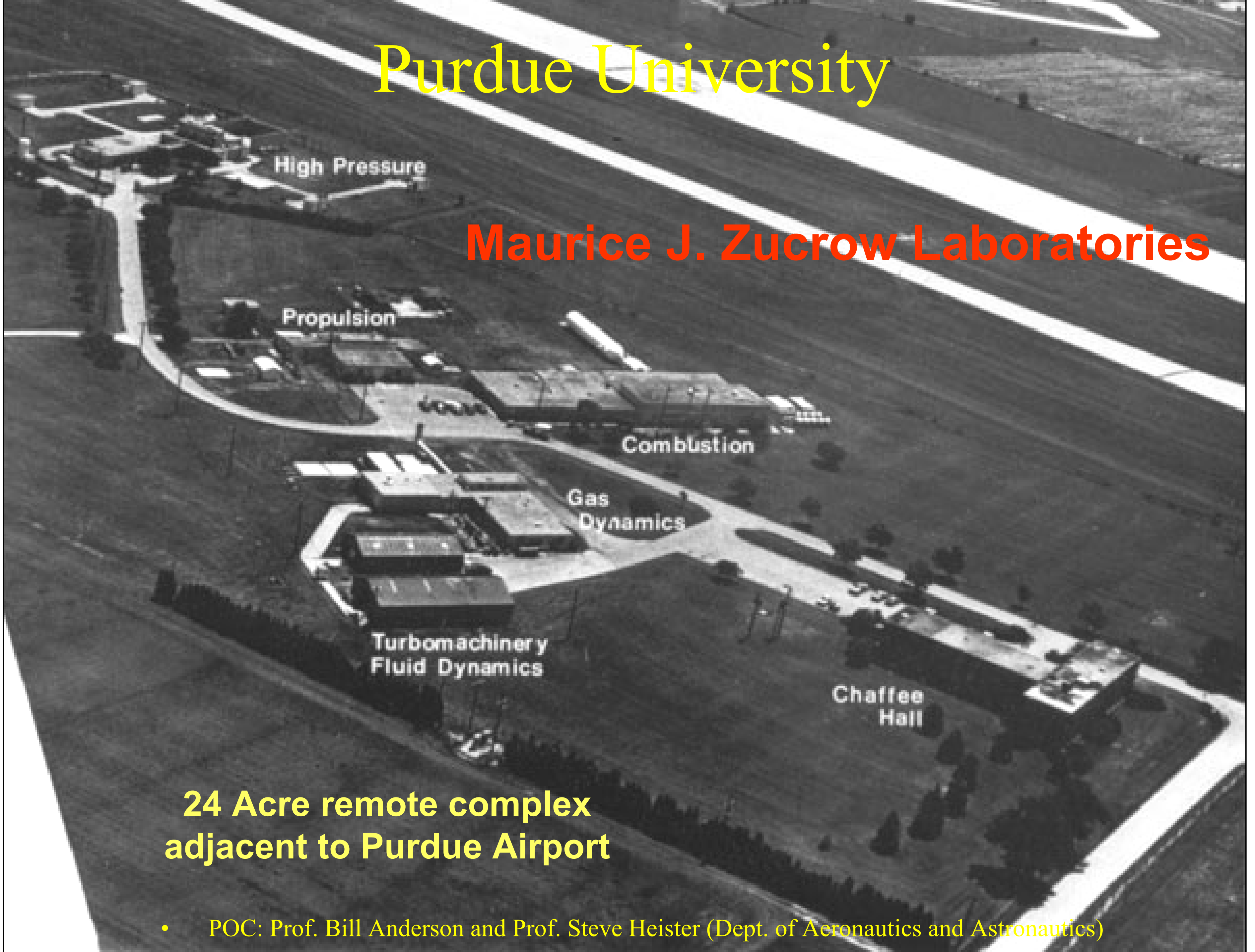
PROPULSION ENGINEERING RESEARCH CENTER

(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. • 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



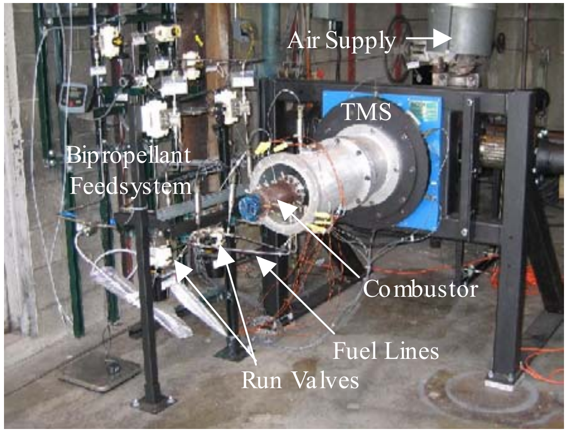
24 Acre remote complex adjacent to Purdue Airport

- 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

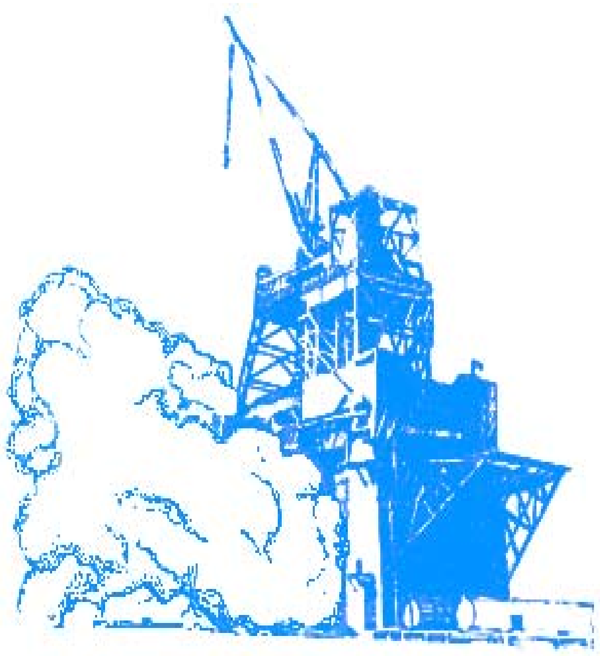
- Comprehensive Liquid Rocket Engine testing is essential to risk reduction for Space Flight
- Test capability represents significant national investments in expertise and infrastructure
- Historical experience underpins current test capabilities
- Test facilities continually seek proactive alignment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

Test What You Fly

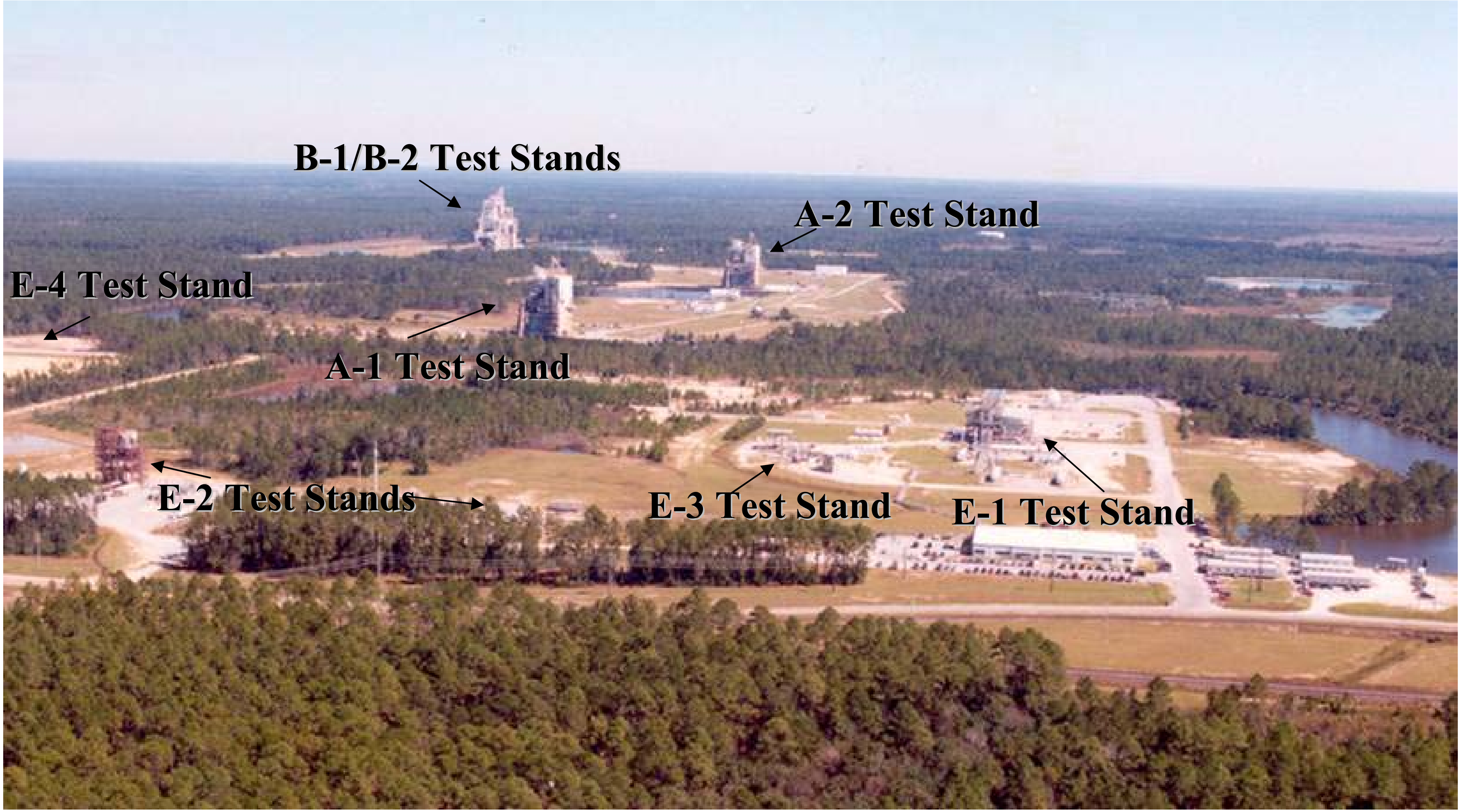
B-2 Test Stand
Stennis Space Center
(Delta 4 Stage installation)

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)

240 Klbf Aerospike … 17 tests
(1999-2001)

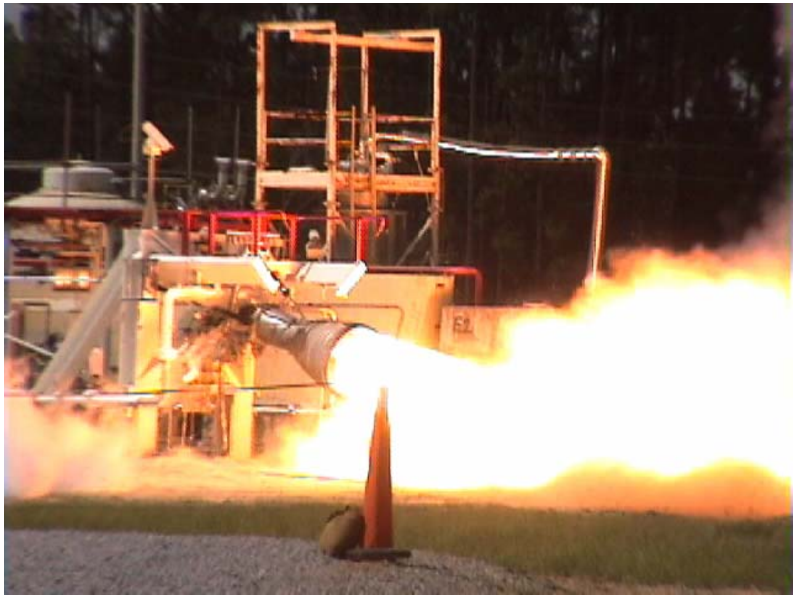
RTF SSME Accep (8-19-04)

IPD Eng. Install (10-15-04)

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

SSC E-2 Test Stand

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



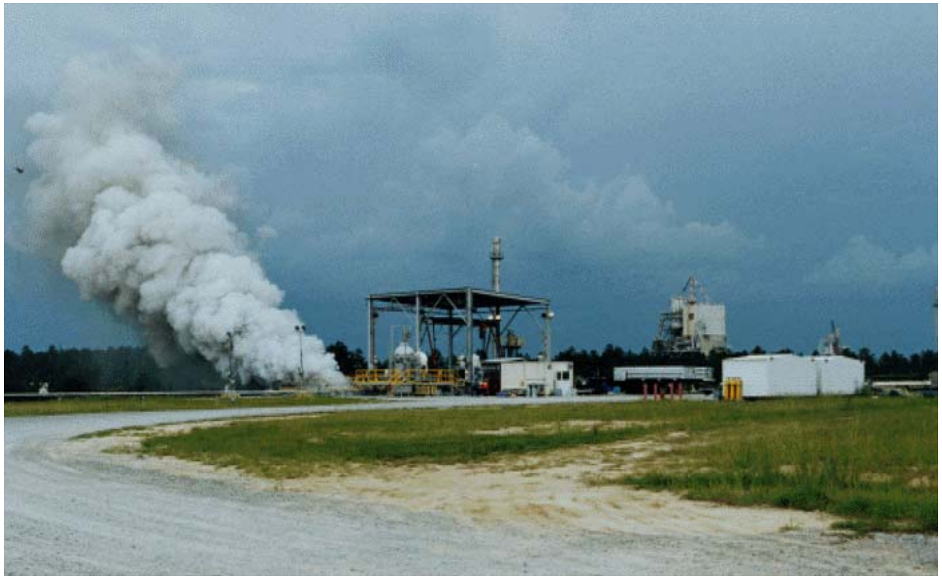
E-2 Cell 1 Test of LR-89 LOX/RP Thrust Chamber

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

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