Conceptual Design for a Dual-Bell Rocket Nozzle System Using a NASA F-15 Airplane as the Flight Testbed

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50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference
July 28th – 30th, 2014
Cleveland, Ohio

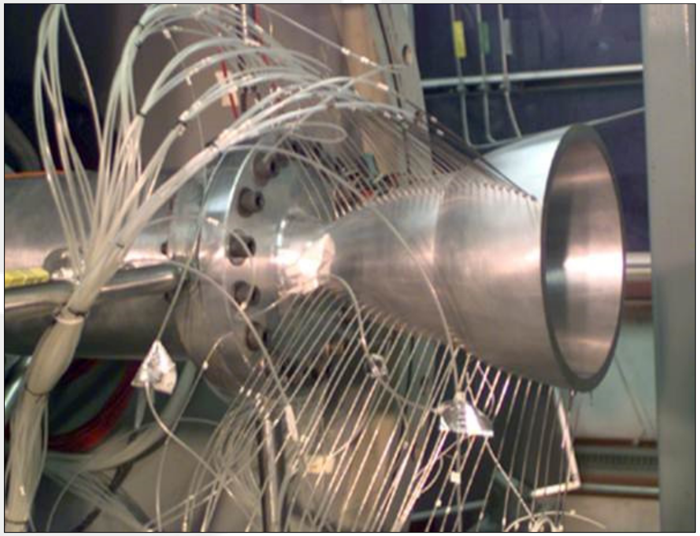
This presentation contains highlights from the conference paper, AIAA 2014-3956, available through www.AIAA.org

Outline

- Introduction
- Conceptual Design for Phase I Flights
- Conceptual Design for Phase II Flights
- Conclusion
- Acknowledgments

Introduction
Dual-Bell Rocket Nozzle Technology

- The dual-bell rocket nozzle has predicted benefits
  - Potential to increase nozzle performance over the integrated rocket trajectory
  - Potential to reduce engine side loads during low-altitude operation
- Predicted benefits could have a significant impact
  - Nozzle performance could increase the mass payload capability to LEO
- TRL advancements have been slow, despite the predicted benefits
  - 1949: Concept first appeared in literature
  - 1993: First publication on static testing
  - 2014: Still requires adequate testing in a relevant flight environment
- Predicted benefits warrant investigation in a relevant flight environment

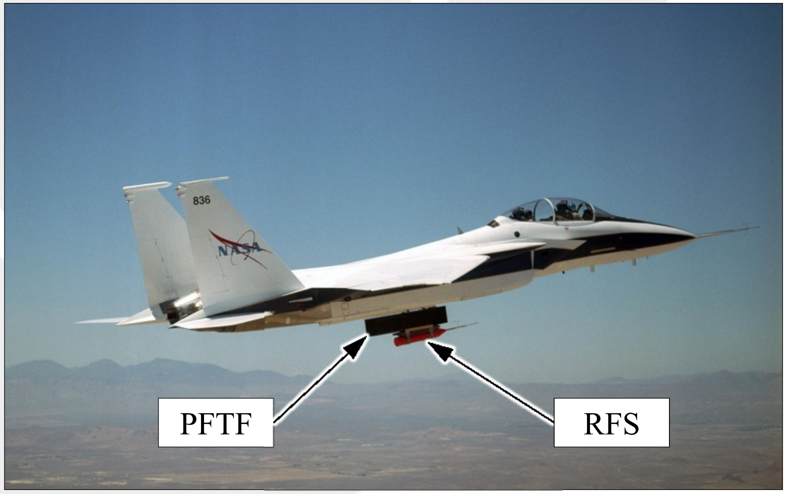


Dual-bell nozzle testing at NASA Marshall

Introduction

Taking the Dual-Bell Rocket Nozzle to Flight

- Proposal was constructed to advance dual-bell nozzle through flight
  - Plan to utilize a NASA F-15 airplane as the flight testbed, with the Propulsion Flight Test Fixture (PFTF) and Rocket Forebody Simulator (RFS)
  - Captive-carried flight permits several benefits over free-flight with a rocket
  - Traceability to NASA goals, as well as Armstrong and Marshall expertise
- Flight research campaign includes three phases:
  - Phase I: External flow-field flights
  - Phase II: Cold-flow nozzle operation
  - Phase III: Reacting-flow nozzle operation
- Current effort details feasibility on Phase I and Phase II flight activity
  - The conceptual design for Phase III will be detailed in a future publication

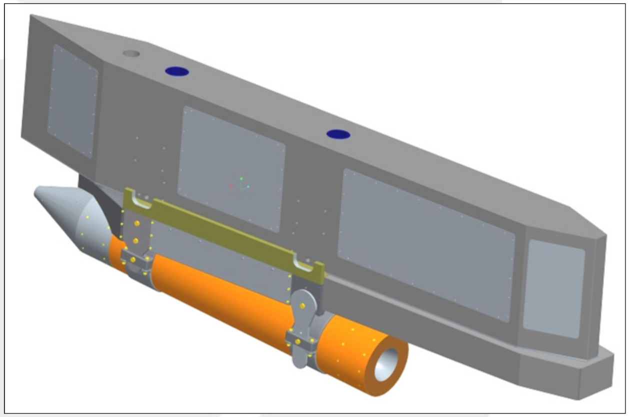


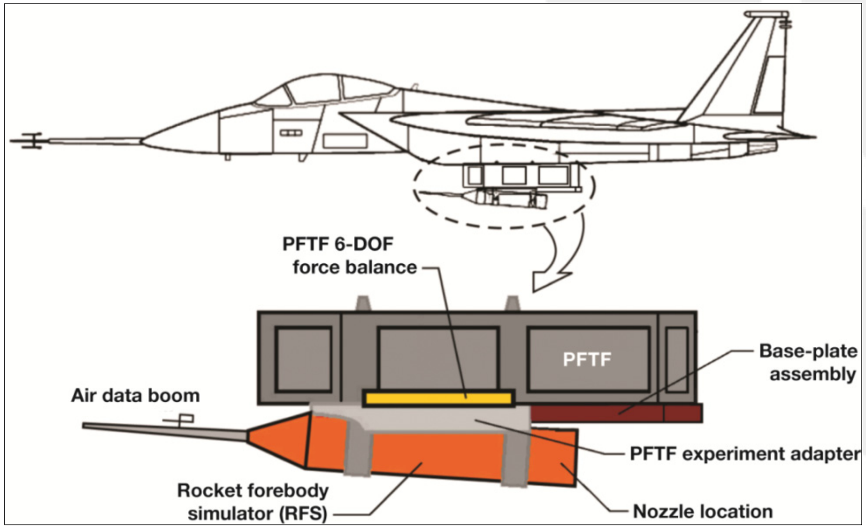
Flight research with an F-15 airplane at NASA Armstrong

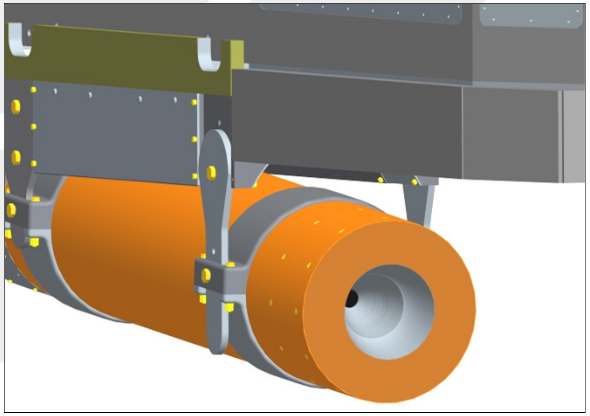
Conceptual Design for Phase I Flights

External Flow-Field Conceptual Design

- Extensive utilization of existing flight-proven hardware
- Phase I primary objective: Quantify the F-15 external flow field
  - RFS outer mold line (OML) will be heavily instrumented
  - Flight data to validate CFD flow-field predictions
- External flow-field data will be obtained at all conditions where nozzle operation will occur (during Phase II and Phase III)



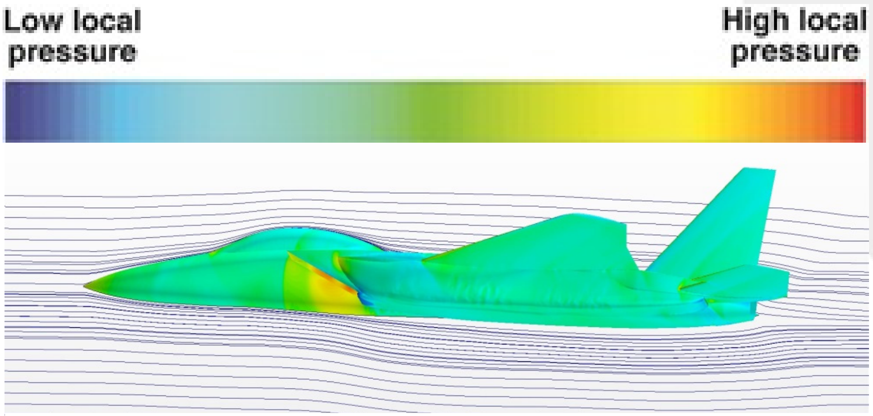




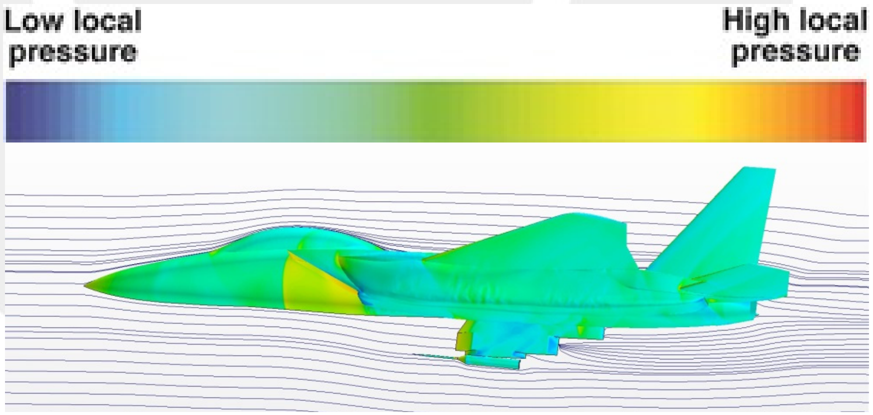
Conceptual Design for Phase I Flights

Initial External Flow-Field Predictions (1 of 2)

- Initial external flow-field analysis conducted to assess feasibility
  - Utilized the Star-CCM+ polyhedral finite-volume unstructured CFD code
  - CFD flow-field analysis with inviscid/Euler assumptions
  - Analysis included two test points (Mach 0.9 and Mach 1.2), both at 46 kft
  - Considered worst-case flow-field scenario, with blocked F-15 engine inlets
- Initial evaluation of model compared against a clean F-15 airplane
  - Results reveal no local flow anomalies when including PFTF and RFS



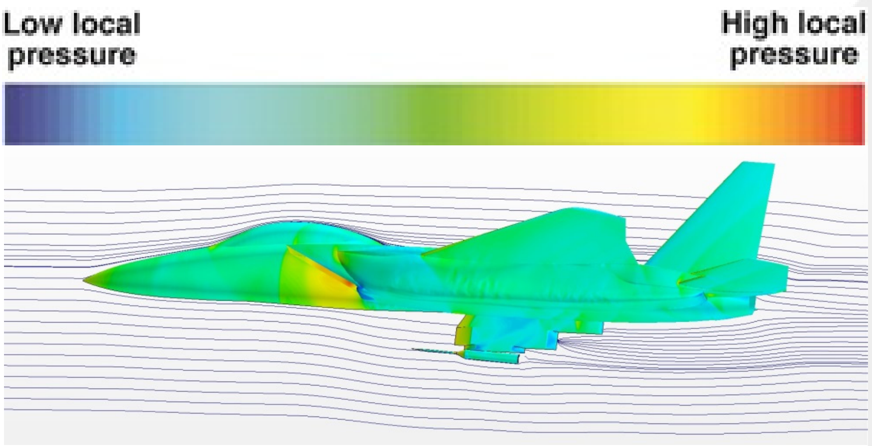
Clean F-15 airplane, Mach 1.2



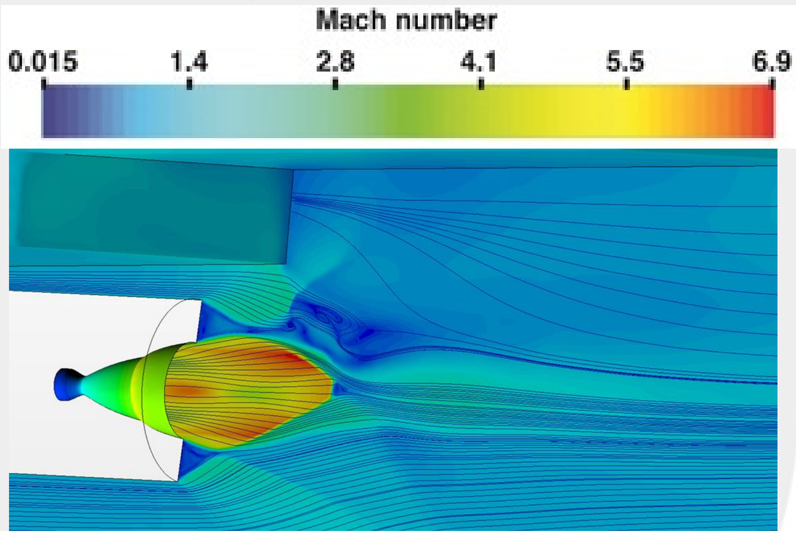
F-15 airplane with PFTF and RFS, Mach 1.2

Conceptual Design for Phase I Flights
Initial External Flow-Field Predictions (2 of 2)

- Analysis included evaluation of flow field during nozzle operation
  - Realistic assessment of nozzle exit pressures (which are sub-ambient)



F-15 airplane with PFTF and RFS, Mach 1.2, with nozzle operating



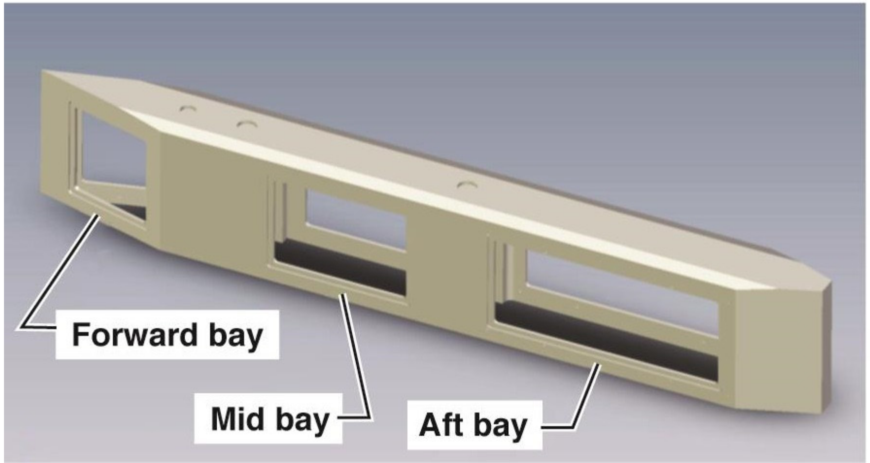
Dual-bell nozzle during operation on F-15 airplane at Mach 1.2 (RFS made invisible to show nozzle)

- Initial results indicate a well-chosen location for nozzle experiment
  - Analysis reveals no areas of concern in the local flow field
- Initial analysis adds greater confidence to operational feasibility

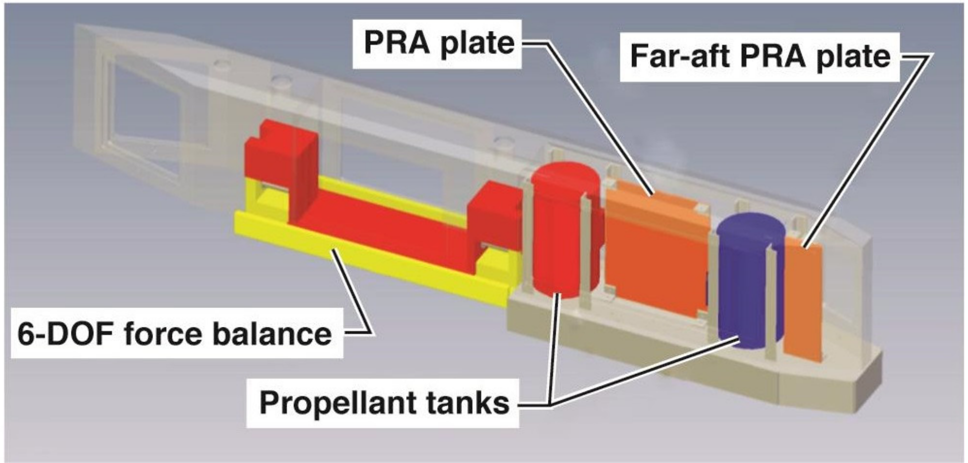
Conceptual Design for Phase II Flights

Propellant Feed System Design (1 of 2)

- Phase II flights will include cold-flow (GN_2) nozzle operation
  - Allows cold-flow static test data to be leveraged
  - Permits an intermediate/build-up approach in system complexity
- Entire propellant feed system is contained within the PFTF and RFS
  - PFTF will include tanks and controls, and routed to nozzle in the RFS
  - Pressure Reducing Assembly (PRA) plate for mounting controls
- Phase II conceptual design adds confidence to packaging feasibility



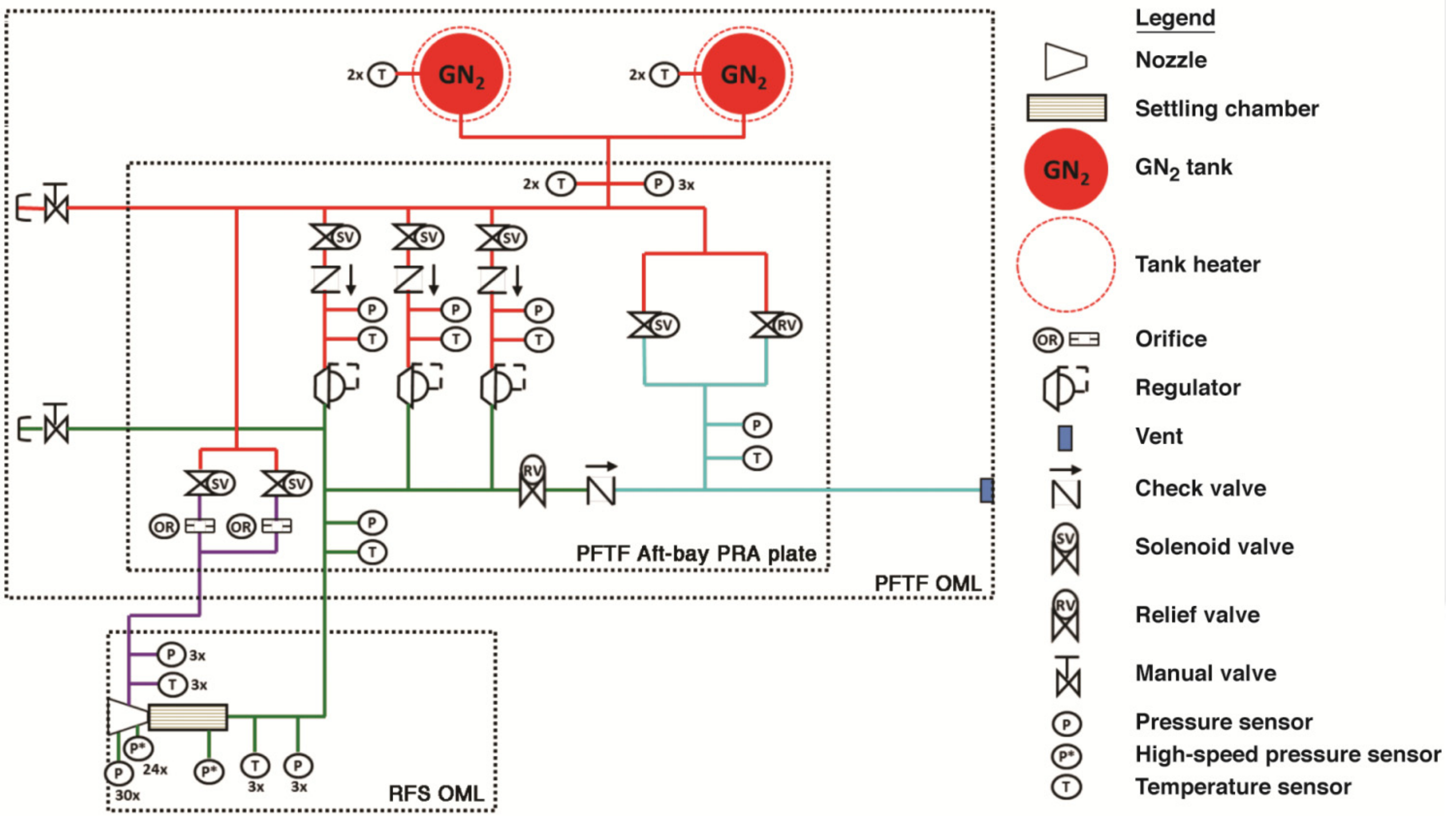
PFTF external Shell



PFTF internal view with primary components

Conceptual Design for Phase II Flights
Propellant Feed System Design (2 of 2)

- System is designed for mission success and flight safety
  - Permits monitoring and control by flight test engineer in back seat of F-15
  - Enables a real-time and post-flight assessment of health and performance



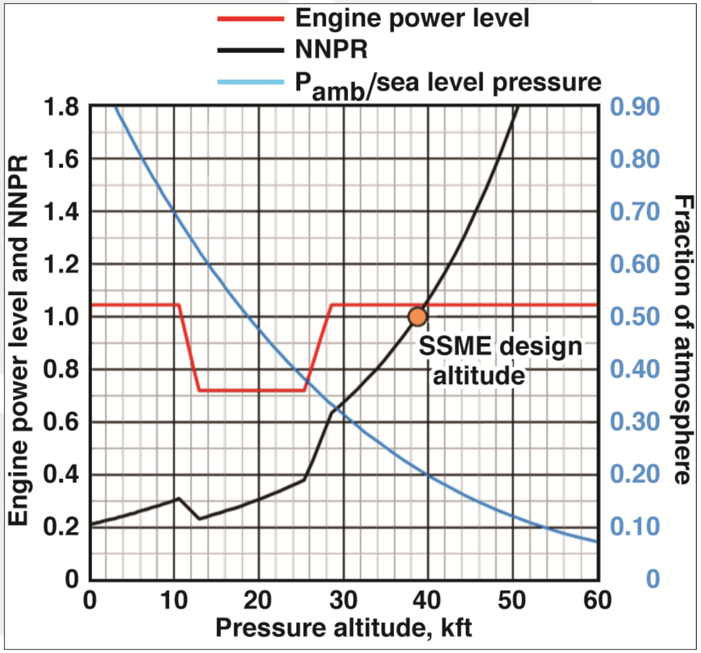
Propellant feed system schematic and instrumentation

Conceptual Design for Phase II Flights
Dual-Bell Nozzle Design Philosophy (1 of 2)

- Design philosophy: Maximize dual-bell nozzle performance
  - Long-term goal: Integrate a dual-bell nozzle into a production rocket engine
  - Conceptual design objective: Demonstrate dual-bell nozzle flow control
- The Space Shuttle Main Engine (SSME) provides an excellent example for illustrating dual-bell nozzle performance benefits
  - NPR = Nozzle Pressure Ratio
  - NNPR = Normalized Nozzle Pressure Ratio

$$NNPR = {NPR}/{NPR_{design}} = \left({P_c}/{P_{amb}}\right) \Big/ \left({P_c}/{P_{amb}}\right)_{design}$$

  - Off-design NPR is apparent
- Standard throttling capability lends itself to dual-bell nozzle performance optimization

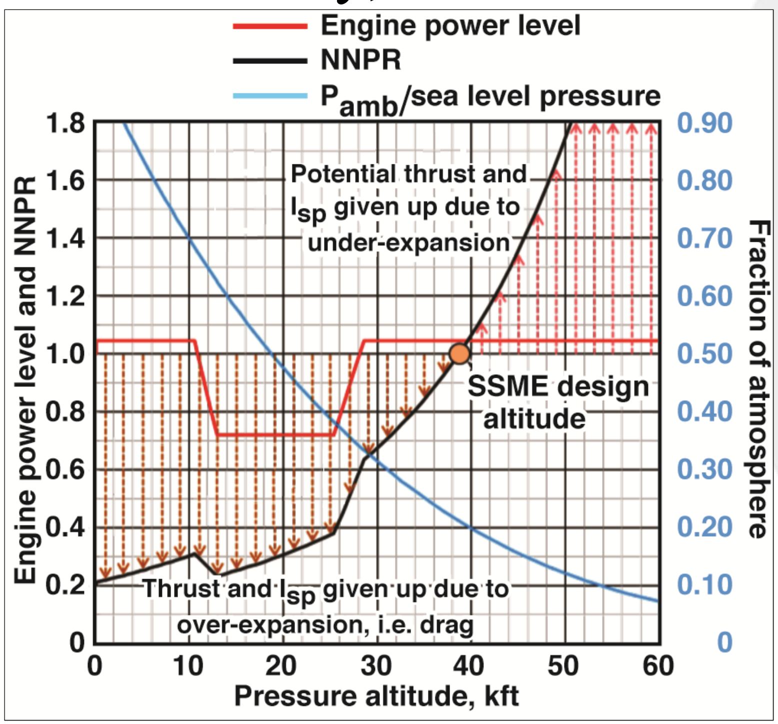


Typical engine parameters on the STS/SSME

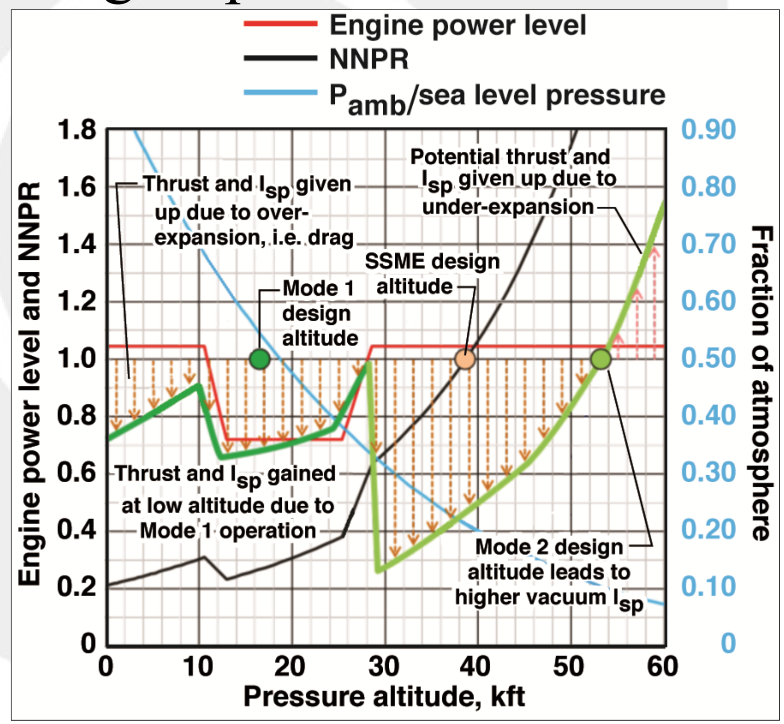
Conceptual Design for Phase II Flights

Dual-Bell Nozzle Design Philosophy (2 of 2)

- Any conventional-bell nozzle has significant performance losses
- Any nozzle design requires several trades to be made
  - Optimized performance at launch competes with optimized vacuum I_{sp}
- Theoretically, a dual-bell nozzle can mitigate performance losses



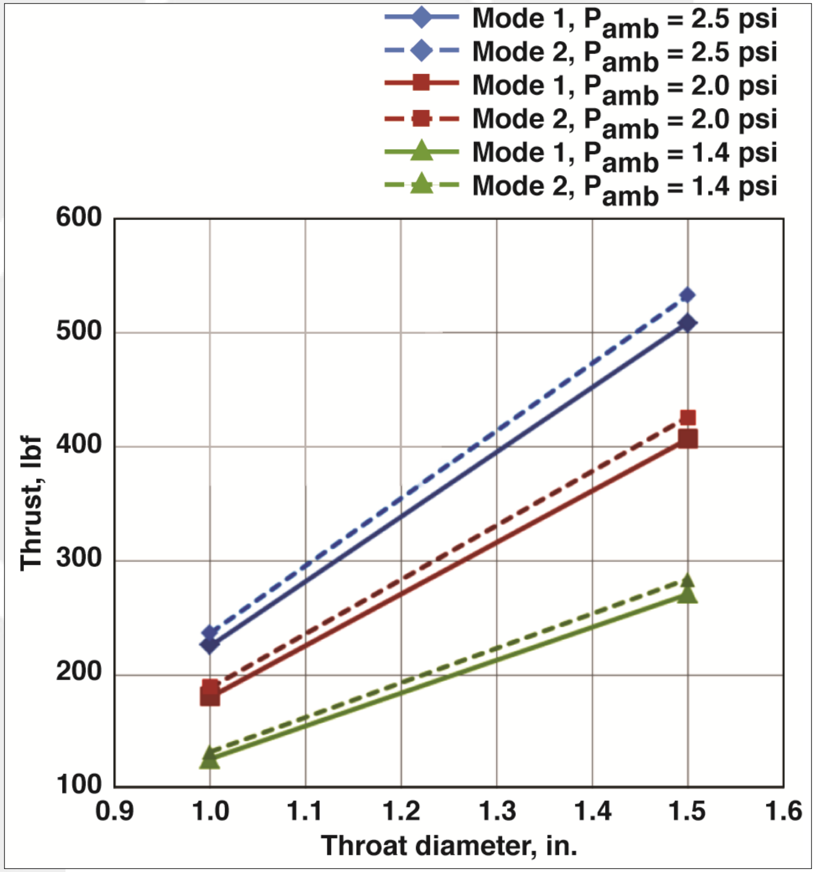
SSME performance losses due to off-design operation



Notional NNPR curves with a dual-bell nozzle

Conceptual Design for Phase II Flights
Dual-Bell Nozzle Sizing Trades

- One-dimensional nozzle sizing trades were completed with GN_2
  - Varied nozzle throat diameter
  - Varied ambient pressure
- Evaluated several performance parameters
  - Mass flowrate
  - Mass fraction consumed per test
  - Thrust (for mode 1 or mode 2 operation)
- Design space available to develop a test article of reasonable size
- Sizing trades add confidence to feasibility of nozzle operation in flight on the F-15 airplane



Thrust generated as a function of throat size, back pressure, and operational mode

Conclusion

- The dual-bell nozzle should be tested in a relevant environment
- A conceptual design for Phase I flight was completed
  - Builds on existing flight-proven hardware
  - External flow-field predictions reveal no local flow areas of concern
- A conceptual design for Phase II flight was completed
  - Propellant feed system design fits within F-15 PFTF and RFS constraints
  - Design based on utilization of existing engine throttling capabilities
  - Dual-bell nozzle design approach will demonstrate nozzle flow control
  - Nozzle sizing trades reveal reasonable design space
- Design and operation of a dual-bell nozzle system with the NASA F-15 airplane as a flight testbed appears to be technically feasible

Acknowledgments

- Contributions by a previous design team at NASA Armstrong
  - The ducted Rocket Experiment (D-Rex)

- NASA organizations contributing resources to foster the development of dual-bell rocket nozzle technology
  - Headquarters – Center Innovation Fund
  - Armstrong Flight Research Center – Center Chief Technologist Office
  - Armstrong Flight Research Center – Exploration and Space Technology Mission Directorate Office
  - Langley Research Center – Game Changing Development Program
  - Marshall Space Flight Center – Technology Development and Transfer Office
  - Kennedy Space Center – Launch Services Program