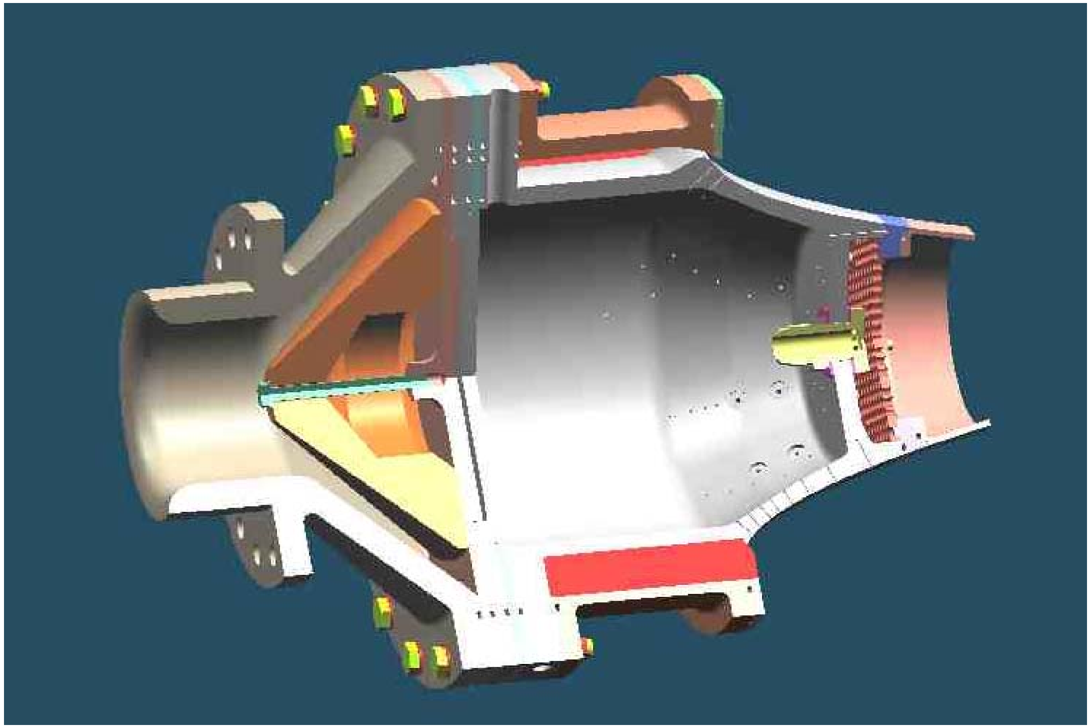
Space Transportation Directorate

Experimental Results for an Annular Aerospike with Differential Throttling



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Overview

- Introduction
- Experimental Hardware
- Results
- Conclusions

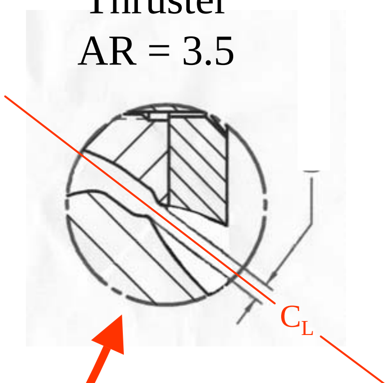
Introduction

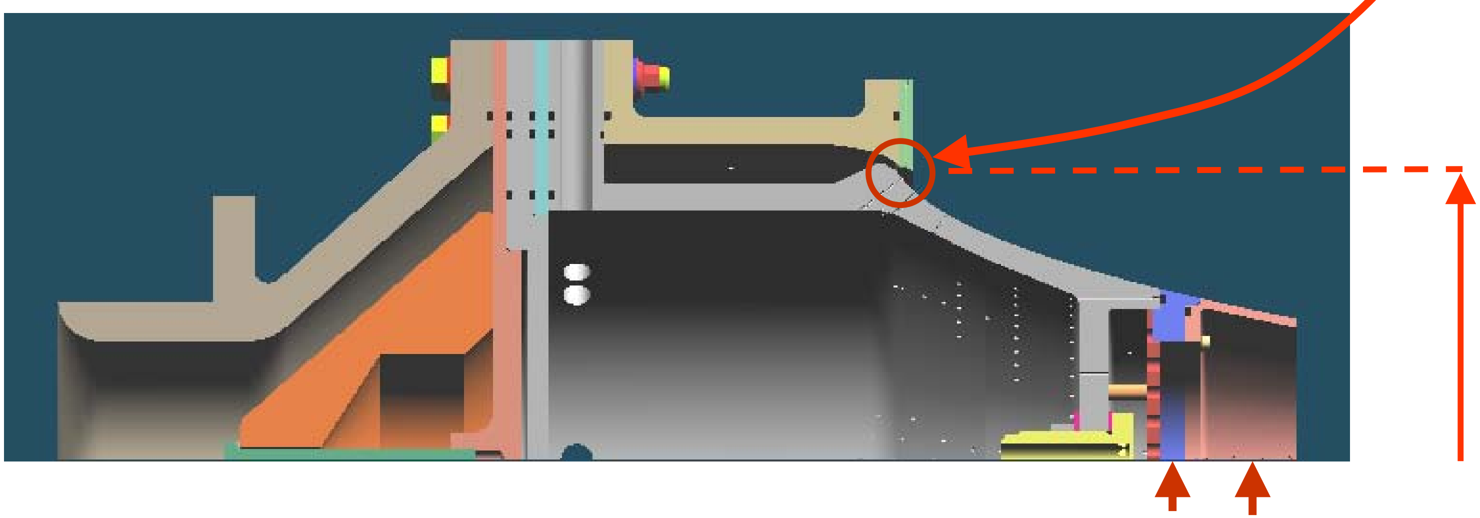
- MSFC funded an internal study on Altitude Compensating Nozzles
  - Develop an ACN design and performance prediction tool.
  - Design, build and test cold flow ACN nozzles
  - An annular aerospike nozzle was designed and tested
  - Incorporated differential throttling to assess Thrust Vector Control
- Objective of the test hardware
  - Provide design tool verification
  - Provide benchmark data for CFD calculations
  - Experimentally measure side force, or TVC, for a differentially throttled annular aerospike

Experimental Hardware

- One Dimensional Design Parameters
  - Overall area ratio, 38:1
  - Internal expansion or 'thruster', 3.5:1. Symmetric expansion.
  - Design point Nozzle Pressure Ratio (NPR) = 995
  - Working fluid was warm air.
  - Two spike lengths, 25% and 40% of equivalent conical nozzle.

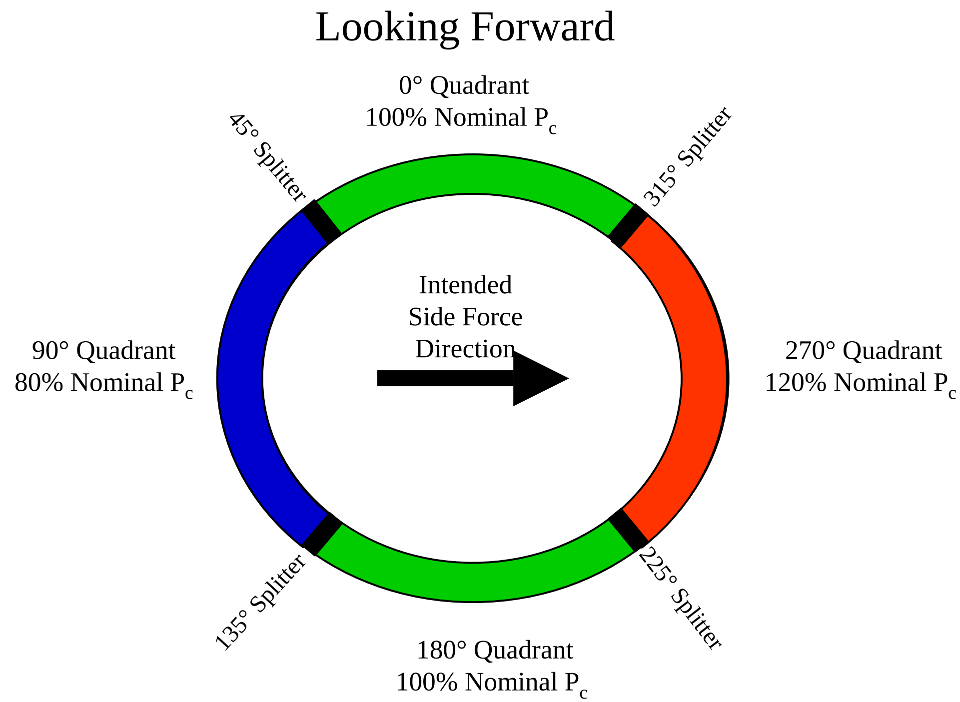
Thruster
AR = 3.5

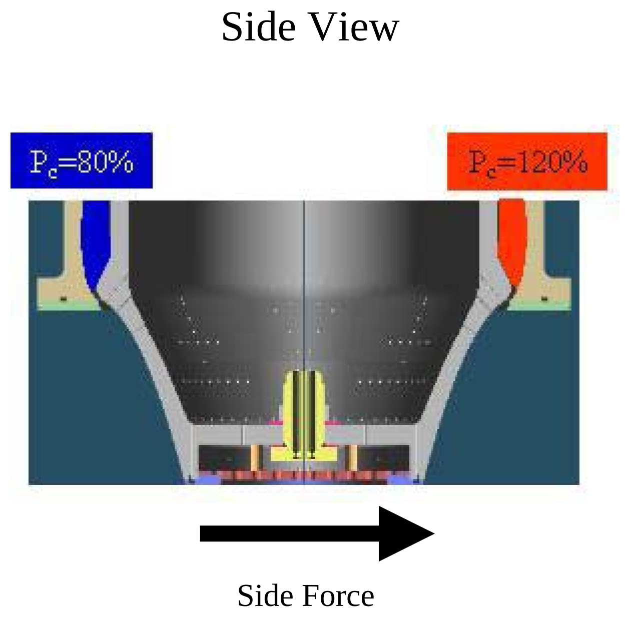




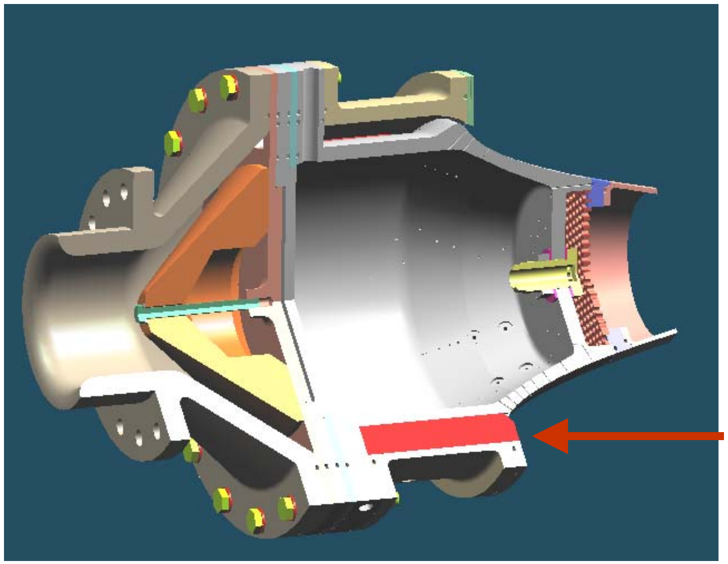
Experimental Hardware, continued

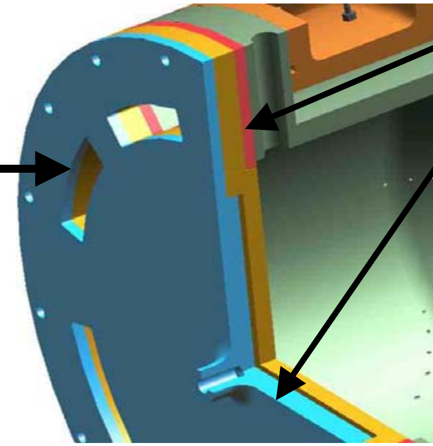
- Differential Throttling
  - Annular manifold and thruster were divided into quadrants with splitter plates
  - Mass flow orificed to produce ±20% differential throttling

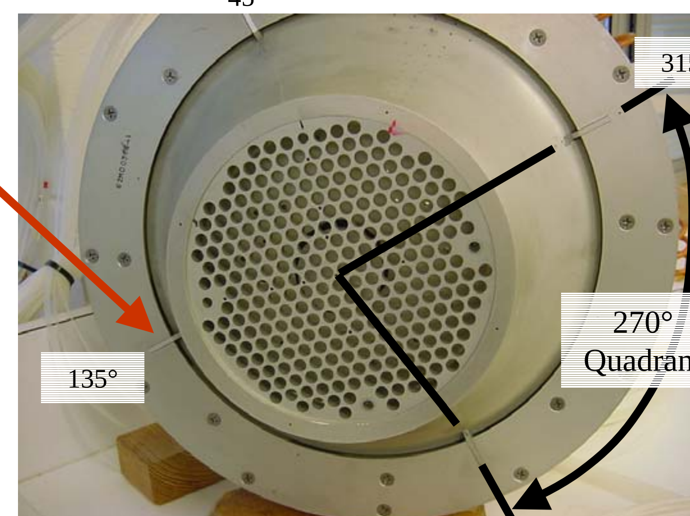




Experimental Hardware, continued

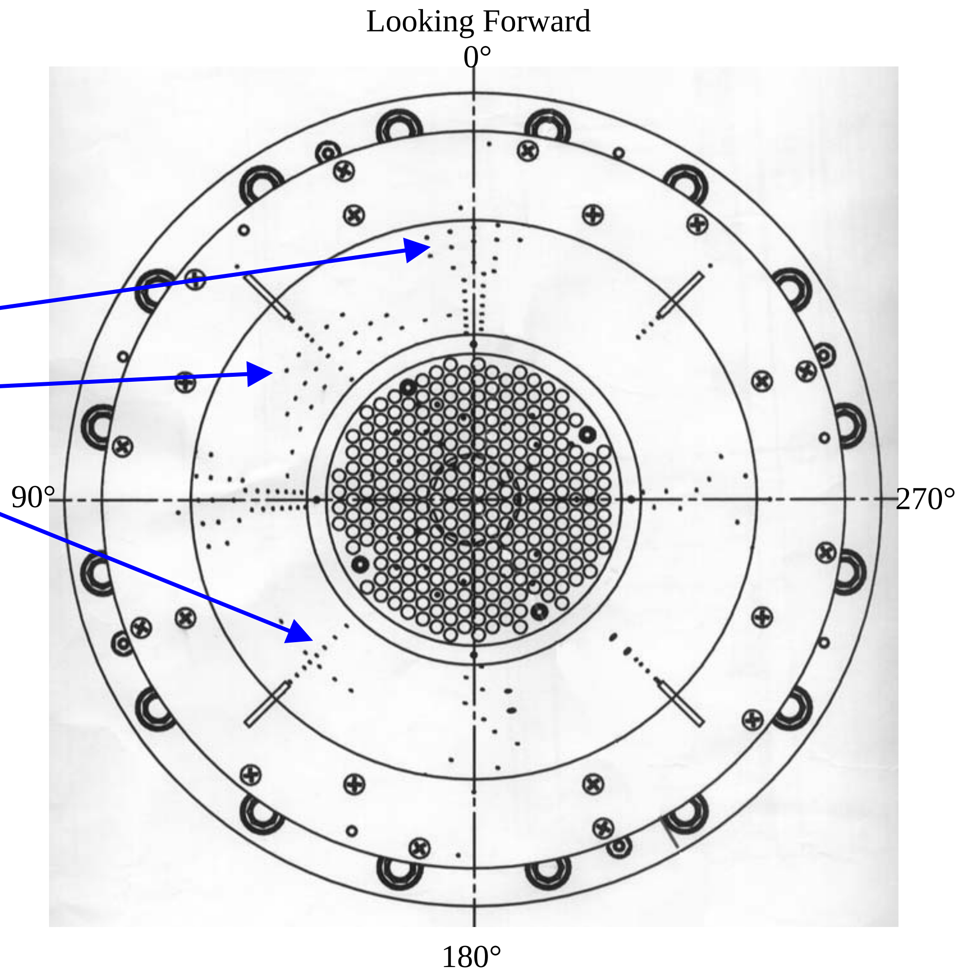






Experimental Hardware, continued

- Nozzle Pressure Field Well Mapped
  - P_{total} and P_{static} in each quadrant manifold
  - More than 160 P_{static} on spike
    - Quadrant centerlines
    - Crossflow
    - Splitter plate profiles
    - Nozzle Base
  - High frequency pressures
    - One each in each quadrant manifold
    - Four on spike
      - two on thruster centerlines
      - two on splitter plate centerlines

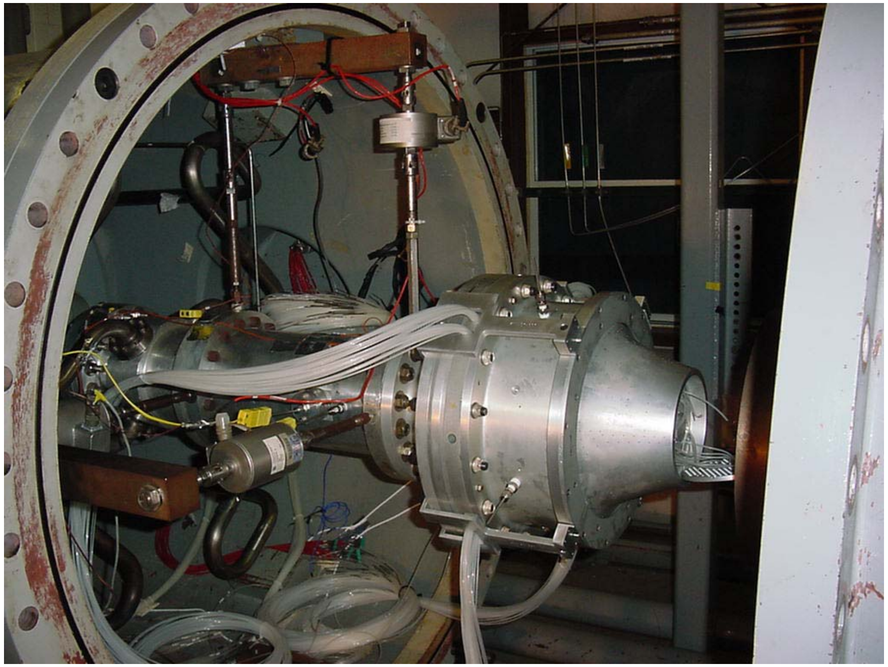


Experimental Hardware, continued

- Test Performed in MSFC's Nozzle Test Facility
  - Test cell evacuated with ejectors
  - Evacuated to near vacuum
  - Measures axial force with load cell
  - Heated Air to 150°C
- Nozzle Efficiency
  - Efficiency = $F_{measured}/F_{optimum}$
  - $F_{opt} = P_c \, A_{throat} \, C_{f\_opt}$

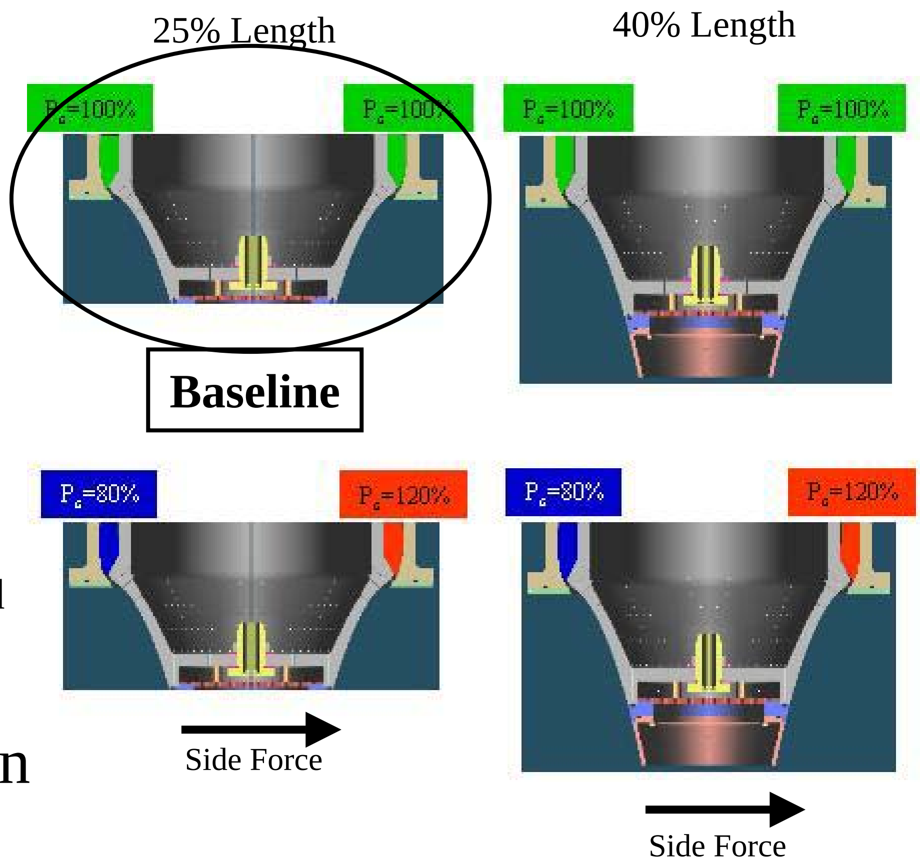
$$C_{f\_opt} \equiv \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}\left[1-\left(\frac{1}{NPR}\right)^{(\gamma-1)/\gamma}\right]}$$

- Side Force
  - Measured with set of small flexures
  - Only measured in horizontal plane



Results

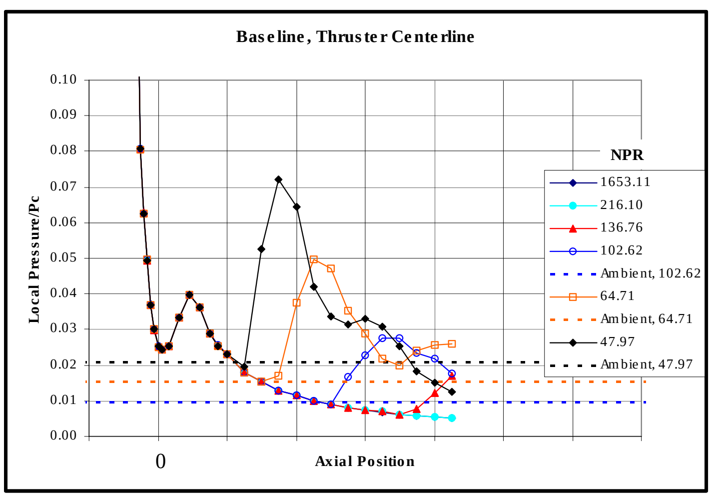
- Four Configurations



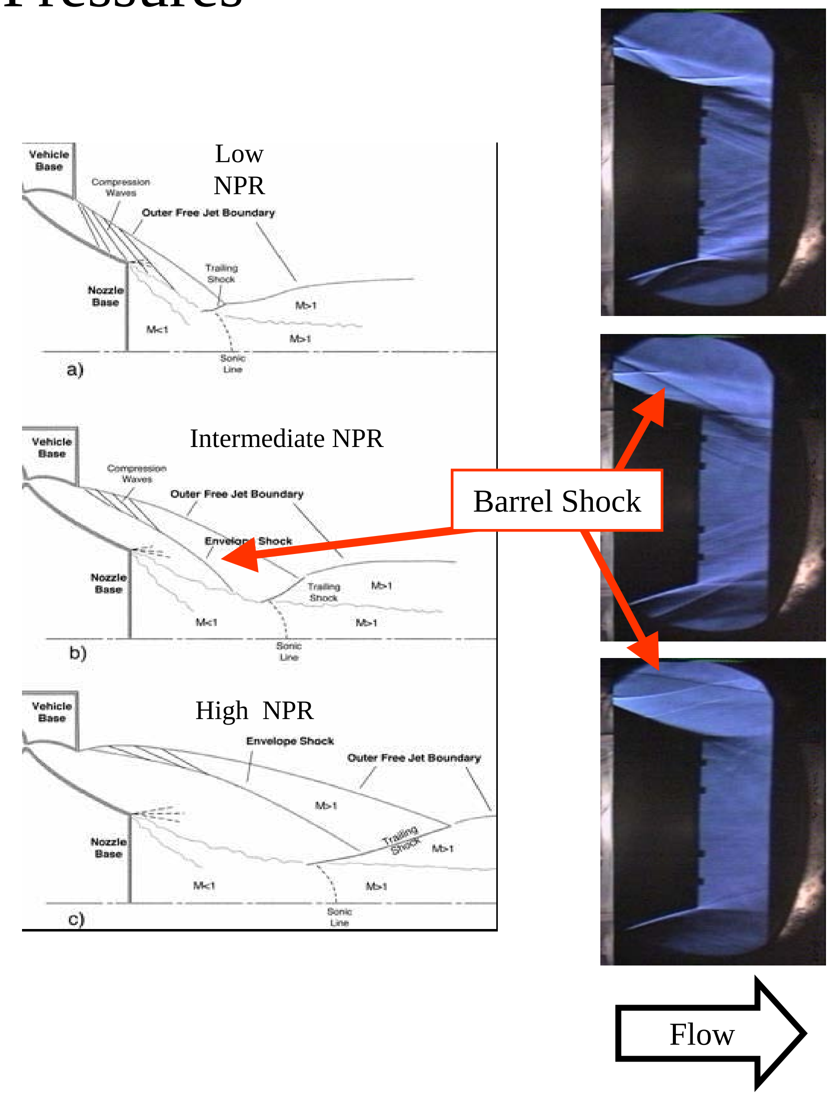
- For Each Configuration
  - Spike wall pressures
  - Nozzle efficiency
  - Side force

Results, continued: Spike Wall Pressures

- Altitude Compensation
  - Altitude compensation at low NPR occurs via recompressions on the spike generated by the Barrel Shock.
  - Barrel, or envelop, shock results from the plume sensing the local ambient pressure.

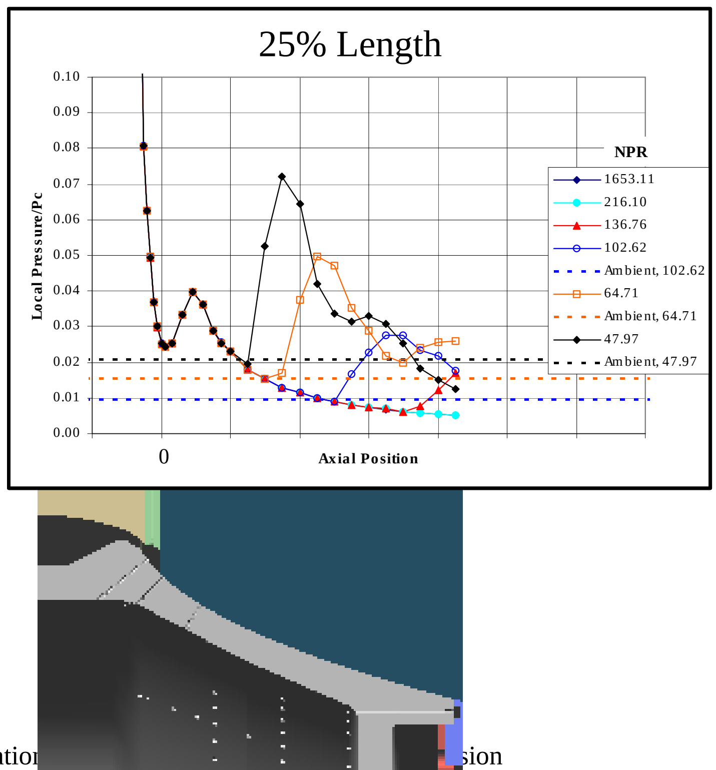


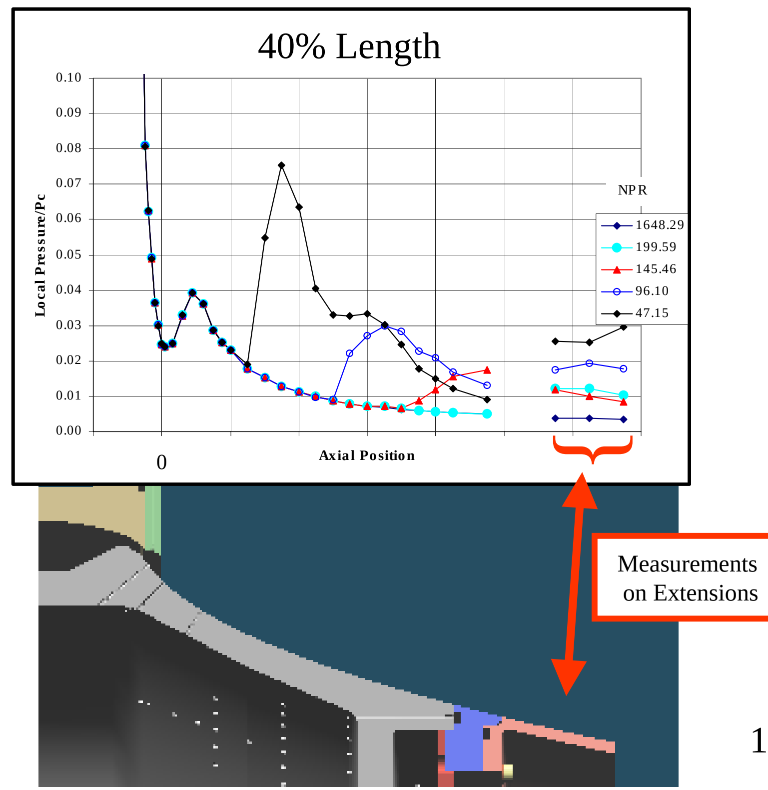
Wall pressure on the annular aerospike centerbody



Results, continued: Spike Wall Pressures

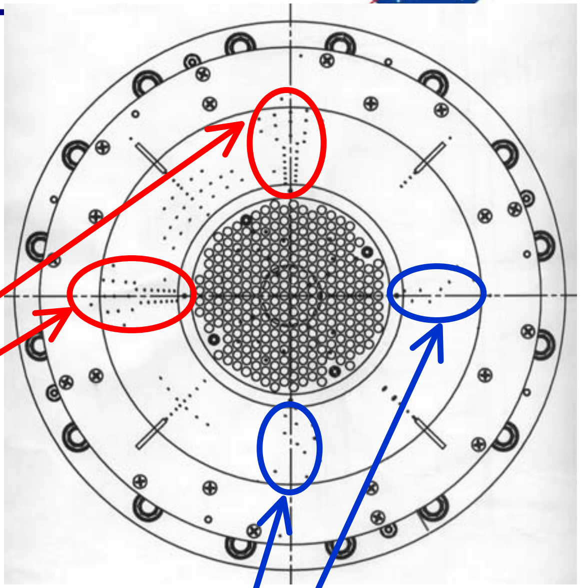
- Non-Throttled
  - Recompression on spike
    - 25% Length, barrel shock moved off spike at NPR ~150
    - 40% Length, barrel shock moved off spike at NPR ~200

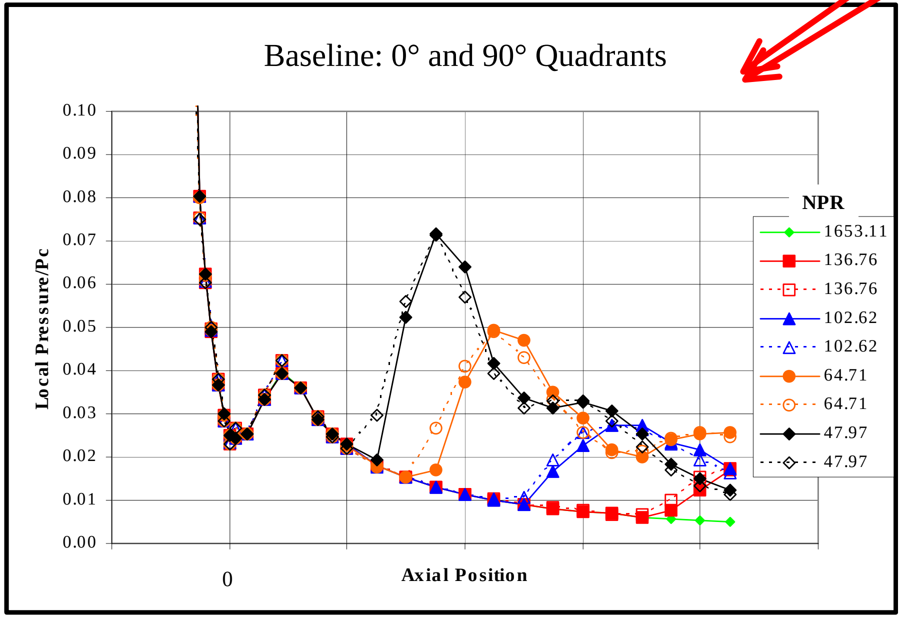


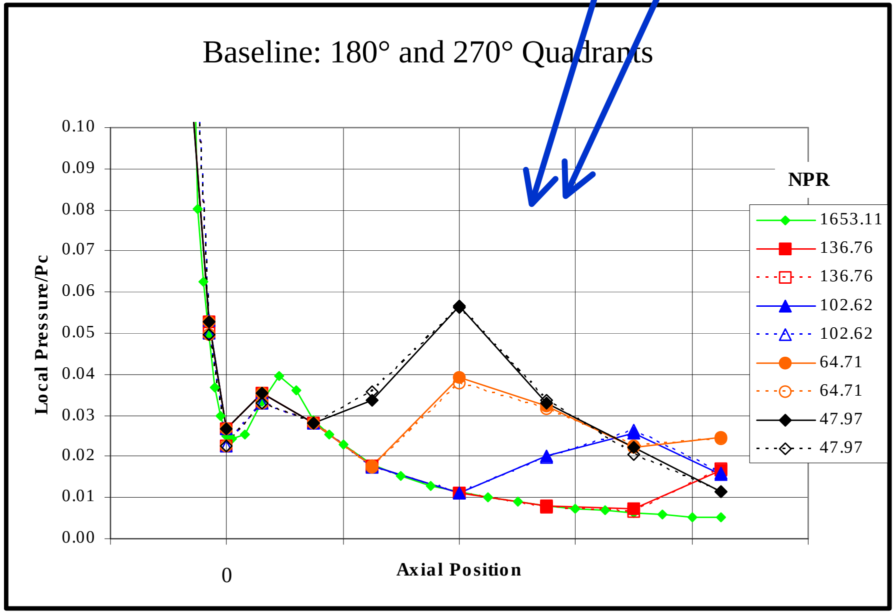


Results, continued: Spike Wall Pressure

- Non-Throttled
  - Quadrant centerline profiles – good agreement
    - 0° & 90° quadrants, high density of measurements.
    - 180° & 270° quadrants, lower density of measurements.
    - 0° & 90 agree with 180 & 270.

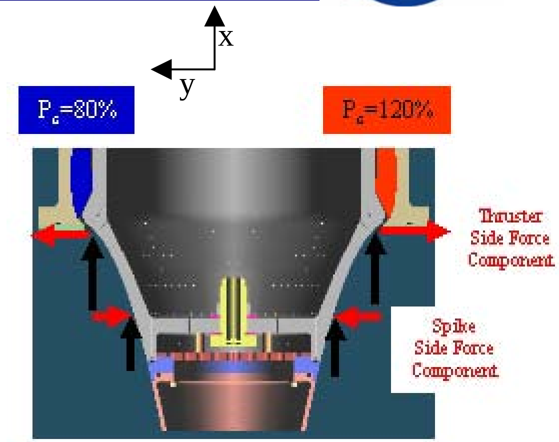


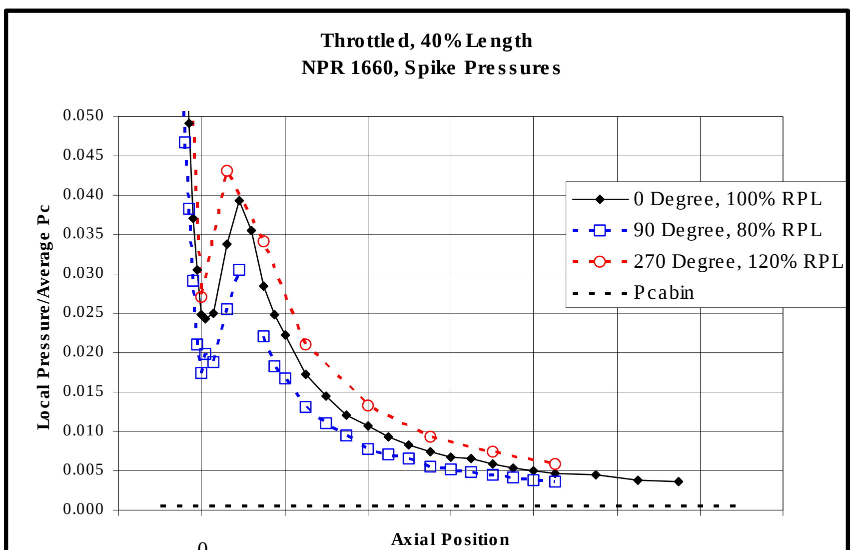




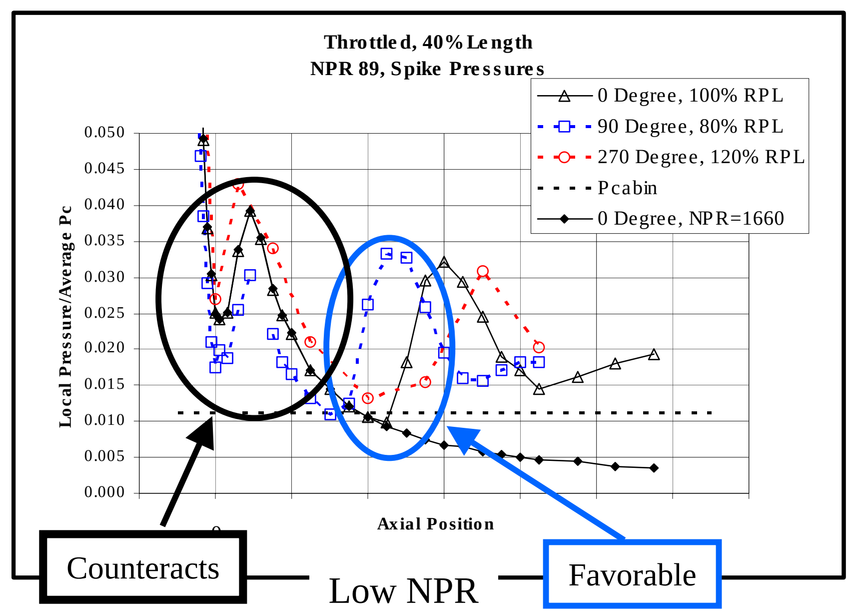
Results, continued: Spike Wall Pressures

- Throttled: 40% Length shown (25% Length Similar)
  - High NPR
    - High pressure quadrant had higher pressures on spike
    - Spike pressures counteract intended side force
  - Low NPR
    - Spike pressures after recompression were favorable to intended side force





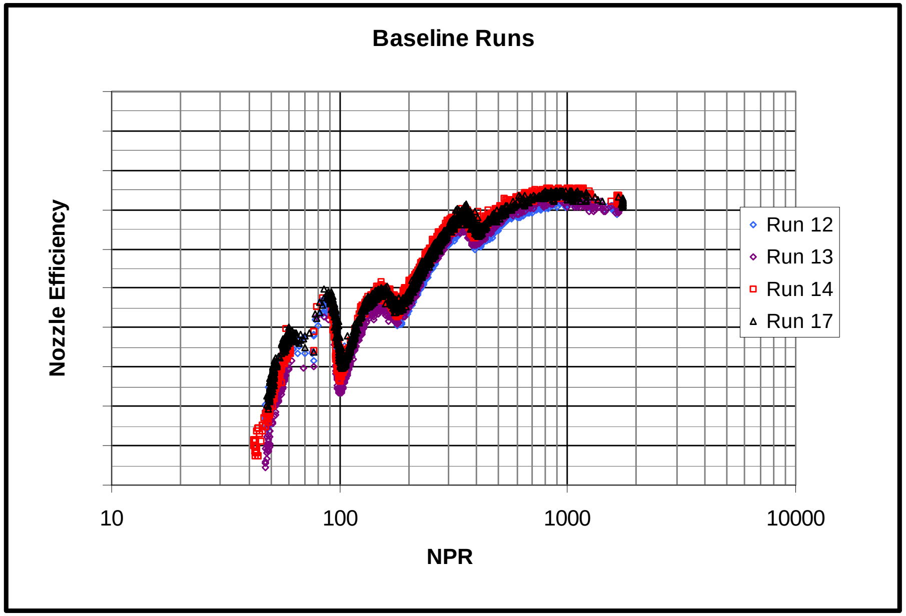
High NPR

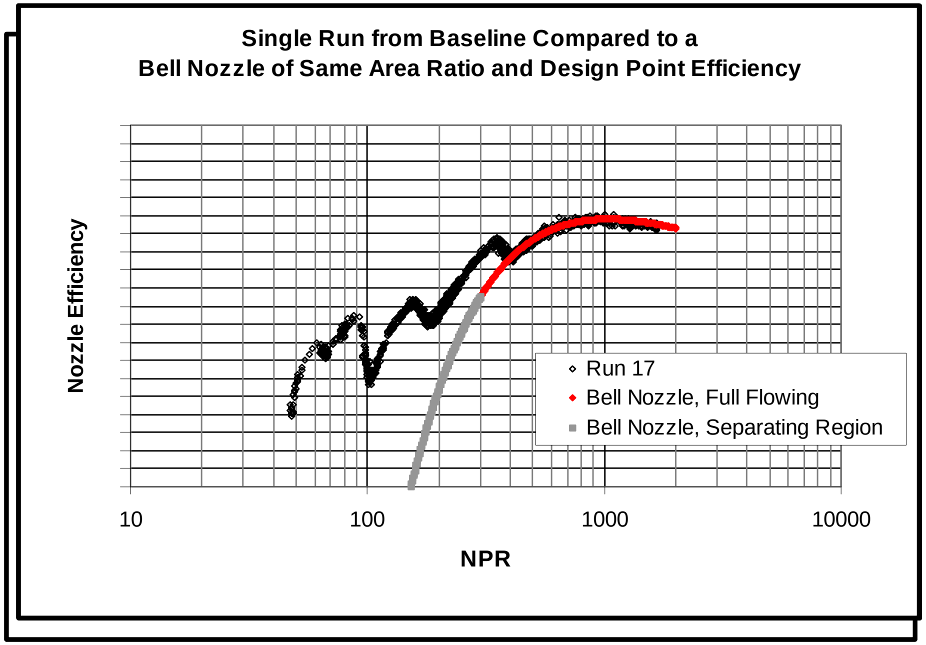


Low NPR

Results, continued: Nozzle Efficiency

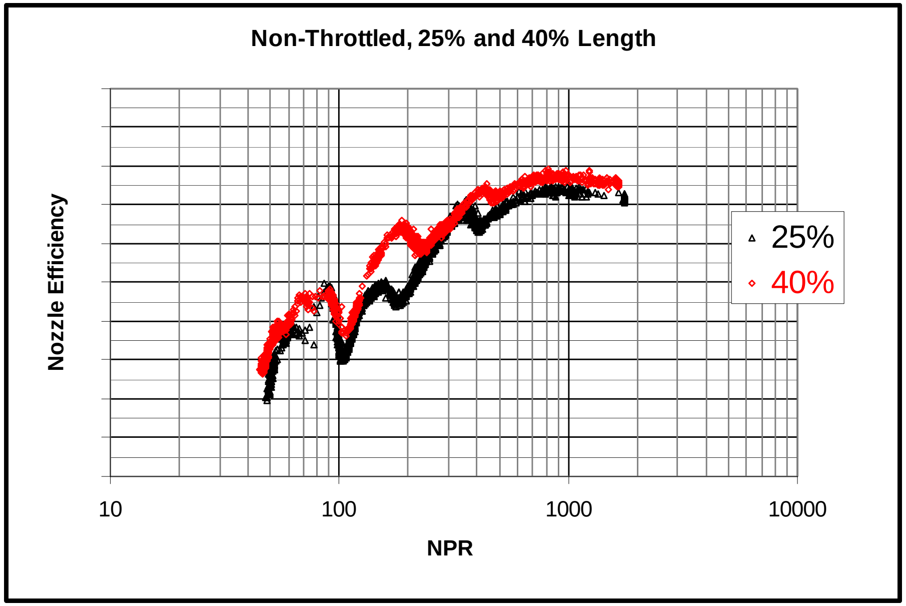
- Non-Throttled: 25% Length, 'Baseline'
  - Fairly good repeatability in test data
  - Several discontinuities in the curves
    - At NPR 400, due to rapid decrease in nozzle base pressure at wake closure
    - At NPR 180, due to recompressions moving off the ramp
    - At NPR 100, due to decrease in base pressure related to barrel shock structure





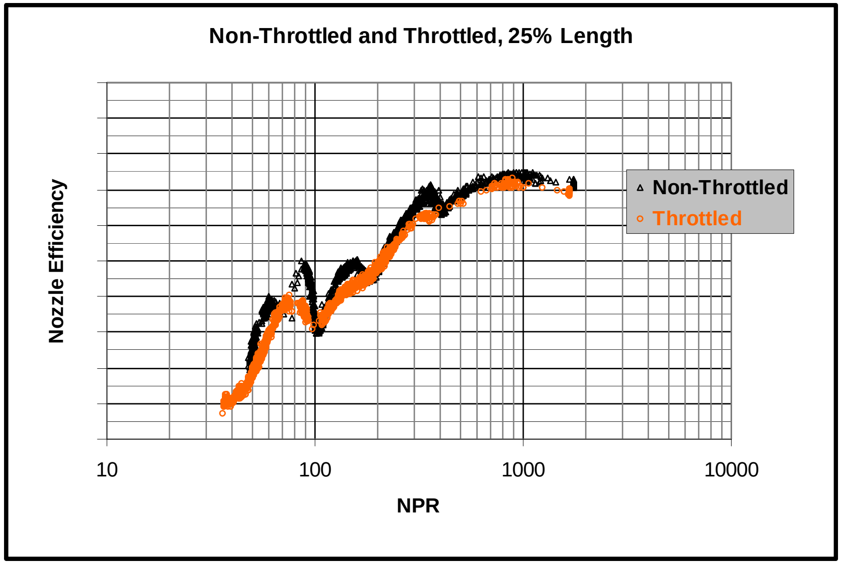
Results, continued: Nozzle Efficiency

- Non-Throttled: 40% vs. 25% Length
  - Longer spike increased nozzle efficiency
  - Discontinuities shifted to higher NPR
    - Wake closure at higher NPR
    - Barrel shock moved off spike at higher NPR
  - Decrease in efficiency at wake closure was smaller
    - Nozzle base area smaller, smaller component of axial thrust



Results, continued: Nozzle Efficiency

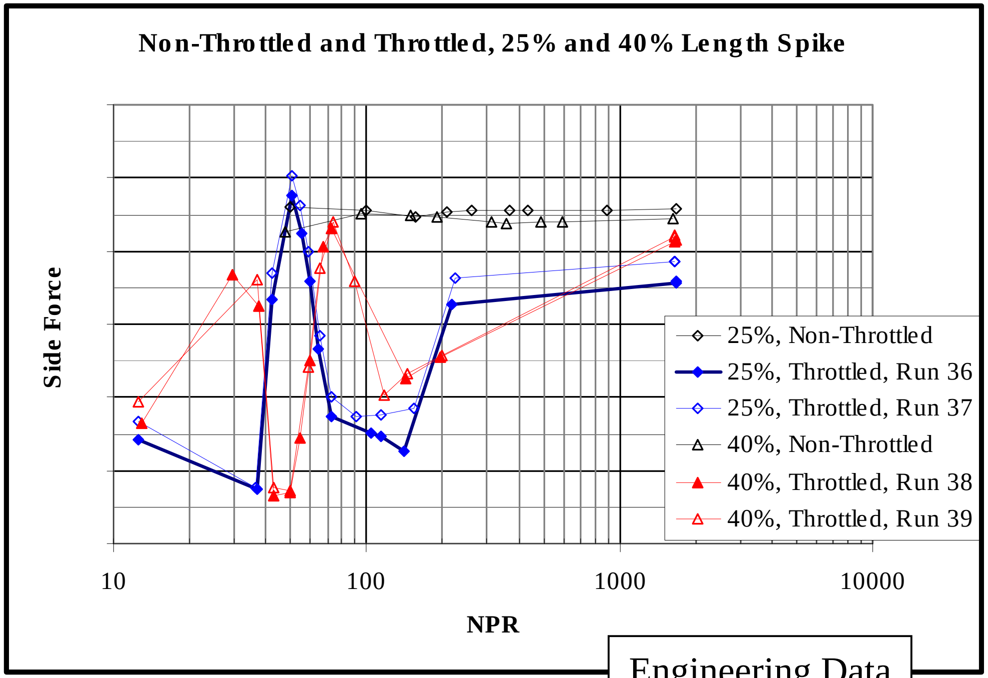
- Throttled: 25% Length
  - Efficiency at the design point was within family of baseline runs
  - Discontinuities smoothed
    - 90° and 270° quadrants had different effective NPR than nominal P_c quadrants
    - Different barrel shock positions on spike smoothed the transitions



- Throttled: 40% Length had Similar Trends

Results, continued: Side Force

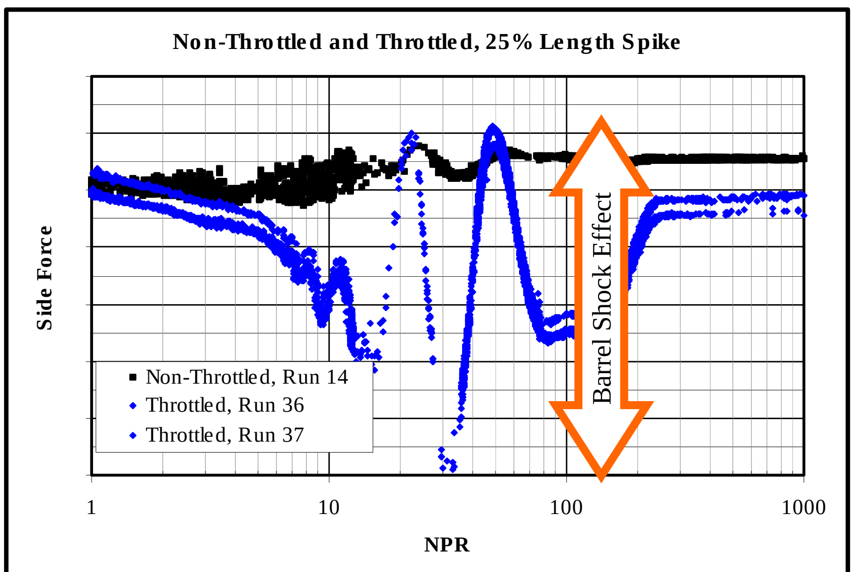
- Overview of 25% and 40% Length Spike
  - Non-Throttled runs plotted as reference
  - Both 25% and 40% length spikes exhibited large variations at low NPR
  - Peaks occurred at different NPR
  - Both had constant value at high NPR
  - 40% length produced less side force at high NPR

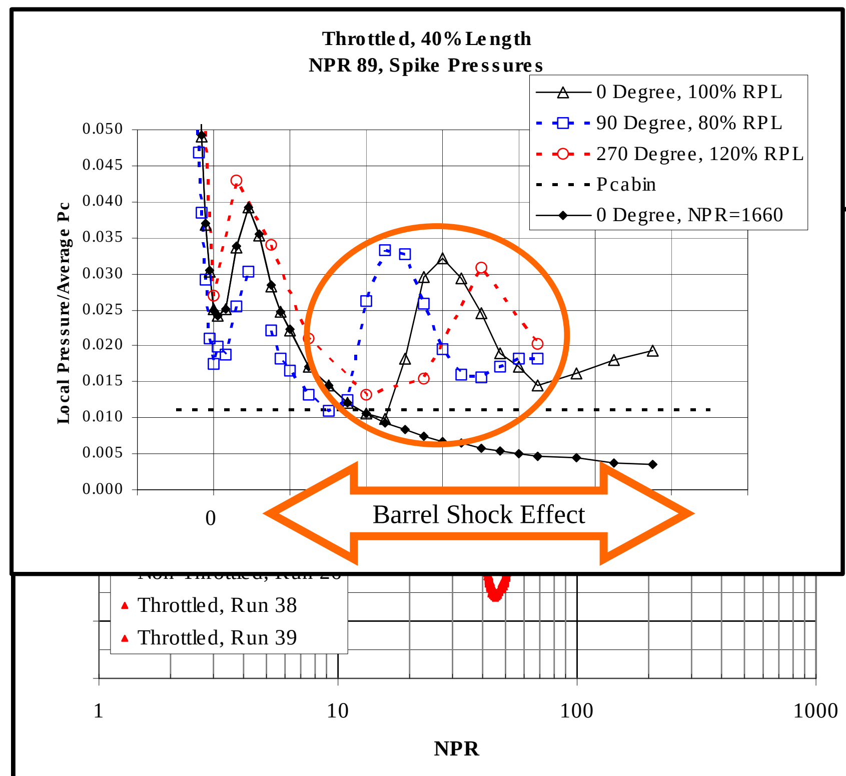


Engineering Data

Results, continued: Side Force

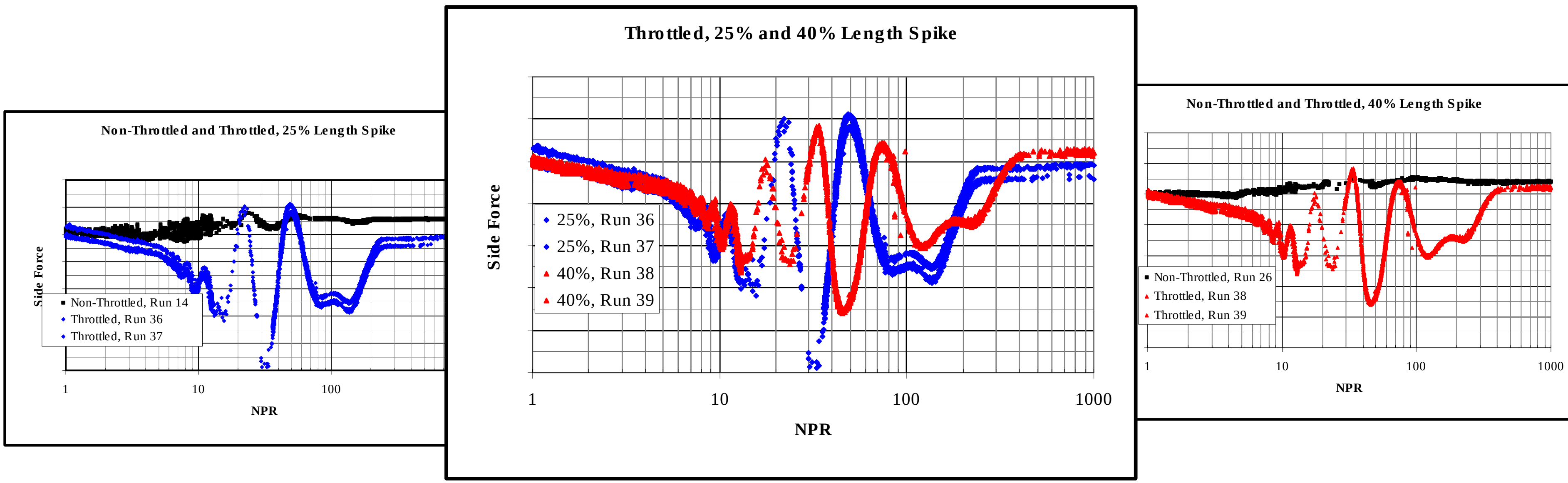
- 25% Length
  - Two peaks of near zero side force. Both indicate TVC reversal.
  - Constant value reached at NPR 230.
- 40% Length
  - Three peaks of near zero side force. One indicated TVC reversal
  - Constant value reached at NPR 400.





Results, continued: Side Force

- Comparing Side Force Directly
  - 25% length spike's peak to peak variation larger than 40% length
  - Peaks were at different NPR



Conclusions

- Non-Throttled
  - 25% Length
    - Details of aerospike nozzle efficiency curve explained.
    - Discontinuities due to altitude compensation by barrel shock.
  - 40% Length
    - Increased efficiency.
    - Subtle changes in details of efficiency curve.
- Throttled
  - 25% Length
    - No discernable effect on efficiency.
    - Large variation of side force at low NPR resulted from barrel shock impingement at different axial stations.
    - Side force became a constant value when last shock moved off centerbody.
  - 40% Length
    - No discernable effect on efficiency.
    - Large variation, but less than 25% length spike, at low NPR.
    - Side force became a constant value when last shock moved off centerbody.
    - Side force at high NPR was approximately ¼ of side force for 25% length spike.