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Rocket Engine Conceptual Design using ModelCenter®

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Introduction

- In 2014 the U.S. government took a firm stand to end the nation's dependence on the Russian engines
  - Russian RD-180 powering the Atlas V rocket
- The president signed into law a measure requiring the U.S. Air Force to develop a domestic next-generation rocket propulsion system by 2019
- The system needs to accommodate multiple launch vehicles and missions while being focused on affordable development (low risk and cost to the taxpayer)

Cost and schedule challenges drive need for techniques that reduce the design cycle time and generate data for Informed decision-making earlier in the process

Design to Cost Implementation

- Heritage development experience on the RS-68 program in the 1990's illustrated that only an upfront design-to-cost (DTC) approach could reduce cost and meet the schedule demand for this activity

- DTC uses cost and risk as inputs in the decision making and design process
  - Versus a design-to-requirements approach with cost as an output
  - Both unit cost (fabrication) and development cost (failures) are considered

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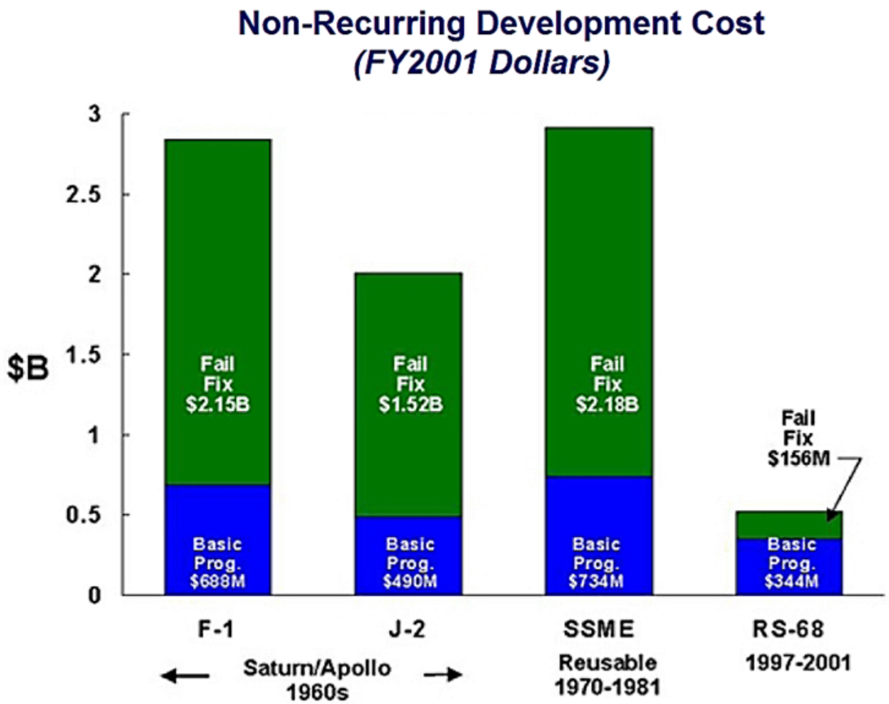
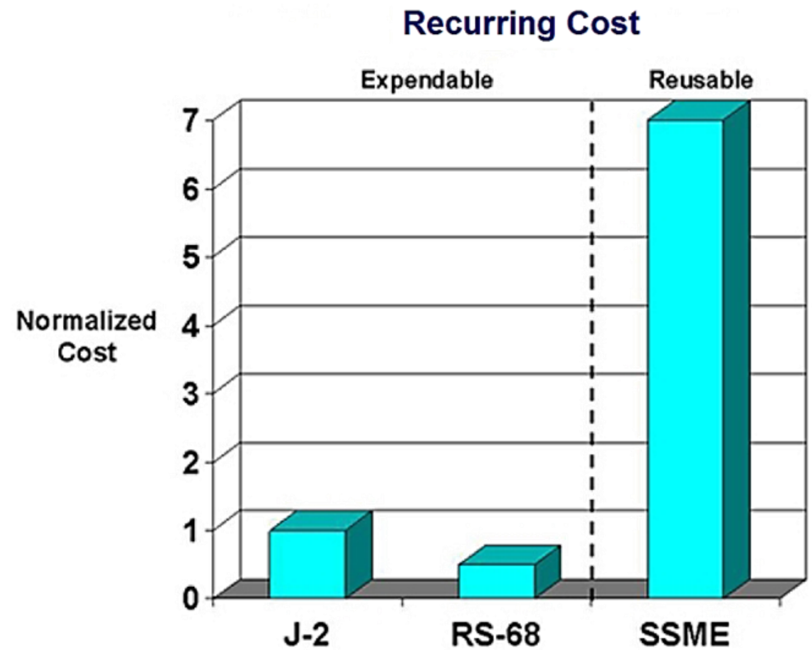
RS-68 DTC approach attacked fail-fix costs with trades on performance and weight
Allowed the system to stay within demonstrated cost and technical experience

DTC Results



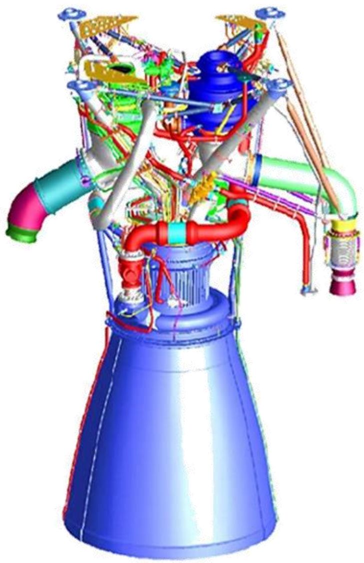


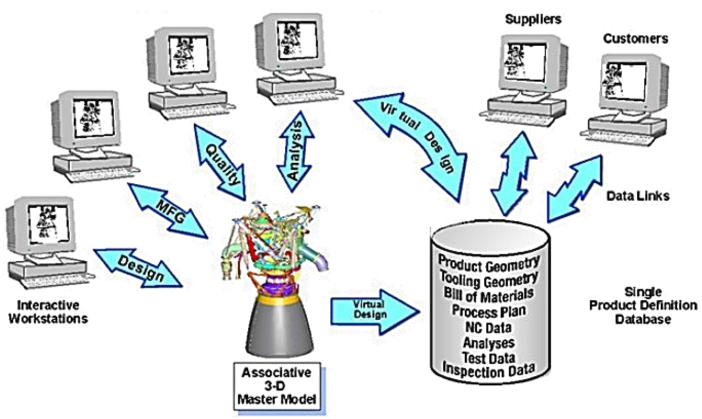
- By staying within existing bounds of experience:
  - Known failure modes eliminated
  - Design was simplified (80% reduction parts / 92% reduction touch labor)
  - Test program shortened (no new technology, processes, material)

DTC enabled RS-68 to go from design to certification in 4.7 years!

DTC in late 90's

- RS-68 used a 3D solid model based virtual design method
- All engineers worked from a common 3D model geometry
- Sharing of information between IPT teams allowed for decisions to be made earlier in the design process and increased efficiency
- However information was <u>manually transmitted and checked</u> and complex systems interaction were not immediately transparent

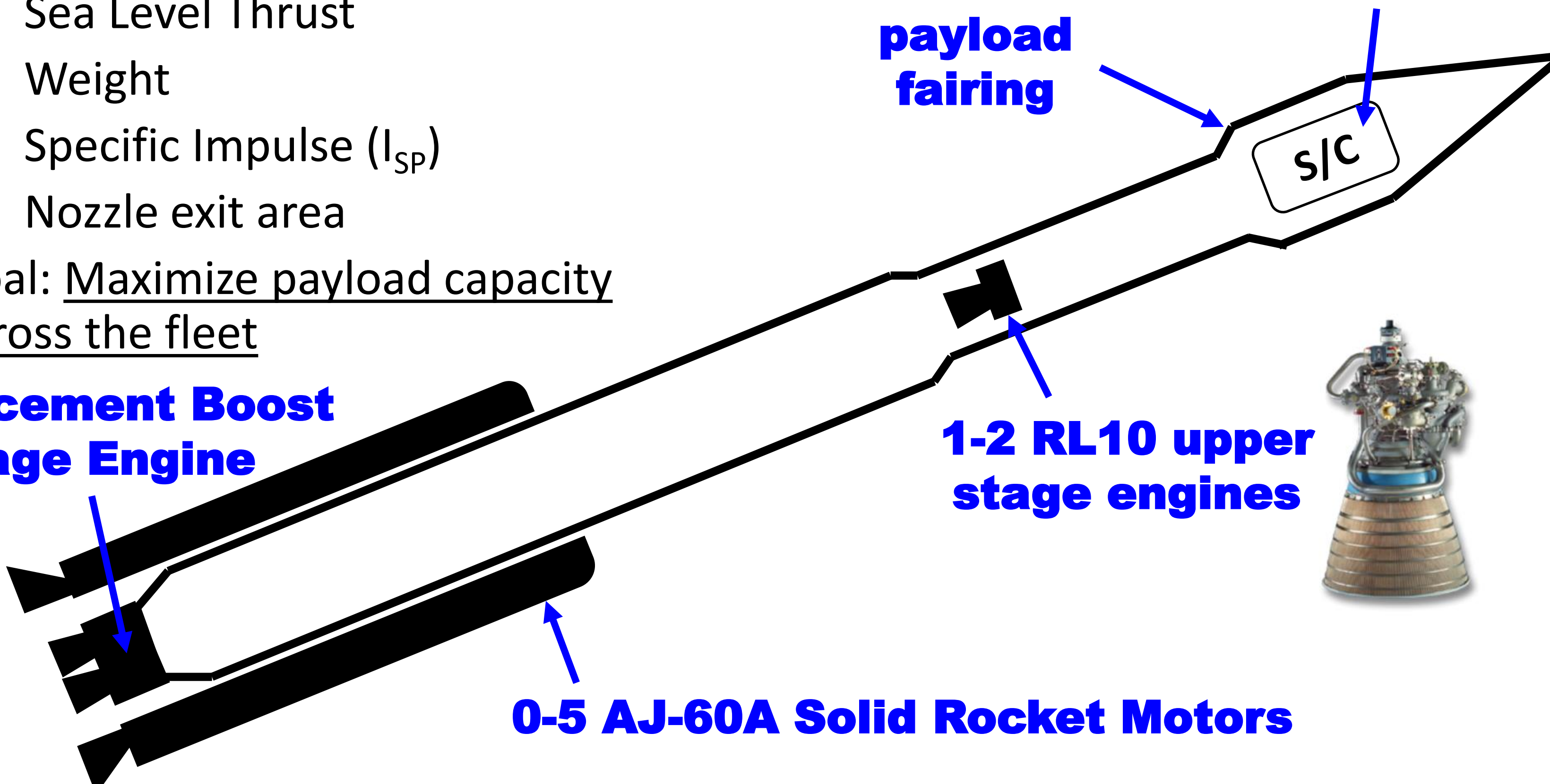




Design impacts at the vehicle/customer level are not immediately transparent in this engine-only manual approach

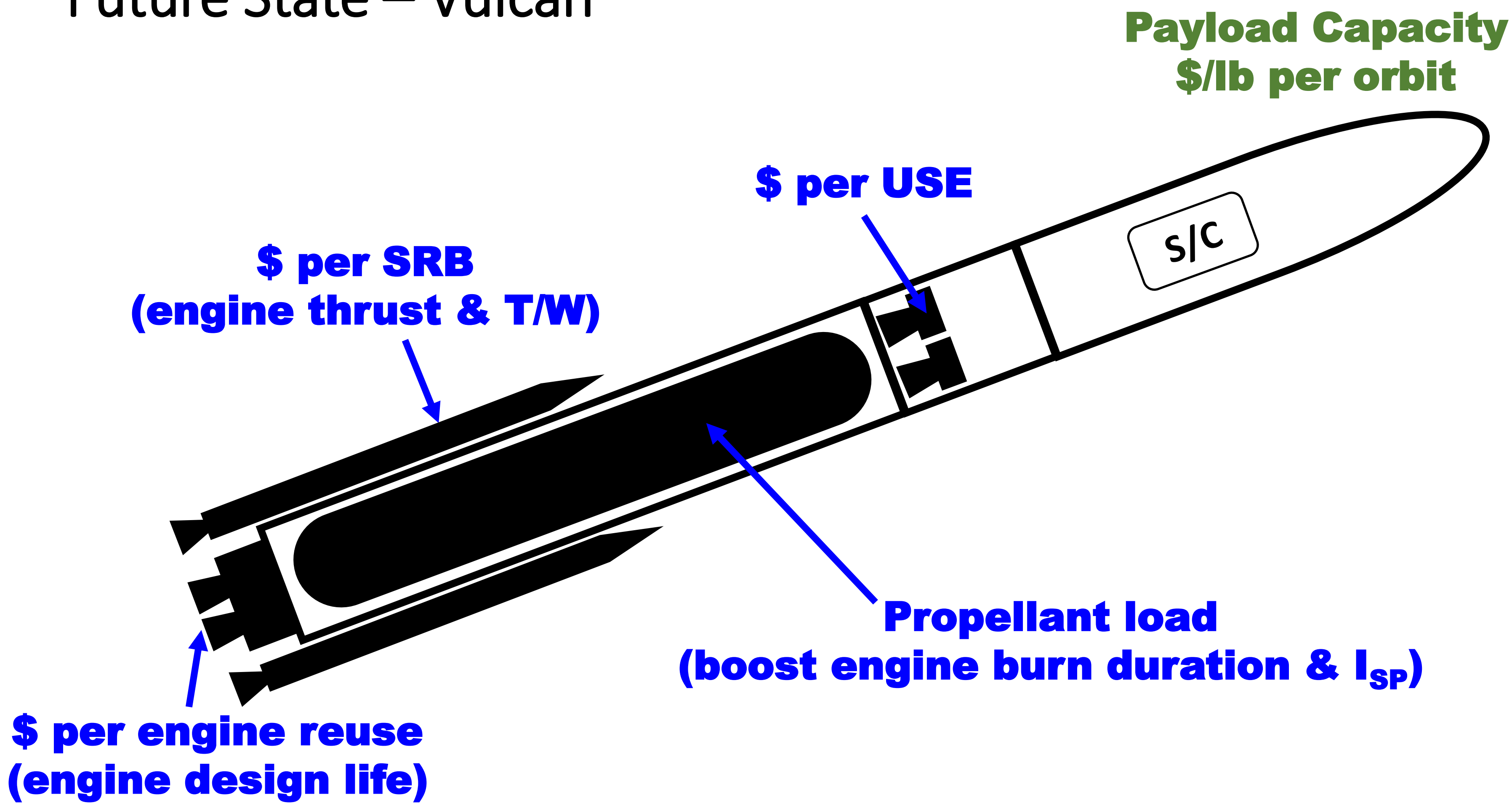
Engine Design Impacts – Atlas V

- Boost Stage Engine Inputs:
  - Sea Level Thrust
  - Weight
  - Specific Impulse (I_{SP})
  - Nozzle exit area
- Goal: <u>Maximize payload capacity across the fleet</u>



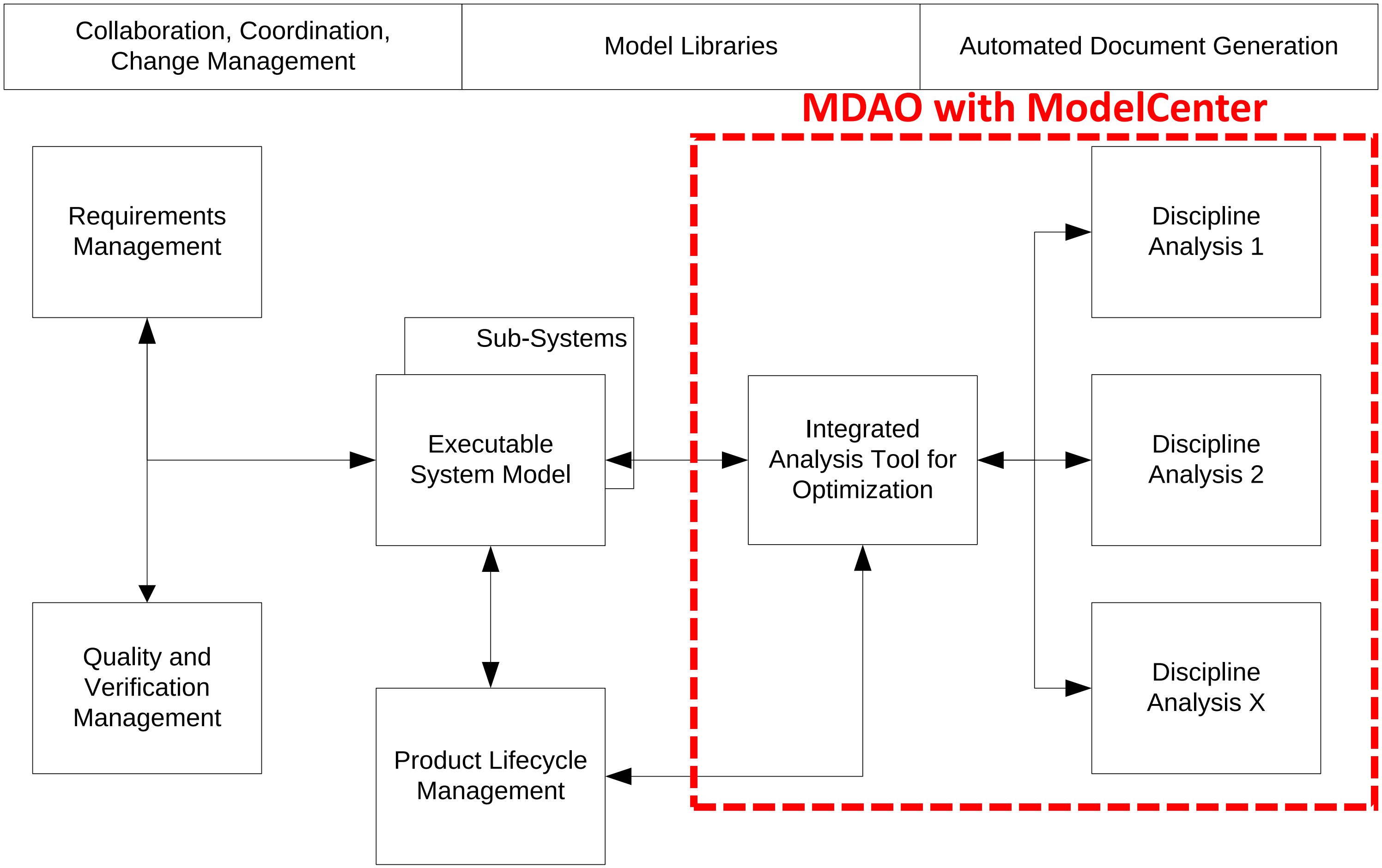
Multiple vehicle configurations to consider

Future State – Vulcan



Integrated modeling allows assessment of total system cost and risk during engine level design decision making process

DTC in the 2010's



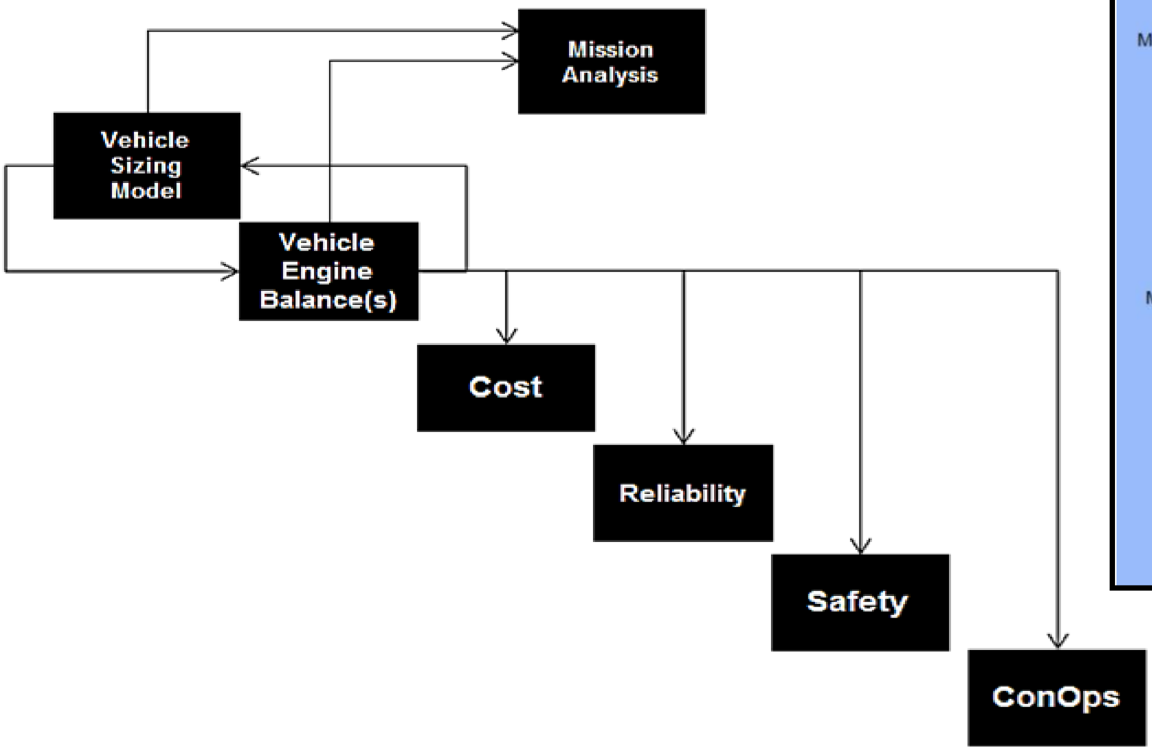
MBSE + MDAO enables rapid evaluation of a total system solution

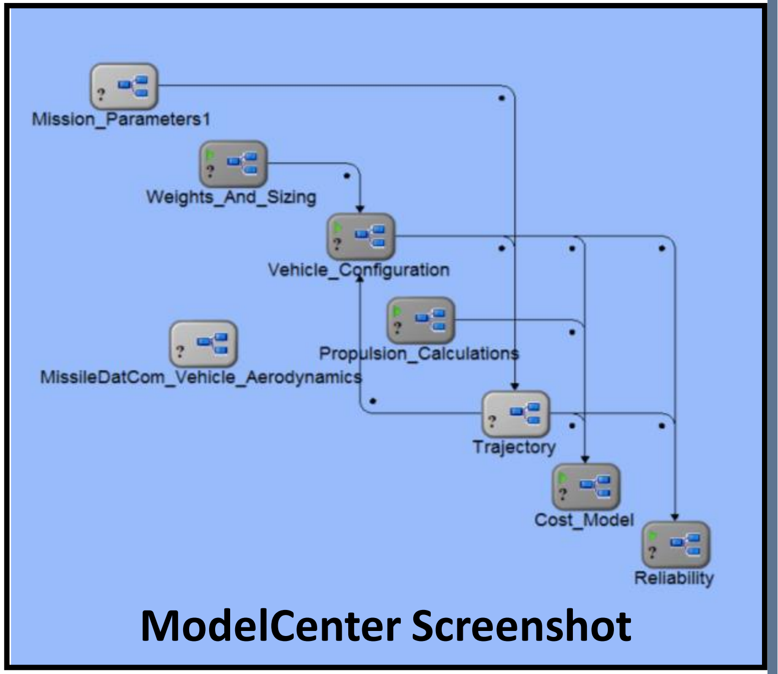
Benefits of MDAO approach

- Larger, integrated model for the seamless sharing of information, reducing potential for handoff errors and decreasing design cycle
- Rapid design space sweeps and multidisciplinary optimization
- Built-in user documentation of the analysis workflow
- This multi-platform approach to integrating disparate discipline tools permits SMEs to be responsible for the development, maintenance and validation of their own unique discipline-specific legacy codes
- Avoids the problem of creating an unwieldy master integrated program

MDAO provides a process for rapid trades early in the design process to reduce cost, get information to the design team real-time, documents design decisions

MDAO model setup in ModelCenter®

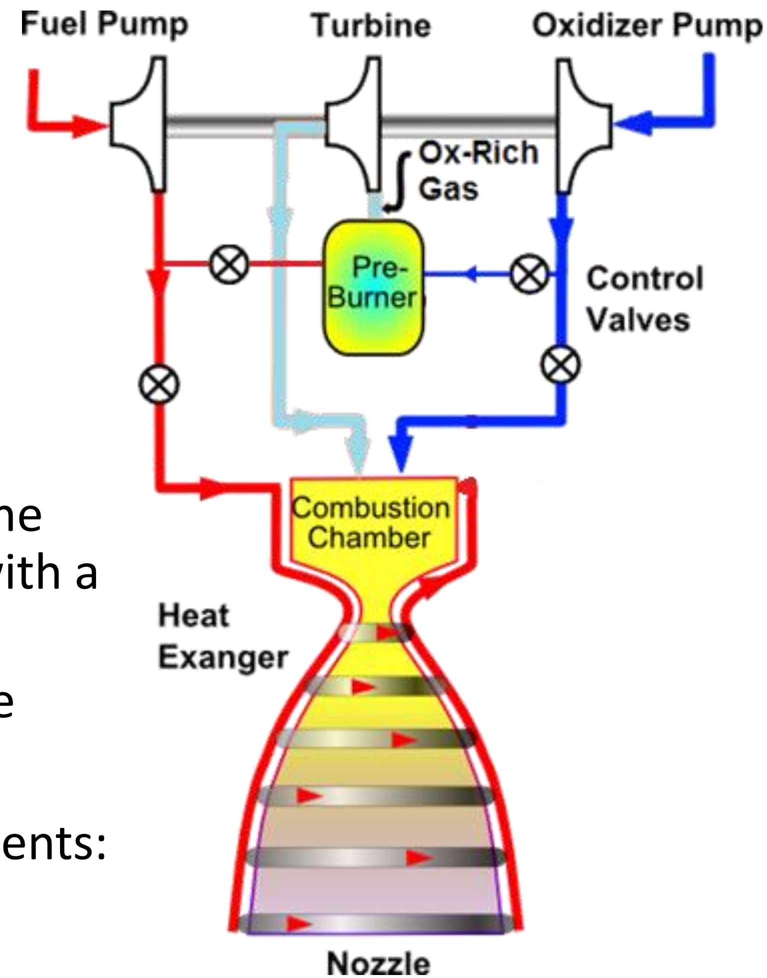




Phoenix's ModelCenter® framework is enabling for MDAO implementation

AR1 Engine Design Approach

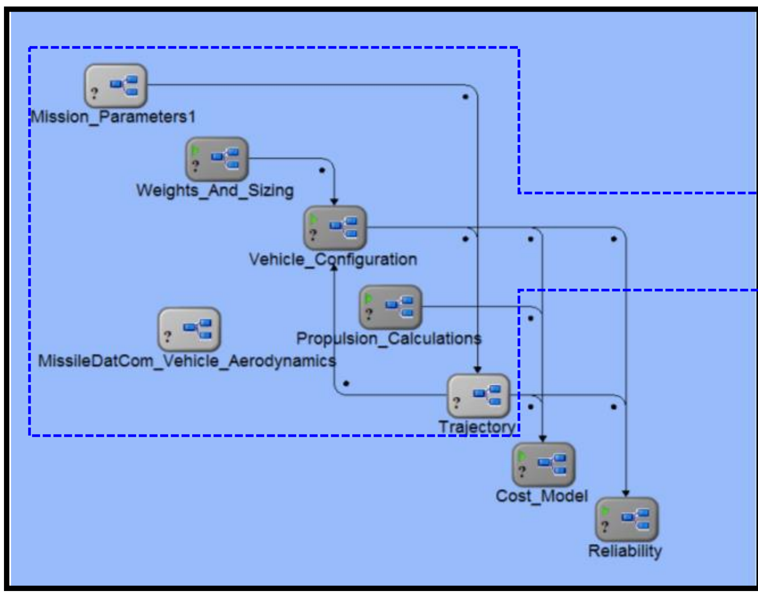
- AR's engine solution is known as the AR1
  - Competing against Blue Origin's BE-4
- Engine operates under an oxygen-rich staged combustion thermodynamic cycle
- The thermal-fluid performance modelled in a anchored, heritage Fortran code (EBAL)
  - Design optimization is performed both at the component level and on the system level with a global optimization
  - Thermodynamic and structural analyses are performed for each component
- Physics-based models of all key system components:
  - Ducting, heat exchanger, turbomachinery, combustion devices, valves, and etc.



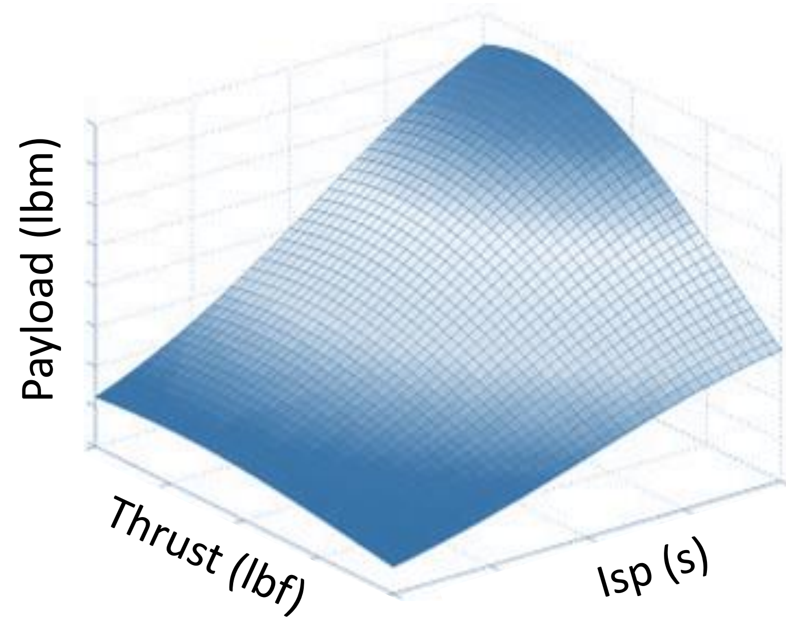
AR1 builds on legacy design approaches, implements new manufacturing techniques for lower cost, and provides high performance via demo'd engine cycle

Launch Vehicle Response Surface Curves

Integrated mission analysis models & codes: Orbital mechanics, LV configuration sizing, Aerodynamics, trajectory optimization (engine throttling)

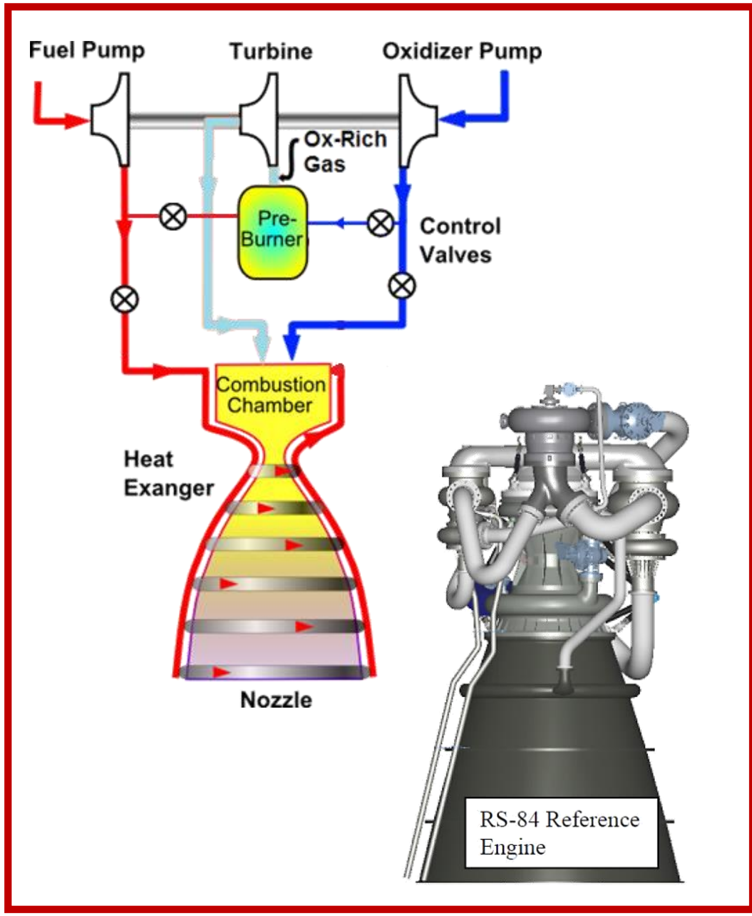


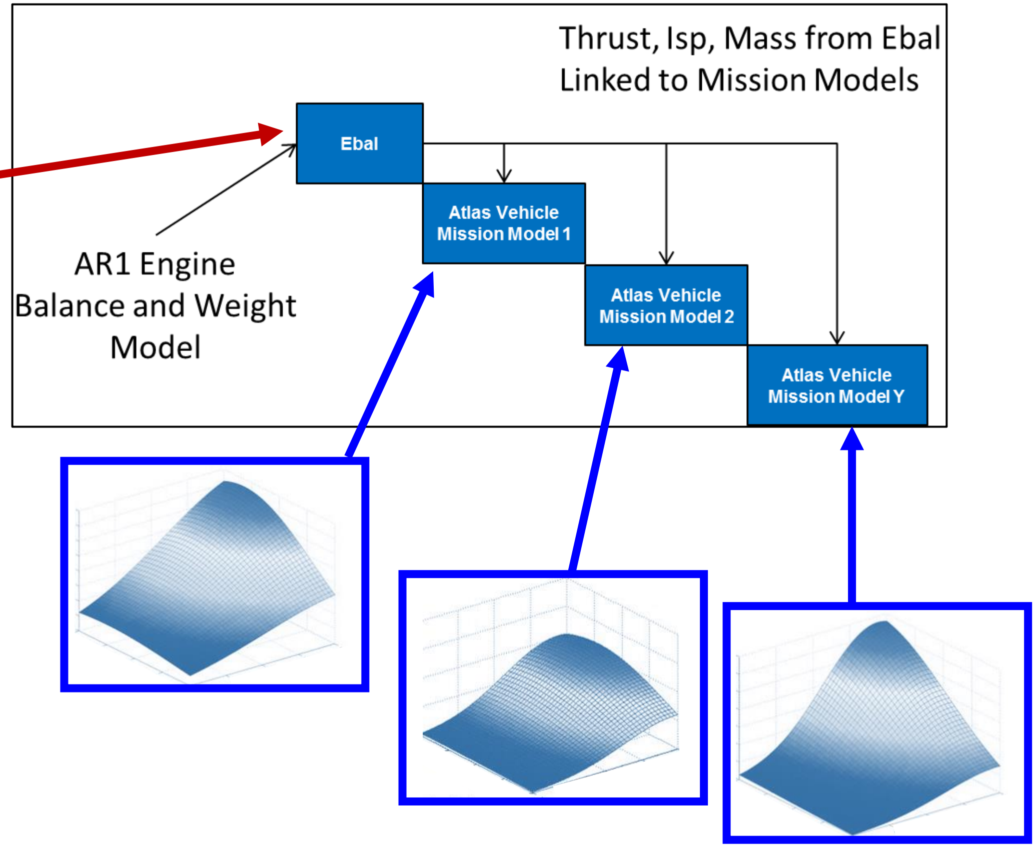
LV Configuration Payload to GTO (lb)



Generated payload RSC for each LV configuration speeds up execution time and trades

Engine Sizing in ModelCenter®

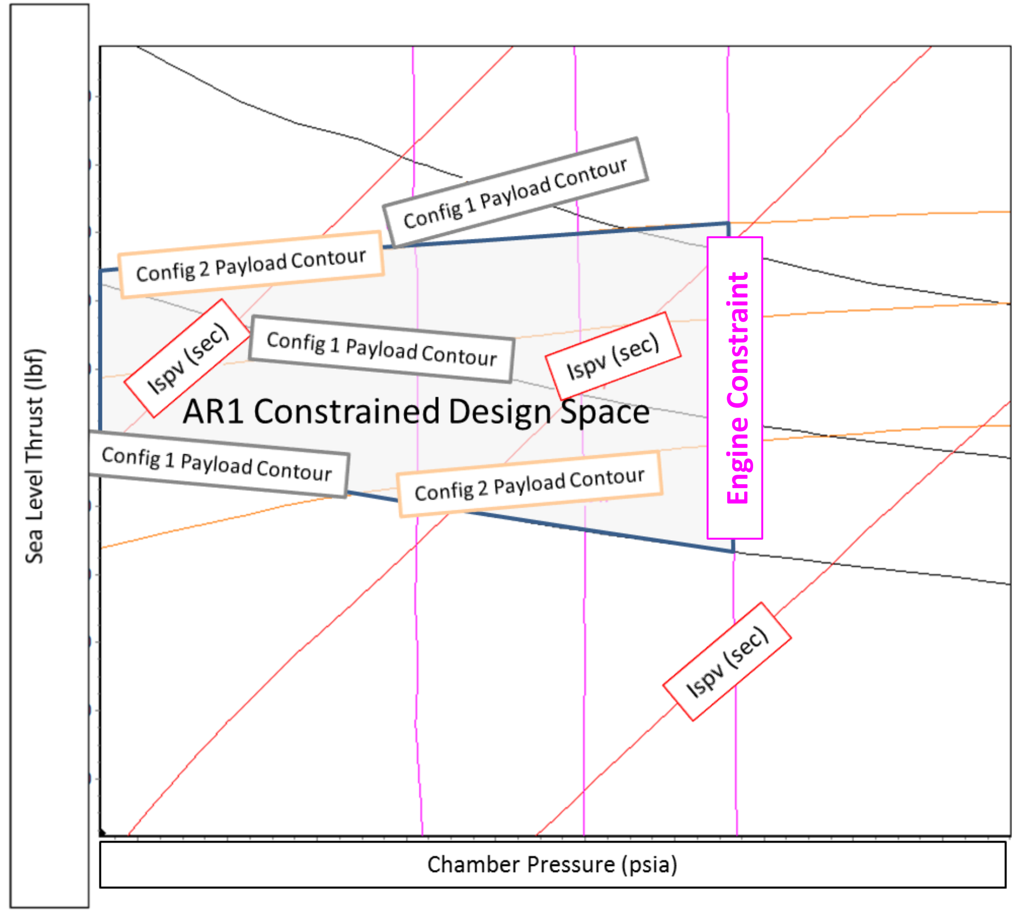




Design parameters that impact the engine can be "Flowed Up" showing the impact on the mission performance

AR1 Integrated Model Output

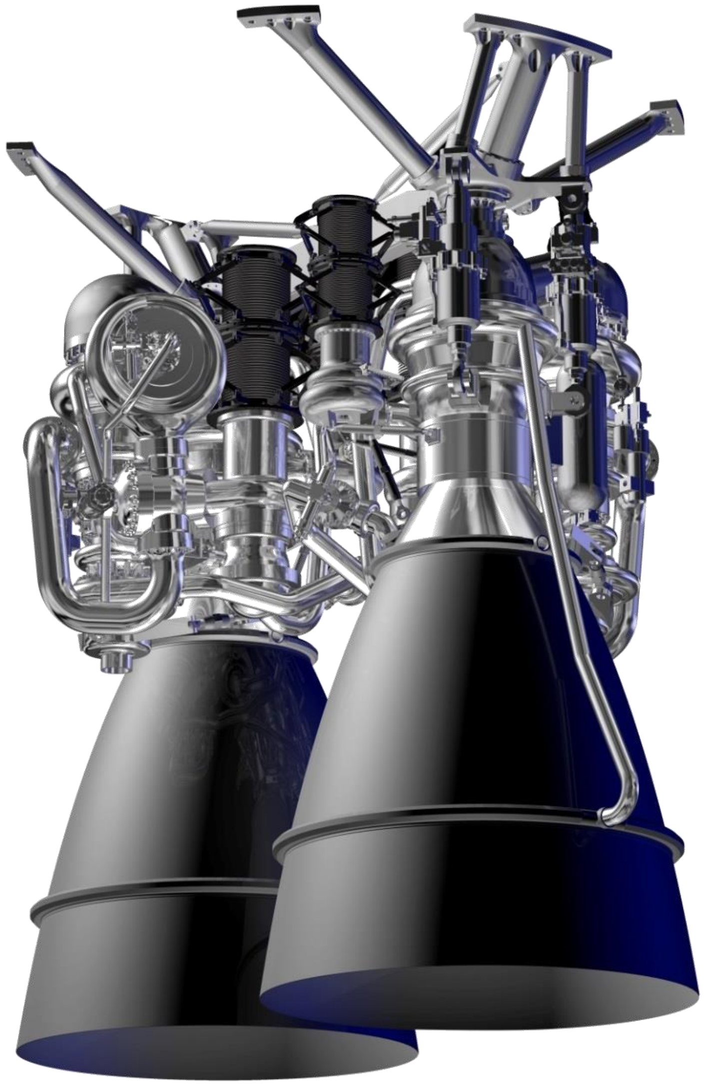
- Flow-down of goals and objectives from customer => AR derived requirements and appropriate figures of merit
- AR1 sea-level thrust and chamber pressure were primary independent variables due to design constraints



Vehicle mission analysis performed with emphasis on evaluating impact of engine technology choices

Visualized Solution – The AR1

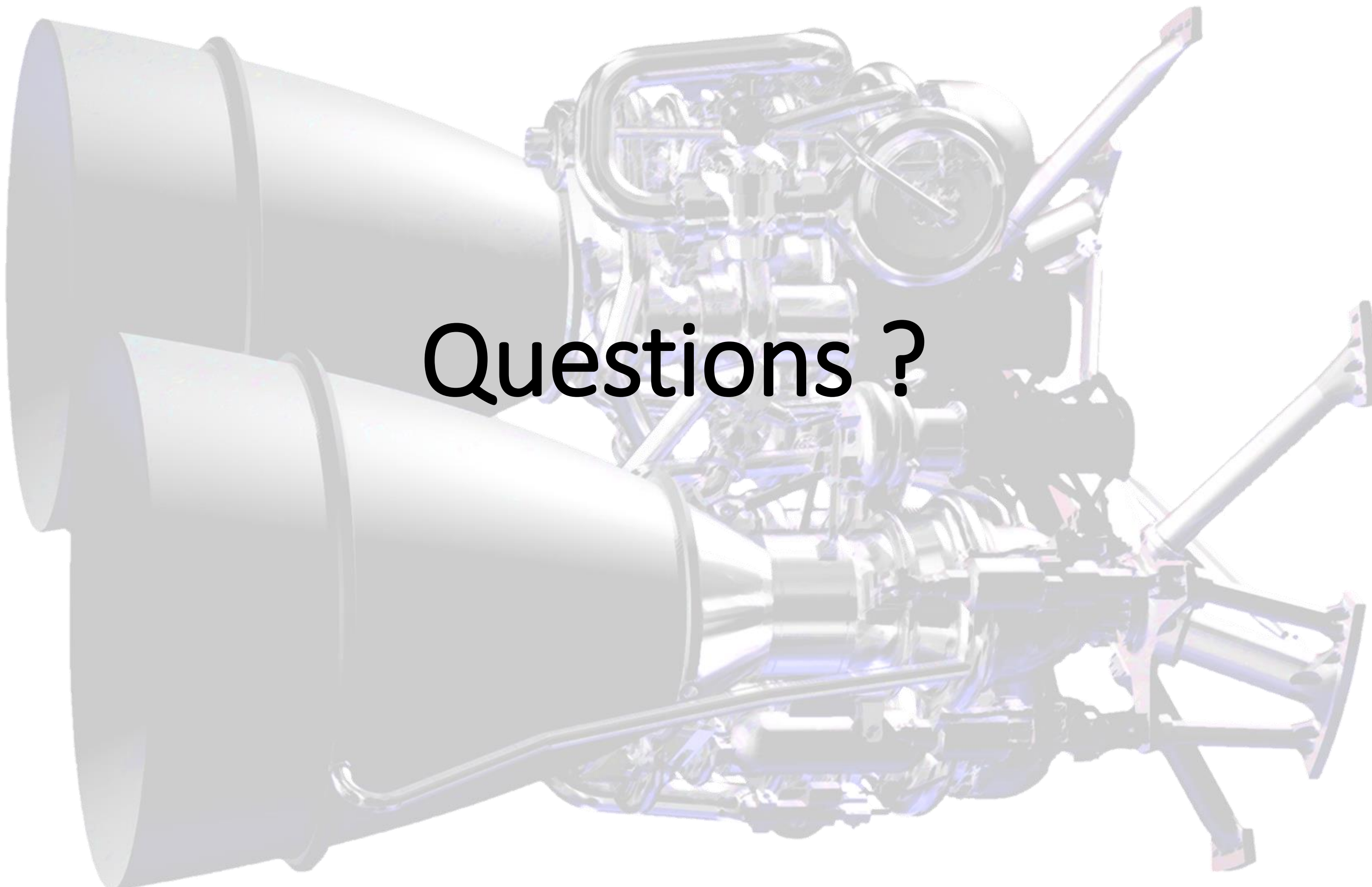
- Cycle: Ox-Rich Staged Combustion
- Propellant: Liquid oxygen and RP-1 (kerosene)
- Engines: 2
- Thrust: 526,000 lbf per engine
  1,052,000 lbf total



Configured to accommodate multiple applications and optimized for a fast-paced and affordable development

Conclusions

- Nation is facing an urgent need to develop alternatives to foreign propulsion by 2019
- MDAO was a key enabler to streamlining the design process in order to meet this aggressive design schedule
- Design space assessment enabled by MDAO on AR1 would have been impractical to conduct with traditional sequential design techniques
- MDAO on the AR1 provided critical guidance to inform program decision makers at key program design gates and accelerated maturation of the design
- MDAO techniques have broad applicability and can have a similar impact on any engineering program



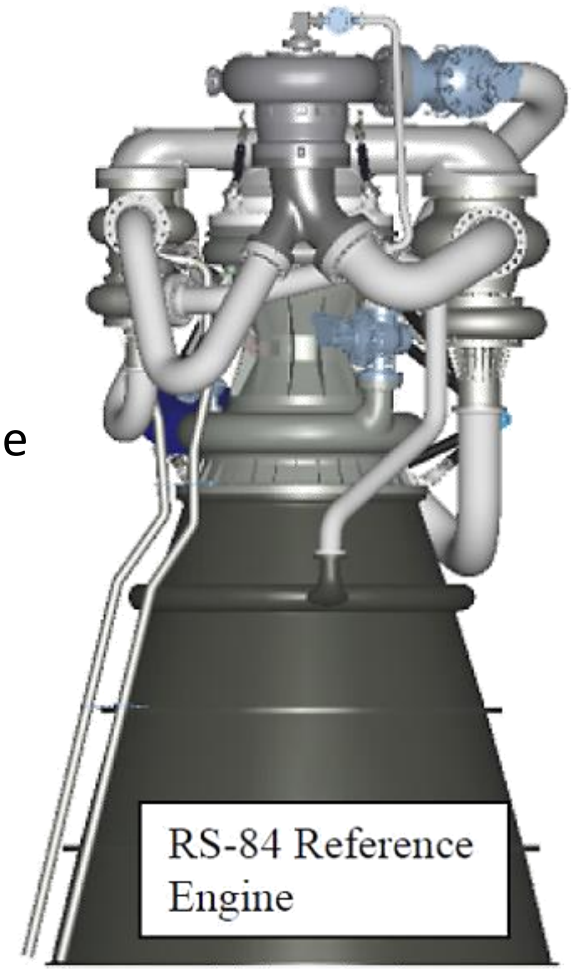
Questions ?

Publications used in this presentation

- Matthew R. Long and James F. Horton. "Application of Multidisciplinary Analysis and Optimization on AR1 Using ModelCenter®", 51st AIAA/SAE/ASEE Joint Propulsion Conference, Propulsion and Energy Forum, AIAA-2015-3770, AIAA, 2015.
- Matthew R. Long, Heidi Davidz, and James Horton "Design-to-Cost and Robust Liquid Rocket Engine Design Using PMDA/PMDO and MBSE", AIAA SPACE 2014 Conference and Exposition, SPACE Conferences and Exposition, AIAA-2014-4408, AIAA, 2014.
- Zillmer, Andrew, Hanks, David, & Wen-Hsiung 'Tony' Tu , “Space Power System Modeling with EBAL”. Proceedings of the 2006 International Congress on Advances in Nuclear Power Plants , American Nuclear Society, 2006.
- Davis, D., “Overview of NASA's Rocket Engine Prototype Project of the Next Generation Launch Technology Program: Next Generation Launch Technology Oxygen-Rich Stage Combustion Prototype Engine RS-84,” 54th International Astronautical Congress of the International Astronautical Federation, IAC-03-V.5.03, September 2003.
- Wood, Byron K., “Propulsion for the 21st Century – RS-68” AIAA-2002-4324, 38th Joint Liquid Propulsion Conference, Indianapolis, Indiana, July 8-10, 2002.

AR1 Engine Balance

- EBAL also has an integrated weight model and component library based upon legacy Aerojet Rocketdyne engines
- Technology for Ox-rich staged combustion studied during Space Launch Initiative (SLI)
  - NASA and U.S. Department of Defense joint research and technology project to determine the requirements for a 2nd Generation Reusable Launch Vehicle
- Rocketdyne RS-84 (2000-2005)
  - Reusable
  - Ox-rich staged combustion
  - Liquid Oxygen & Kerosene
  - 1,064 klbf sea level thrust (1,130 klbf vacuum)
  - 305 s Isp Sea level (324 s vacuum)



Rocketdyne RS-84 ORSC Engine