Reusable Hydrocarbon Rocket Engine Maturity for USAF RBS

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Agenda

- Vehicles Launched with PWR Engines
- PWR Booster Engines
- AF RBS Requirements
- What Does Reusability Mean?
- RP Engine Technology Maturity
- RD-180 Engine
- RS-84 Engine
- Advanced HC Expander Engine
- Propulsion Summary

50 Years of PWR Engines
>1700 Launches

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ACTIVE

Redstone	Navaho	Jupiter	Thor	Atlas I/II	Saturn I/1B	Saturn V	Titan Centaur-T	PK	Space Shuttle	THAAD	Delta I/II/III	Atlas III/V	Delta IV
85	11	46	380	568	19	13	17	51	135	23	341	34	15

Last updated: Jan. 16, 2012

PWR Is The Industry Leader For Hydrocarbon-Fueled Engines

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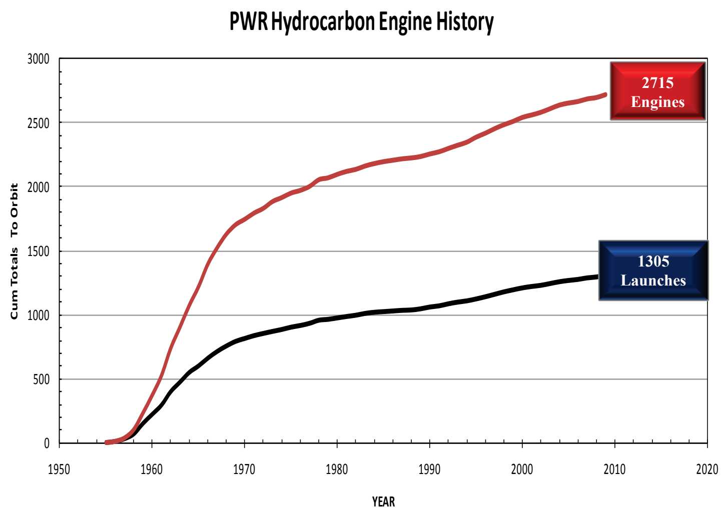

PWR Is The Industry Leader For Hydrocarbon (HC) Fueled Engines

- ✓ Over 50 years of experience
- ✓ Over a dozen engine models to production
- ✓ Advanced state-of-the-art technology through continued development – GG, SC

Continuous HC Engine Evolution and Advancement Over 50 Years

Launches Powered To Orbit By PWR Hydrocarbon Engines

✓1312 launches

✓2722 Hydrocarbon engines

PWR Has Over 50 Years of Hydrocarbon Engine Experience

PWR Booster Engines Flown

Engine	Engines Flown	Fuel	Thrust (sl, lbf)	Vehicle
S-3D	46	RP	150k	Jupiter / Juno
MB-1 / RS-27A	721	RP	135k / 200k	Thor / Delta II
H-1	152	RP	205k	Saturn 1B
MA-1, 5A	1,704	RP	430k + 60k	Atlas I, II
F-1	65	RP	1,520k	Saturn V
RD-180	34	RP	860k	Atlas V
SSME	51	H2	510k	Shuttle
RS-68	28	H2	663k	Delta IV

PWR Has Flown the Most Large RP Engines

PWR Continuous Propulsion Improvement in 2011

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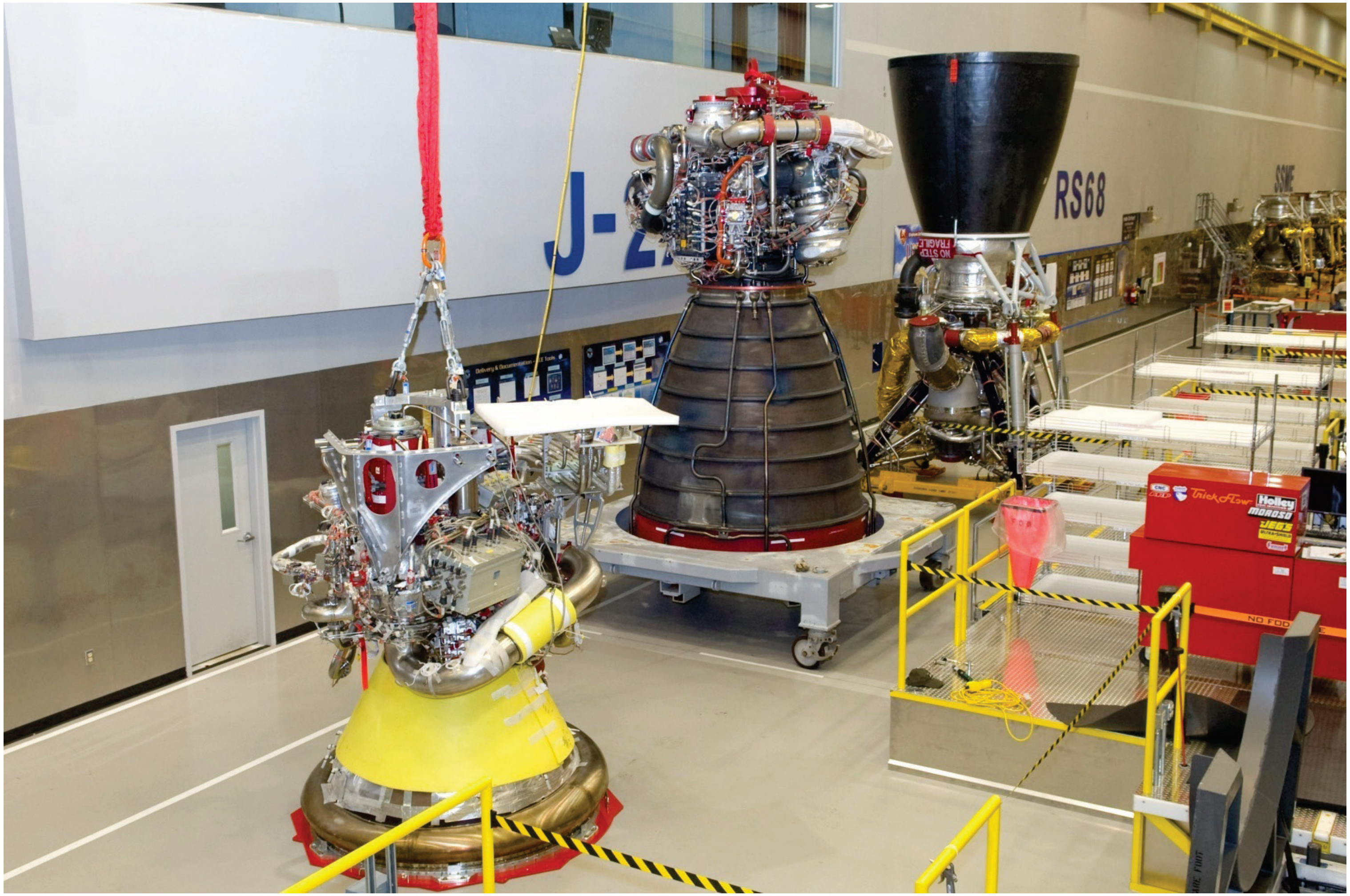
- Engine Flight Support (14 launches)
  - 5 Atlas V flights (RD-180, RL10)
  - 3 Delta II flights (RS-27A)
  - 3 shuttle flights (SSME RS-25)
  - 3 Delta IV flights (RS-68, RL10)
- Engine Production
  - RD-180, RS-68A
- Engine Development
  - J-2X, RL10 upgrade, RS-68A upgrade
    - First J-2X development engine achieved full power level in 3rd test & full mission duration in 8th test
- Engine Technology Development (internal and contract)
  - NASA HC engine technology, AF advanced HC engine technology, J-2X, RL10

HC engines

PWR Large Engine Assembly, Test & Servicing at SSC



J-2X SSME RS-68

USAF Reusable Booster System

- Propulsion Needs
  - Reusable
  - Reliable – Mission success
  - Operable - Rapid ground turnaround
  - Support booster Return to Launch Site (RTLS)
    - Multiple approaches under study

- A high thrust booster engine likely required
  - Determined by payload, system architecture, booster return approach, etc.

Reusable RP engine technology development required to meet known requirements

Possible Reusable RP Engine Technical Risks

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- Combustion Stability
- Oxidizer-rich Environments
- Combustion Chamber Cooling
- Restartability
- Reusability

What Does Engine Reusability Mean?

- Restartable engines a limited form of reusability
- Reusability requires more in-depth analyses to assure reliability
- Significant design life to useful life margin required for high reliability
- Material selection strongly driven by reusability
- Reusability drives Non-Destructive inspection capability to reliably detect small critical flaw sizes
- Maintainability & operability must be considered early in design
- Certification demonstrates flight configuration meets mission & life requirements

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RP Engine Technology Maturity

- Expendable RP
  - GG cycle - extensive US & foreign development, production & flight experience (TRL 9)
  - SC cycle - foreign dev, prod & flight experience (TRL 9); US integration & flight experience with imported engine (34 flights; TRL 9); US co-development of RD-180
- Reusable RP
  - GG cycle – AR2 aircraft rocket propulsion (Peroxide/RP engine on NF-104, F-86; TRL 9) & In-space propulsion (NASA X-37)
  - SC cycle – None operationally demonstrated
    - Foreign RD-170 certified reusable engine for Energia booster; US development of RS-84 for NASA reusable booster
    - Foreign RD-58 restartable upper stage propulsion demonstrated (TRL 9); multiple flight failures (failure to restart) on Proton Block DM

RD-180 Engine

- **Lox/RP Ox-Rich Staged Combustion (ORSC) cycle**
  - **860k lbf sea level thrust**
  - **339 sec vacuum Isp**
- **RD-180 engine developed from 1995 to 2000**
  - **RD Amross (RDA) Joint Venture – PWR & NPO Energomash**
  - **Derived from RD-170 engine family (Energia, Zenit)**
  - **Successfully flown on 34 Atlas launches**

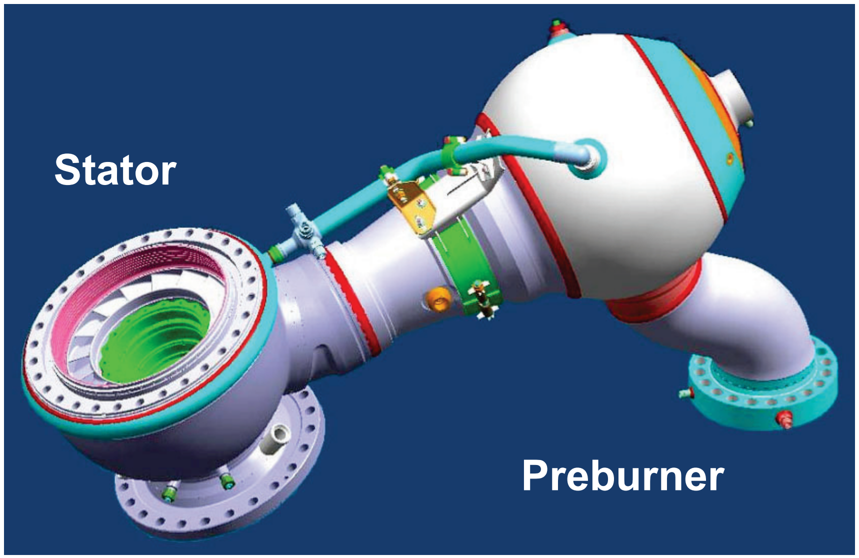
Atlas V launch

US RD-180 Engine

- US RD-180 Co-production Status
  - Obtained all technical data required for US production
  - Identified or developed substitute US materials
  - Developed US fabrication & inspection processes
  - Key processes & materials demonstrated at subscale; majority demonstrated at full scale
  - Manufactured and successfully burst tested US-produced full scale preburner and stator assembly

Ref AIAA-2007-5487

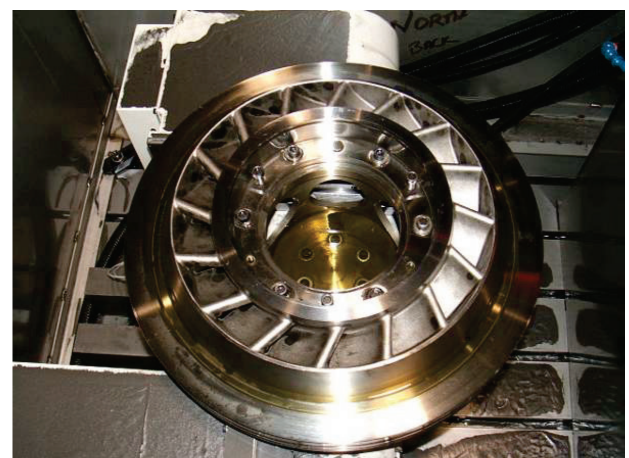
US Co-Production of RD-180 Engine



Fabricated Details

>1,000 Engineering Models Developed

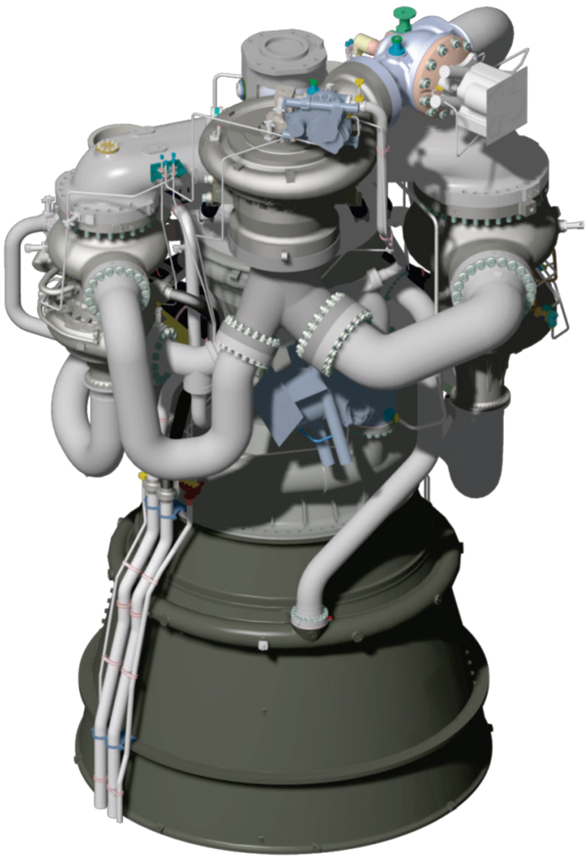
EDM'd Stator Vanes



Ref AIAA-2007-5487

RS-84 Engine

- Oxidizer-rich staged combustion cycle
- 1,049 klbf sea level thrust
- 100 mission life
- Reliability >10x improvement vs SSME
- HIP bonded chamber & channel wall Nozzle
- Engine health management system



Designed for high reliability and reduced cost

RS-84 ORSC Engine Program

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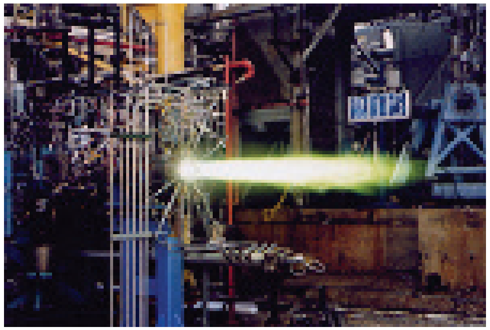
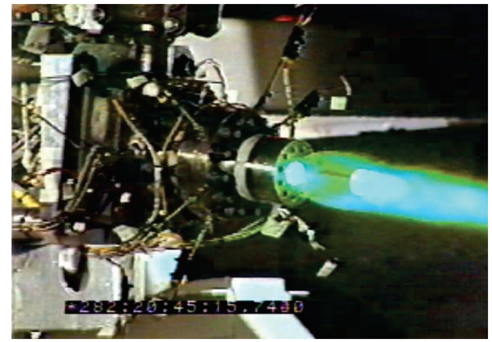
- **1997-2001: Key ORSC IR&D Demonstrations**
  - **Single element & multi-element 40k ox-rich preburner injector**
  - **Single element main injector staged combustion**
  - **Developed ox-compatible high strength superalloy to eliminate protective coatings**

- **2001-2004: NASA RS-84 Engine contract**
  - **1M lbf reusable engine design & analysis proceeded beyond system PDR**
    - Achieved CDR on full scale PB, 40k staged combustion rig
  - **Conducted extensive materials, fabrication and component test risk mitigation efforts**

RS-84 Engine Risk Mitigation

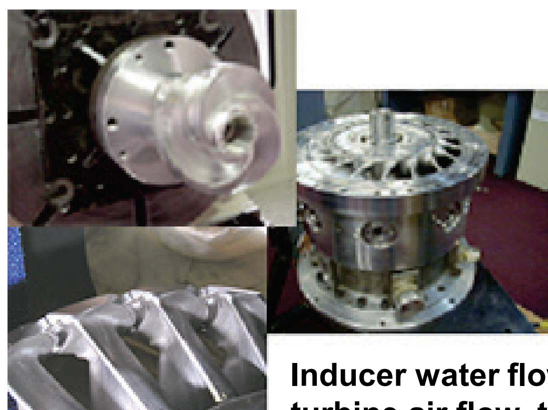


Single-Element PB + MI
Staged Combustion
Hot Fire



40k Multi-Element PB
Hot Fire
(High Pc)

Valve water flow test



Inducer water flow, turbine air flow, turbine damping tests

Selective Net
Shape Turbine
Manifold

Expander-Heat Exchanger Cycle

- Advanced HC expander engine power cycle
- High operability, reusability & reliability engine with closed cycle performance
  - High chamber cooling margins
  - No coolant coking concerns
  - No turbine drive circuit combustion (no preburner)
  - Reduced turbopump total power requirements

- AF HC engine key component technology maturation contract in work

Propulsion Summary

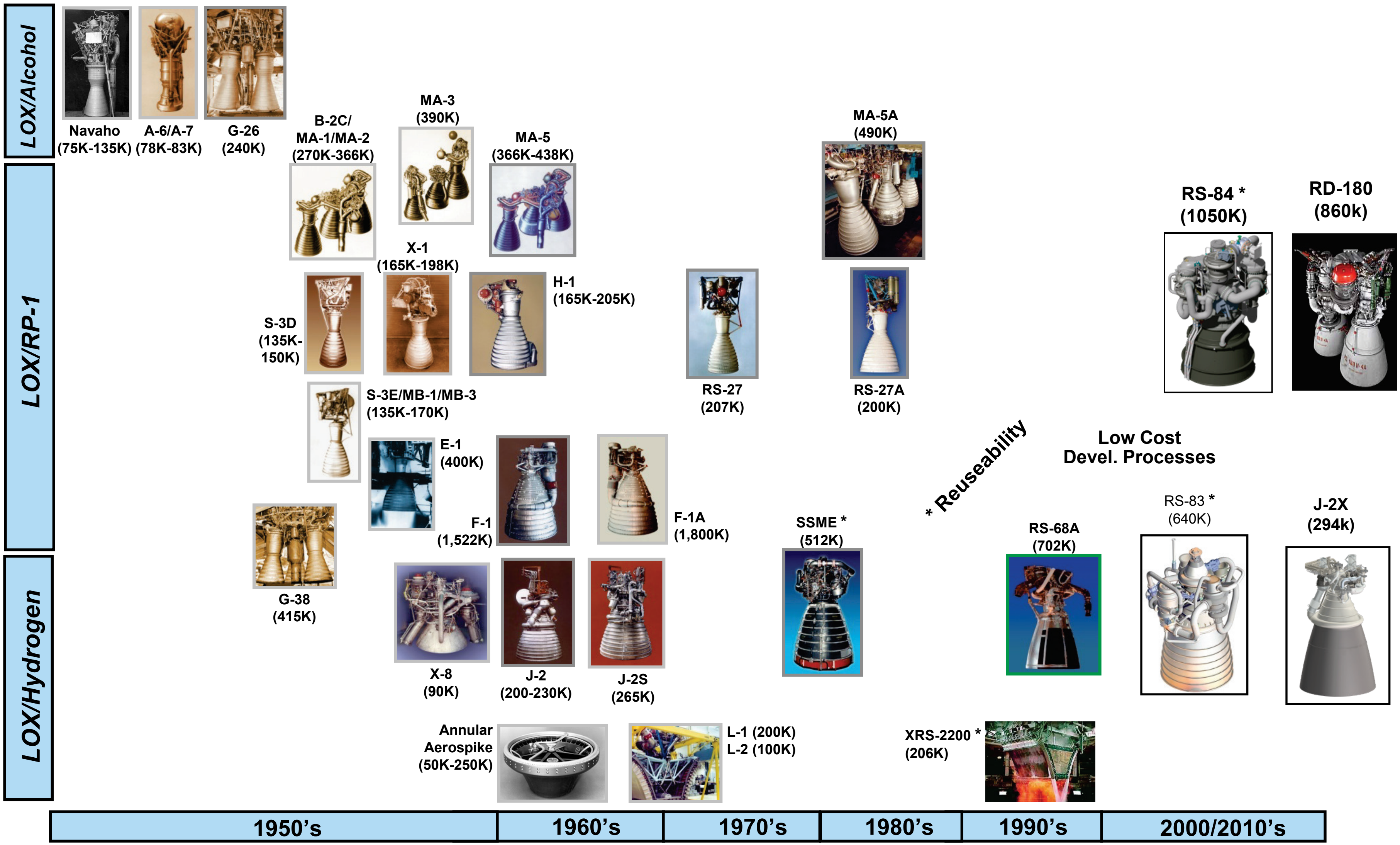
- AF goals achievable; highly reusable, operable RP ORSC engine never developed
  - Key Technologies immature for a reusable RP ORSC engine
  - Development challenges comparable to reusable H2 SC SSME
- Build upon recent RP ORSC engine development efforts
  - Flight-proven RD-180 & US co-production
  - RS-84 engine technology development
  - Also: AF Ox-rich Turbopump
- PWR has relevant experience, engineering capabilities & staff, existing engine factory and supplier base to develop and produce large RP engines

Backup Charts

Acronyms

- CDR: Critical Design Review
- EDM: Electro-Discharge Machining
- EMA: Electro-Mechanical Actuator
- GG: Gas Generator
- H2: Hydrogen
- HC: Hydrocarbon
- HIP: Hot Isostatic Pressure
- IPD: Integrated Powerhead Development
- IR&D: Internal R&D
- Isp: Specific Impulse
- JV: Joint Venture
- MI: Main Injector
- ORSC: Oxidizer Rich Staged Combustion
- PB: Preburner
- PDR: Preliminary Design Review
- RBS: Reusable Booster System
- RP: Rocket Propellant (aka; RP-1, kerosene)
- RTLS: Return To Launch Site
- SC: Staged Combustion
- SSME: Space Shuttle Main Engine
- TRL: Technology Readiness Level

Liquid Propulsion Booster Evolution



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Booster Engines

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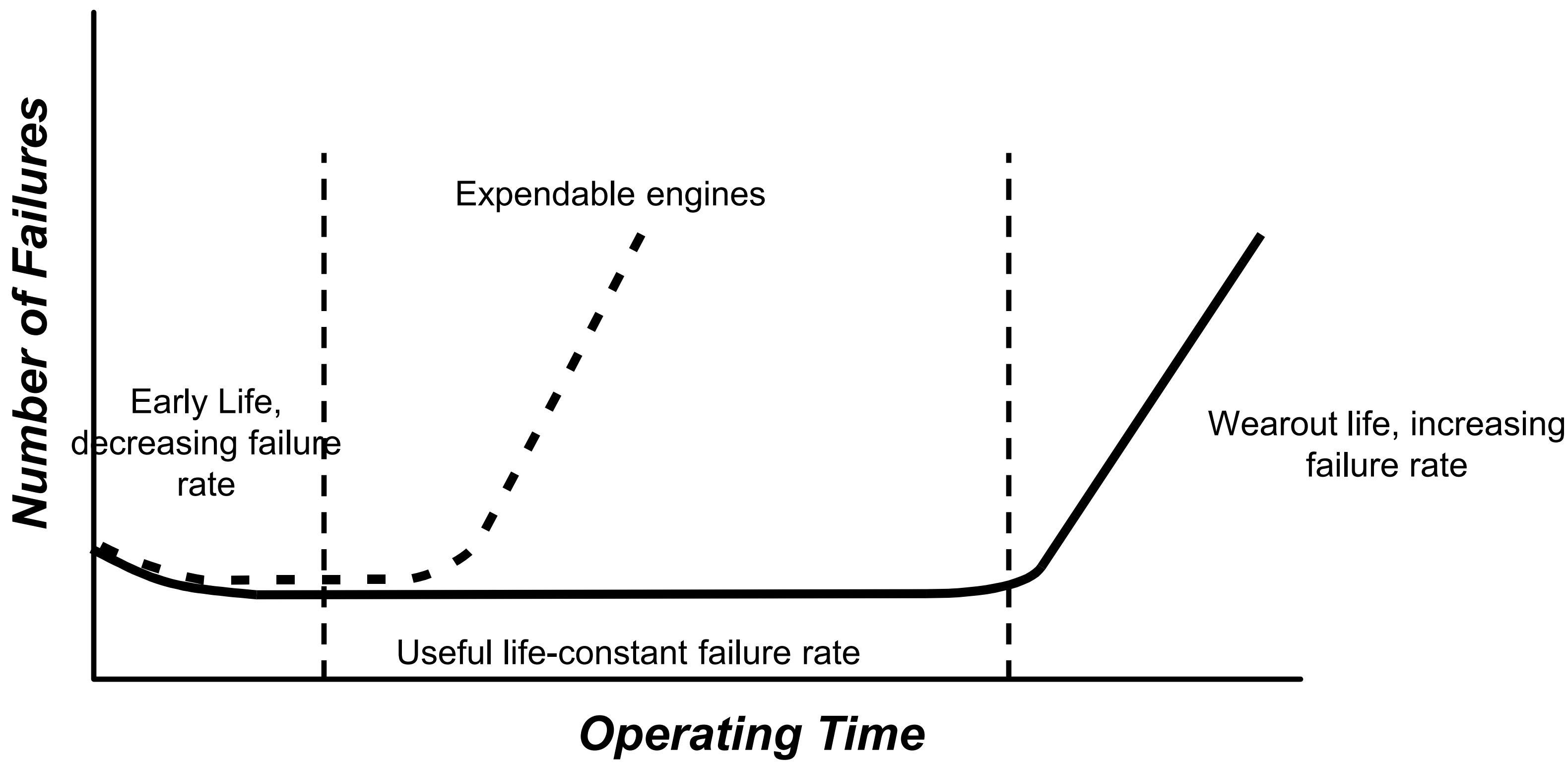
- Production/Flight
  - A-7 (Redstone) – Alcohol GG cycle 75k lbf
  - S-3D (Jupiter/Juno) – RP kerosene GG 150k
  - MB-1/H-1/RS-27 (Thor/Saturn I/Delta II) – RP GG 200k (flight support)
  - MA-1/MA-5 (Atlas I/II) – RP GG 490k (3 engines)
  - RS-25/SSME (Space Shuttle, SLS) – H_2 SC 500k (future production)
  - RS-68A (Delta IV) – H_2 GG 700k
  - RD-180 (Atlas III/V) – RP ORSC 860k (RDA JV)
  - F-1 (Saturn V) – RP GG 1,520k

- Development (through engine system level testing)
  - XRS-2200 (X-33) – H_2 GG 200k Linear Aerospike
  - XLR71 (G26 Navaho II) – Alcohol GG 240k (2 chamber engine)
  - AF Integrated Powerhead Development (IPD) – H_2 FFSC 250k
  - XLR83 (G38 Navaho III) – RP GG 400k (3 chamber engine)
  - F-1A – RP GG 1,800k

In Production

Reusable vs. Expendable Engine Reliability



Reuse reliability determined by design practices

PWR Responses to AF RBS RFIs

- PWR has identified RP ORSC engine key technology challenges and recommended technical and programmatic risk mitigation approaches to support successful development of a future AF RBS engine

- PWR has suggested multiple existing or near-term RP engines to support AF RBS needs
  - Pathfinder Demo, RB-X Demo, Operational RBS

PWR Reusable RP GG Cycle Engine

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NF-104

AR2-3 Engine

Tested in 1999-2000 for NASA X-37