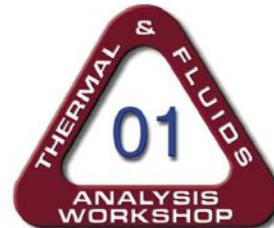


## Status of Nozzle Aerodynamic Technology at MSFC

Joseph H. Ruf/TD64  
David M. McDaniels/TD63  
Bud Smith/Plumetech  
Zachary Owens/U. of Virginia



Thermal and Fluid Workshop  
September, 2001  
Huntsville, AL.



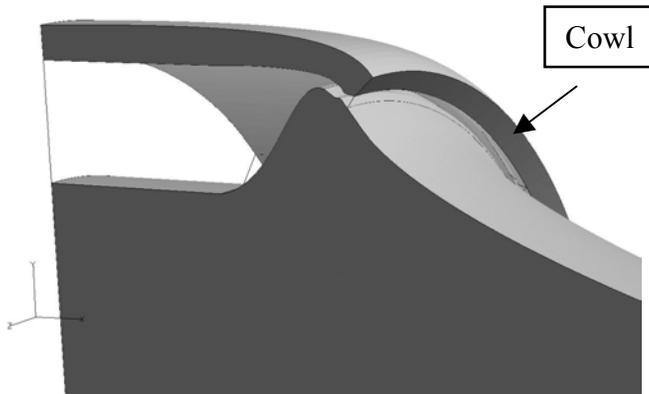
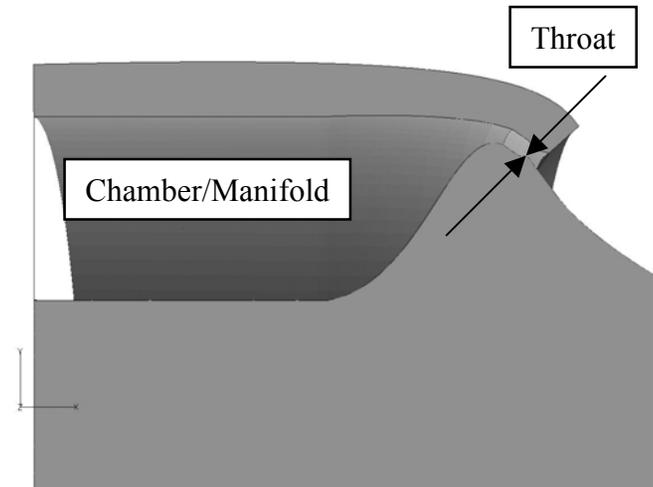
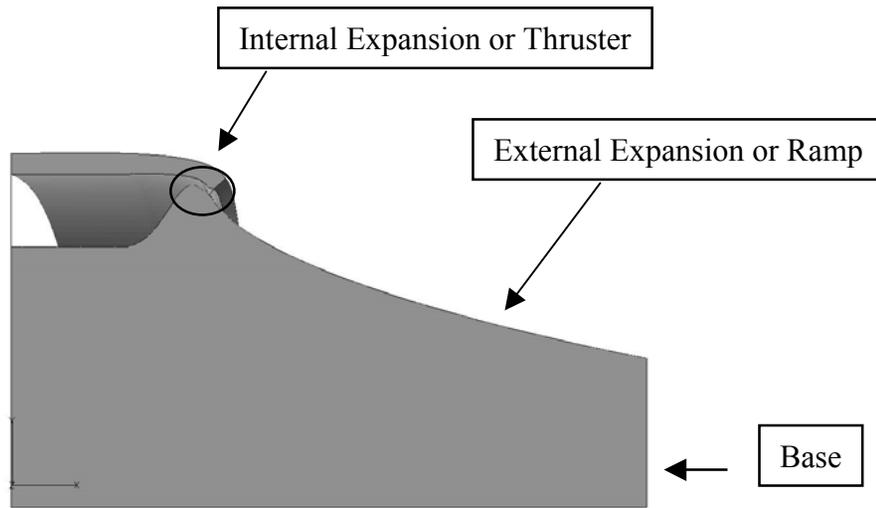
- Overview
  - Objectives
  - Analytical Tool Development
  - Cold Flow Nozzle Test Hardware
  - Analytical TVC Model
  - Related Work

- Objectives

- Of this Presentation: Provide Insight Into MSFC In-house Nozzle Aerodynamic Technology; Design, Analysis & Testing
- CDDF ‘Altitude Compensating Nozzle Technology’
  - Develop In-house ACN Aerodynamic Design Capability
  - Build In-house Experience for all aspects of ACN via End-to-End Nozzle Test Program
  - Obtain Experimental Data for Annular Aerospike: Thrust  $\eta$ , TVC capability and surface pressures

- Analytical Tool Development
  - To support selection/optimization of future Launch Vehicle propulsion we needed a parametric design and performance tool for ACN
  - Chose Aerospike Nozzles as the ACN to Start With
  - Aerospike Design And Performance Tool (ADAPT)
    - Developed by Bud Smith/Plumetech
    - Parametrics on:
      - Aerospike Configuration
        - » Linear
        - » Annular
        - » Axisymmetric
      - Thruster Configuration
        - » 2D/Slot, or Clustered-Axisymmetric
        - » Rao, Ideal, Truncated Ideal

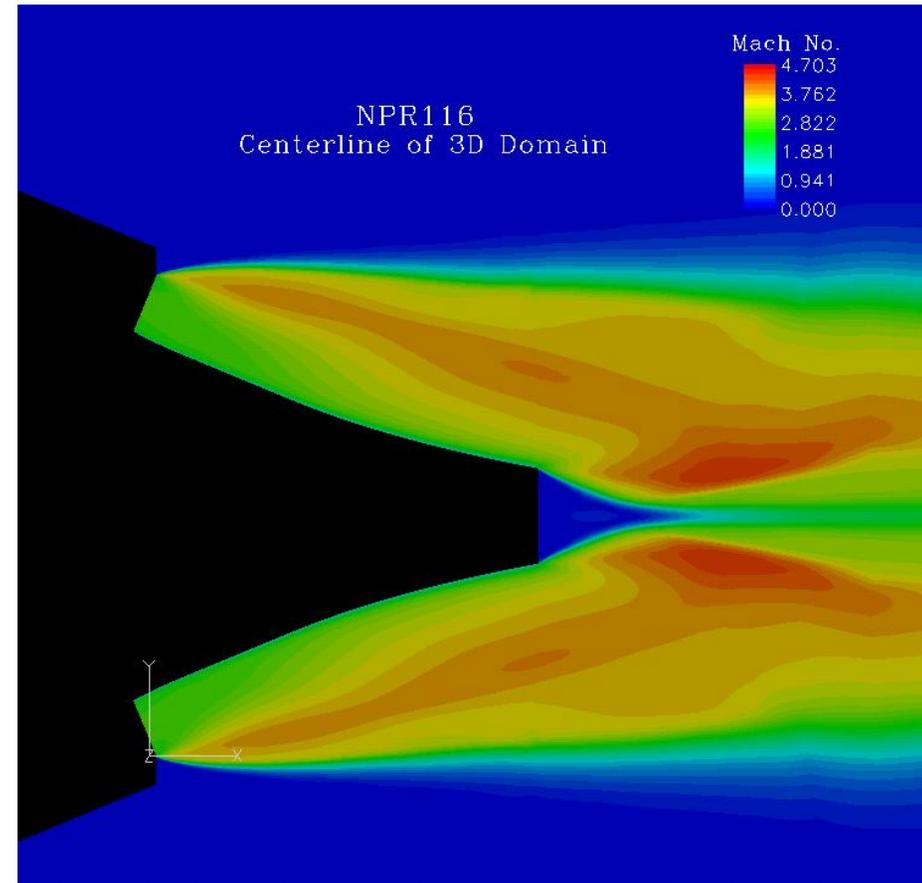
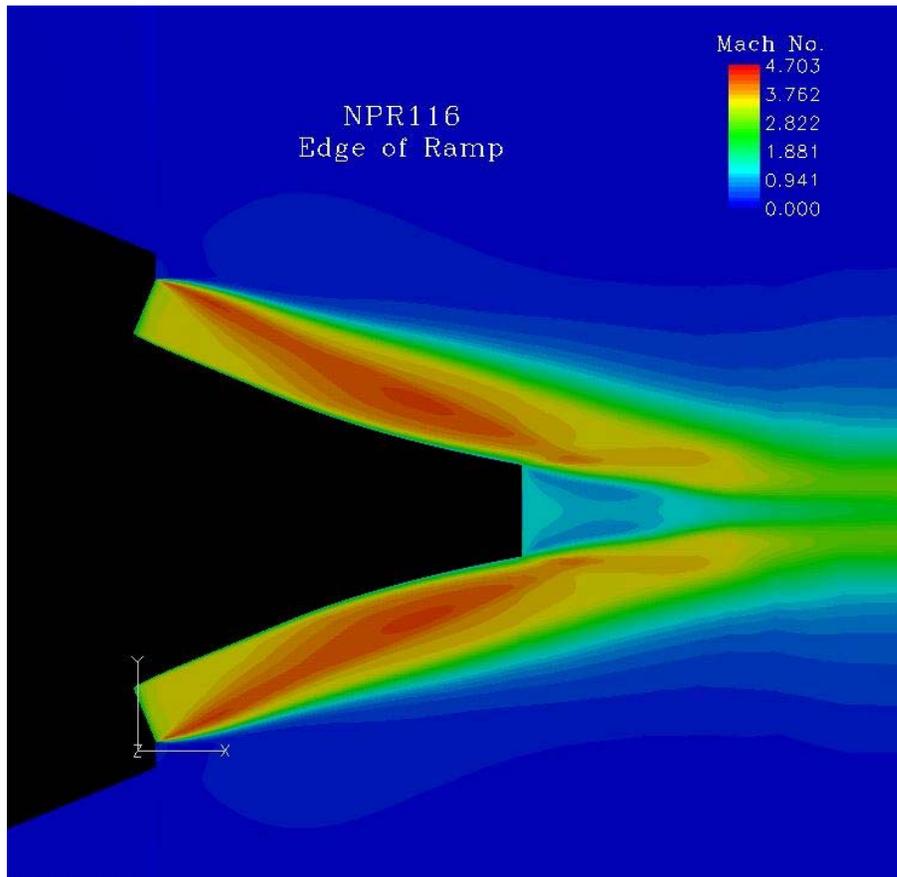
## Aerospike Nozzle Terminology



## Aerospike Nozzle Terminology

### Low Altitude or NPR

### High Altitude or NPR



- Analytical Tool Development

- Chose Aerospike Nozzles as the ACN to Start With
- To support future propulsion selection we needed a parametric design and performance tool for ACN
- Aerospike Design And Performance Tool (ADAPT)

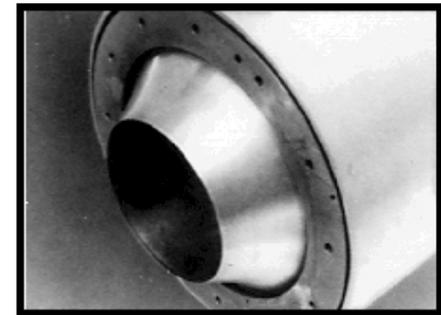
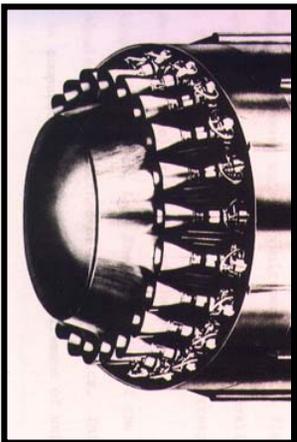
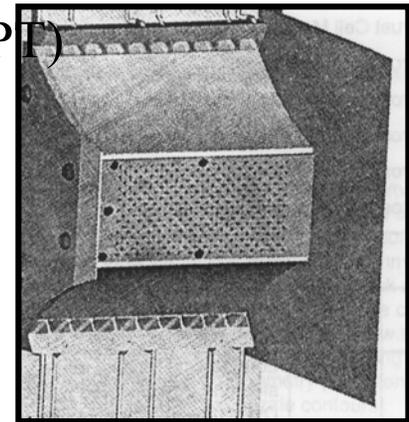
- Developed by Bud Smith/Plumetech
- Parametrics

- Aerospike Configuration

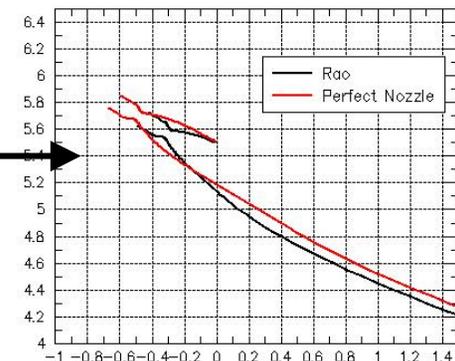
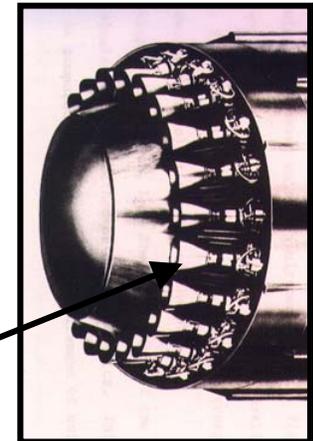
- » Linear
- » Annular
- » Axisymmetric

- Thruster Configuration

- » 2D/Slot, or Clustered-Axisymmetric
- » Rao, Ideal, Truncated Ideal

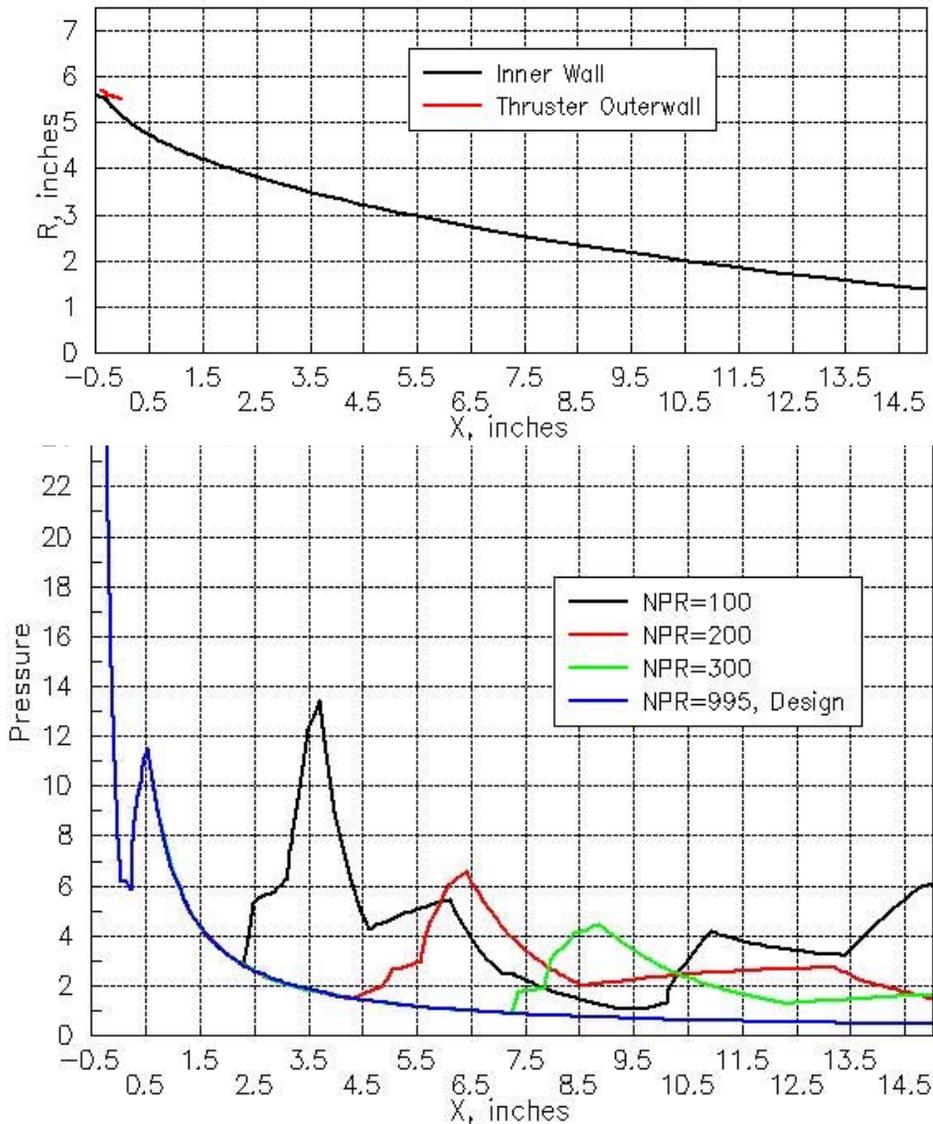


- Analytical Tool Development
  - Chose Aerospike Nozzles as the ACN to Start With
  - To support future propulsion selection we needed a parametric design and performance tool for ACN
  - Aerospike Design And Performance Tool (ADAPT)
    - Developed by Bud Smith/Plumetech
    - Parametrics
      - Aerospike Configuration
        - » Linear
        - » Annular
        - » Axisymmetric
      - Thruster Configuration
        - » 2D/Slot, or Clustered-Axisymmetric
        - » Rao, Ideal, Truncated Ideal



- Analytical Tool Development, cont.
  - Parametrics, cont.
    - Sizing and Design Point
      - » Radius, Area Ratio or  $NPR_{\text{design}}(10)$
      - » Mass Flow or Throat Area
      - »  $P_c$ ,  $P_{a\_des}(10)$ , Expansion Split(10)
    - Working Fluid; Air, Lox/RP, Lox/H<sub>2</sub>, Others
    - Performance
      - » Each Geometric Combinations Performance Calculated at up to 10 Altitudes (NPR)
      - » Nozzle Ramp Truncation(10)
      - » Outputs;  $P$  vs.  $X$ , a Summary Table, Thrust,  $I_{sp}$ ,  $C_f$  ...

- Analytical Tool Development, cont.



- Analytical Tool Development, cont.
  - Example Table Output

Summary of Aerospike Design And Analysis Results For ' Problem: case1ra

Case1 Rao

Case Number - 0101

Cluster Design Pressure	=	0.3014 psia
Cluster Design Area Ratio	=	38.6300
Thruster Design Pressure	=	11.0742 psia
Thruster Design Area Ratio	=	3.4962

Case Number 0101

**Cluster - 1-D**

Area Ratio	38.630
Cluster Radius (in)	5.5000
Area (in**2)	95.033
Length (in)	29.9768
Mass Flow Rate lbm/s	14.2361
Prandtl-Meyer Ang (deg)	81.8045
Mach Number	5.5621
Pressure (psia)	0.3014
Temperature (R)	105.74
Density (lbm/ft**3)	0.769E-02
Velocity (ft/sec)	2803.6414
Specific Heat Ratio	1.4000
Molecular Weight	28.9700
Equivalent 15 deg noz length - in	17.224

**Thruster - 1-D**

Area Ratio	3.496
Exit Height (in)	0.2548
Throat Height (in)	0.0704
Throat Area (in**2)	2.4601
Exit Area - in**2	8.641
Nozzle Length - in	0.283
Prandtl-Meyer Ang (deg)	45.7879
Mach Number	2.7988
Pressure (psia)	11.0742
Temperature (R)	296.10
Density (lbm/ft**3)	0.101E+00
Velocity (ft/sec)	2360.8020
Specific Heat Ratio	1.4000
Molecular Weight	28.9700
Tilt Angle (Deg)	36.0166

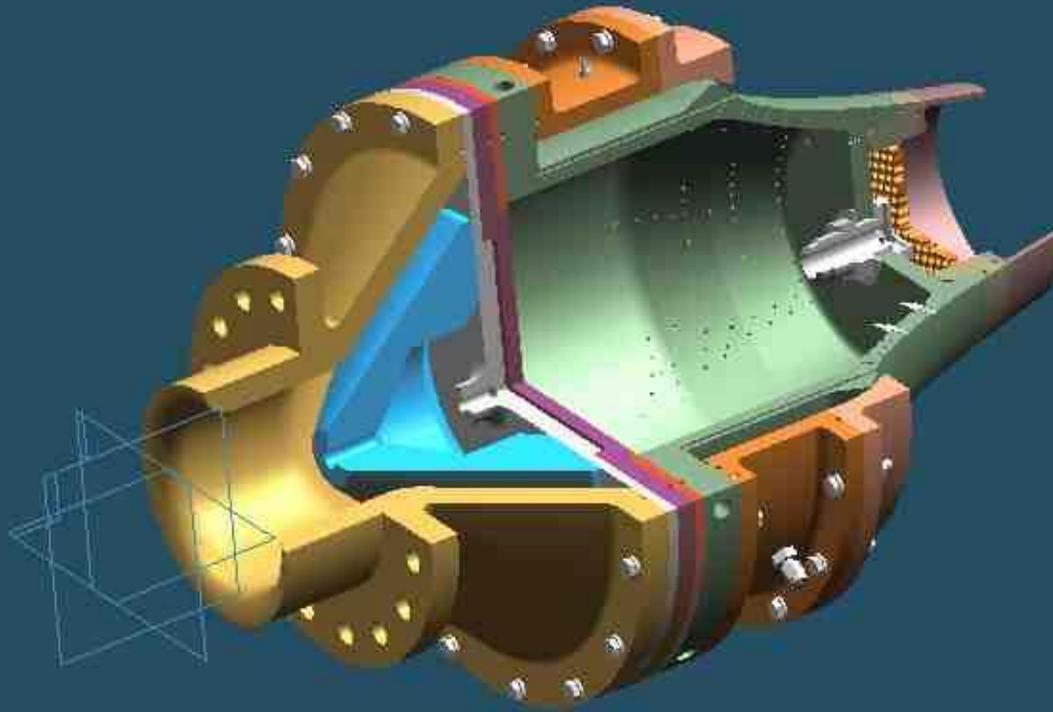
- Analytical Tool Development, cont.
  - Example Table Output, Page 2

Case Number	010100	010101	010102	010103	010
Ambient Pressure - psia	0.3014	6.0300	3.0150	1.5080	1.0
Pressure Ratio - Pc/Pa	995.3800	49.7512	99.5025	198.9390	298.5
<b>Performance</b>					
<b>Thruster</b>					
1-D Vacuum Thrust (no tilt) - lbf	1140.0	1140.0	1140.0	1140.0	114
1-D Delivered Thrust (no Tilt) - lbf	1137.4	1088.1	1114.1	1127.0	113
1-D Vacuum Isp (no tilt) - sec	80.067	80.067	80.067	80.067	80.
1-D Delivered Isp (no Tilt) - sec	79.885	76.424	78.245	79.156	79.
1-D Vac. Thrust Coefficient(no tilt)	1.5447	1.5447	1.5447	1.5447	1.5
1-D Del. Thrust Coefficient(no Tilt)	1.5412	1.4744	1.5095	1.5271	1.5
1-D Vacuum Thrust (tilt) - lbf	926.3	926.3	926.3	926.3	92
1-D Delivered Thrust (tilt) - lbf	924.2	884.1	905.2	915.7	91
1-D Vacuum Isp (tilt) - sec	64.762	64.762	64.762	64.762	64.
1-D Delivered Isp (tilt) - sec	64.614	61.815	63.288	64.025	64.
1-D Vac. Thrust Coefficient(tilt)	1.2551	1.2551	1.2551	1.2551	1.2
1-D Del. Thrust Coefficient(tilt)	1.2522	1.1980	1.2265	1.2408	1.2
Boundary Layer Thrust loss - lbf	1.442	1.444	1.443	1.443	1.
Vacuum Thrust - lbf	916.0	916.0	916.0	916.0	91
Delivered Thrust - lbf	914.5	885.8	900.9	908.4	91
Vacuum Isp - sec	64.478	64.478	64.478	64.478	64.
Delivered Isp - sec	64.372	64.372	64.372	64.372	64.
Vac. Thrust Coefficient	1.2411	1.2411	1.2411	1.2411	1.2
Del. Thrust Coefficient	1.2391	1.2002	1.2207	1.2309	1.2
Nozzle Efficiency(cf_del/cf_1d_del)	0.9895	1.0019	0.9952	0.9920	0.9
<b>Cluster</b>					
1-D Vacuum Thrust - lbf	1269.2	1269.2	1269.2	1269.2	126
1-D Delivered Thrust - lbf	1240.5	1240.5	1240.5	1240.5	124
1-D Vacuum Isp - sec	89.152	89.152	89.152	89.152	89.
1-D Delivered Isp - sec	87.140	87.140	87.140	87.140	87.
1-D Vac. Thrust Coefficient	1.7197	1.7197	1.7197	1.7197	1.7
1-D Del. Thrust Coefficient	1.6809	1.6809	1.6809	1.6809	1.6
Boundary Layer Thrust loss - lbf	10.102	0.000	15.263	12.673	11.
Delivered Thrust - lbf	1223.0	1120.3	1142.9	1173.5	118
Delivered Isp - sec	86.084	86.081	86.081	86.079	86.
Del. Thrust Coefficient	1.6571	1.5179	1.5486	1.5901	1.6
Nozzle Efficiency(cf_del/cf_1d_del)	0.9858	0.9031	0.9213	0.9460	0.9
Results for Cluster <b>Truncation of 25.00 Percent</b> ( X = 4.31 INCHES)					
Case Number	010100	010101	010102	010103	010
Ambient Pressure - psia	0.3014	6.0300	3.0150	1.5080	1.0
Pressure Ratio - Pc/Pa	995.3800	49.7512	99.5025	198.9390	298.5
<b>Performance</b>					
<b>Cluster</b>					
Delivered Thrust - lbf	1215.5	1093.5	1134.4	1143.7	117
Delivered Isp - sec	85.552	76.968	79.848	80.500	82.
Boundary Layer Thrust loss - lbf	8.047	11.288	9.340	8.039	8.
Base Drag Thrust Loss - lbf	0.000	0.000	0.000	0.000	0.

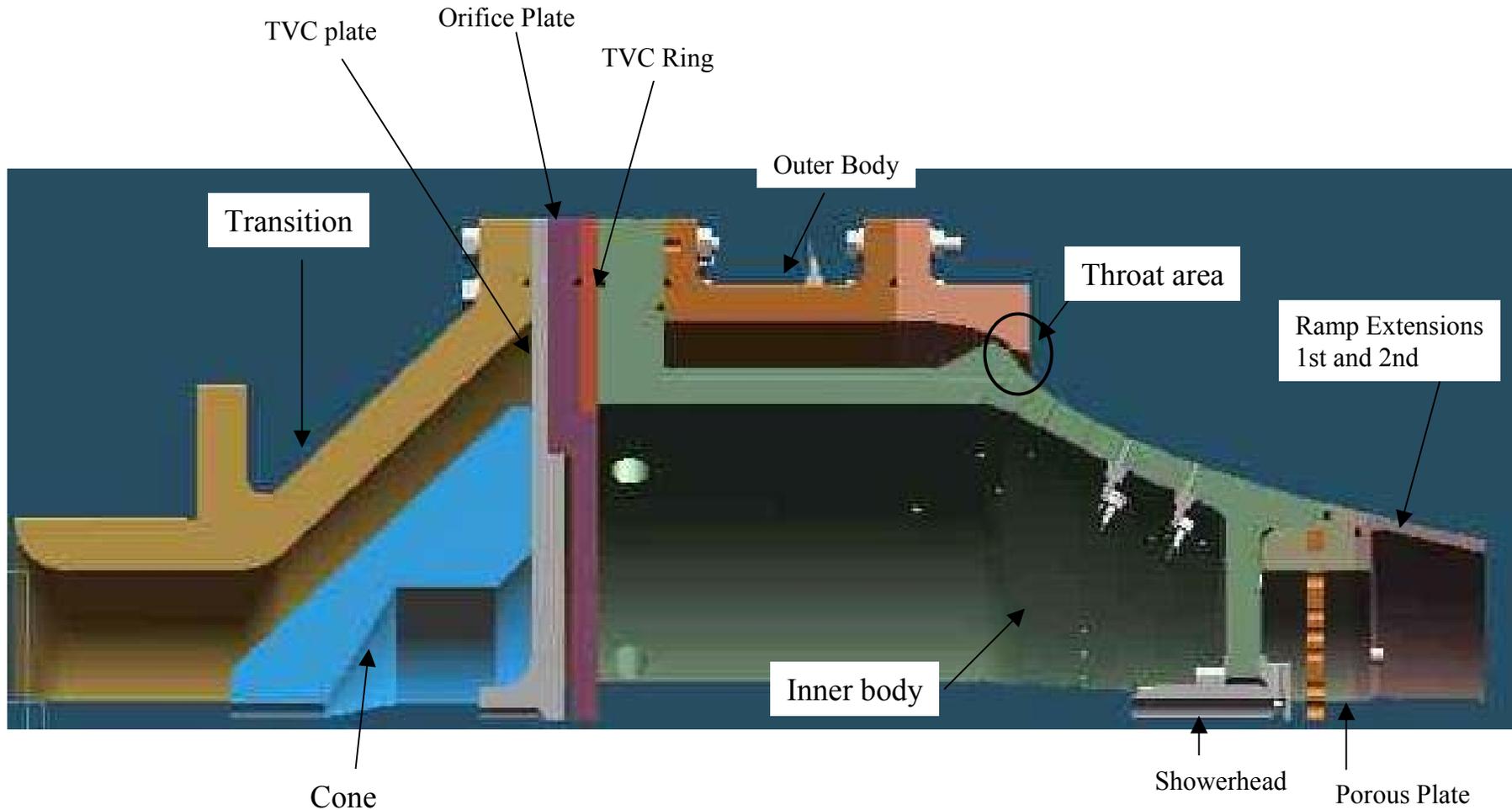
- Analytical Tool Development, cont.
  - Methodology
    - Namelist Driven
    - Runs in Seconds on PC or Unix
    - Bud Smith Wrote Aerospike Specific Driver Routines Around the Standard Nozzle Aero Codes
      - » CEC, MOC, Rao and Perfect Nozzle Design, BLIMPJ
    - External Expansion, Lee & Thompson Method
  - Verification & Validation - In Work
    - Currently Testing ADAPT's Functionality
    - ADAPT Used to Design Cold Flow Test Article - Design & Performance Validation
  - Future Growth
    - Base Pressure Correlation
    - Reverse MOC to Design the External Expansion Ramp with the Thruster Exit Conditions
    - Input Specific Geometries for Analysis
    - Other ACN Concepts; Single Expansion Ramp Nozzles, Expansion-Deflection

- Cold Flow Test Hardware Design
  - Objective of Test Article
    - Validation of ADAPT Design & Performance Methods
    - Exercise Skills from End-to-End. Learn by Doing
      - Aero Design, Mechanical Design, Build, Cold Flow Test, Data Interpretation, Validation of Design Tools
    - Axial Thrust and TVC Force Test Data for an Annular Aerospike
    - CFD Validation Data Set - Lots of Static Pressure Measurements
  - Model Description
    - Area Ratio = 38.6,  $NPR_{des}=995$ ,  $P_{c\_des}=250\text{psi}$
    - Throat = 0.072 in.,  $R_e = 5.5$  in.
    - Mass Flow  $\sim 11$  lbm/s, Thrust  $\sim 1000\text{lbf}$
    - TVC, +/- 10% and 20% Differential Throttling
  - Status: Mechanical Design is Nearly Complete, Testing in Jan. 2002

## Cold Flow Nozzle Test Hardware Annular Aerospike with TVC Capability



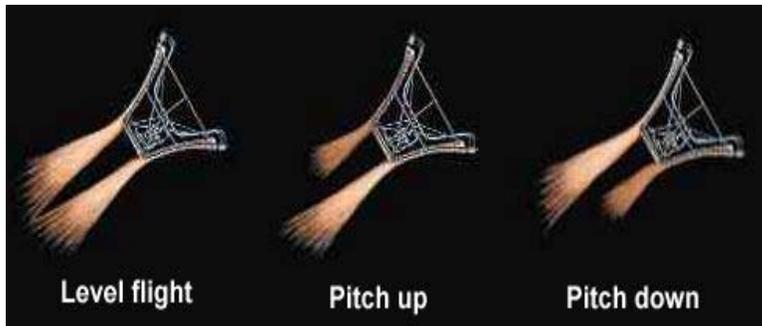
## Cold Flow Nozzle Test Hardware Annular Aerospike with TVC Capability



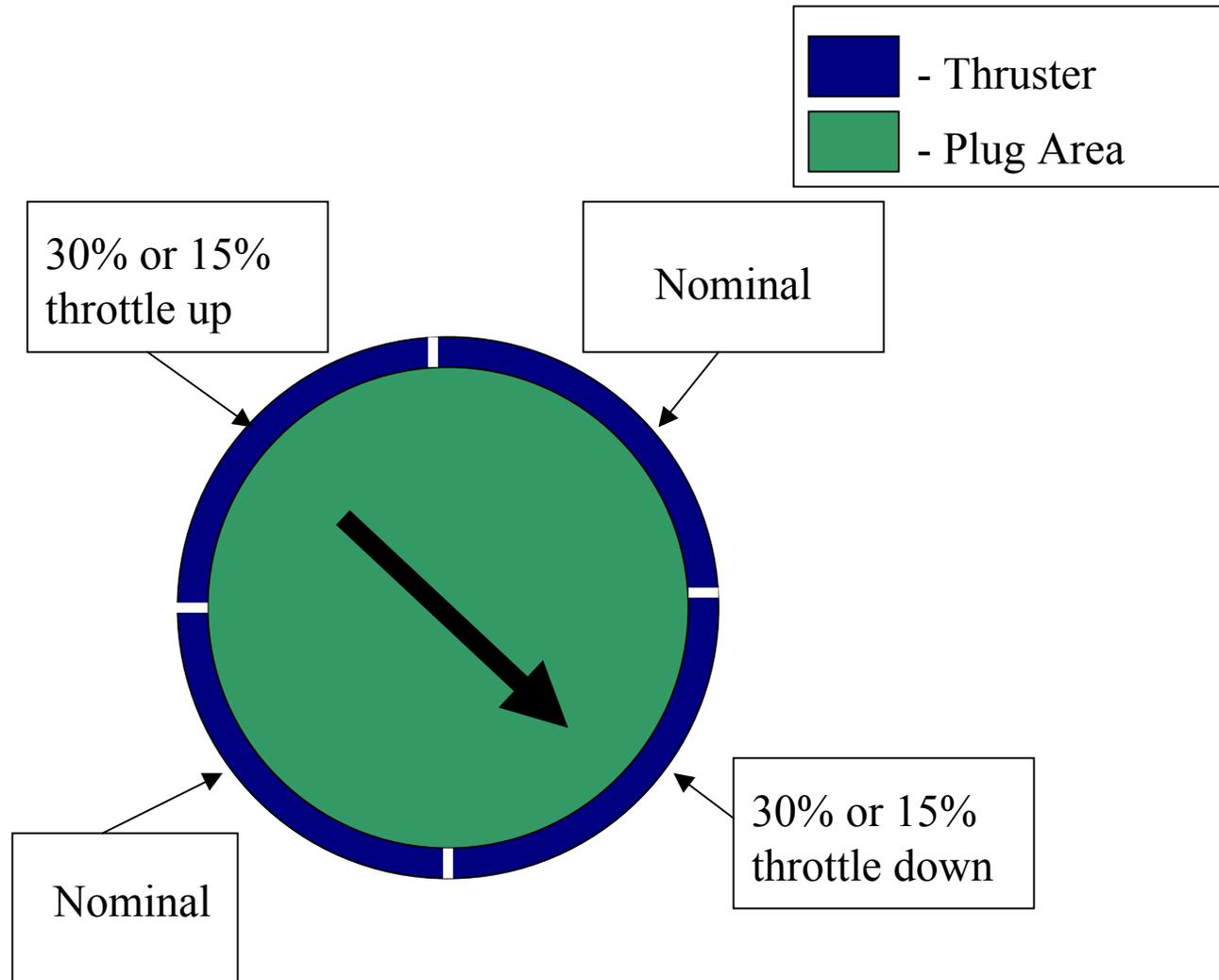
Note: the splitter plates are not shown

- Analytical TVC Model

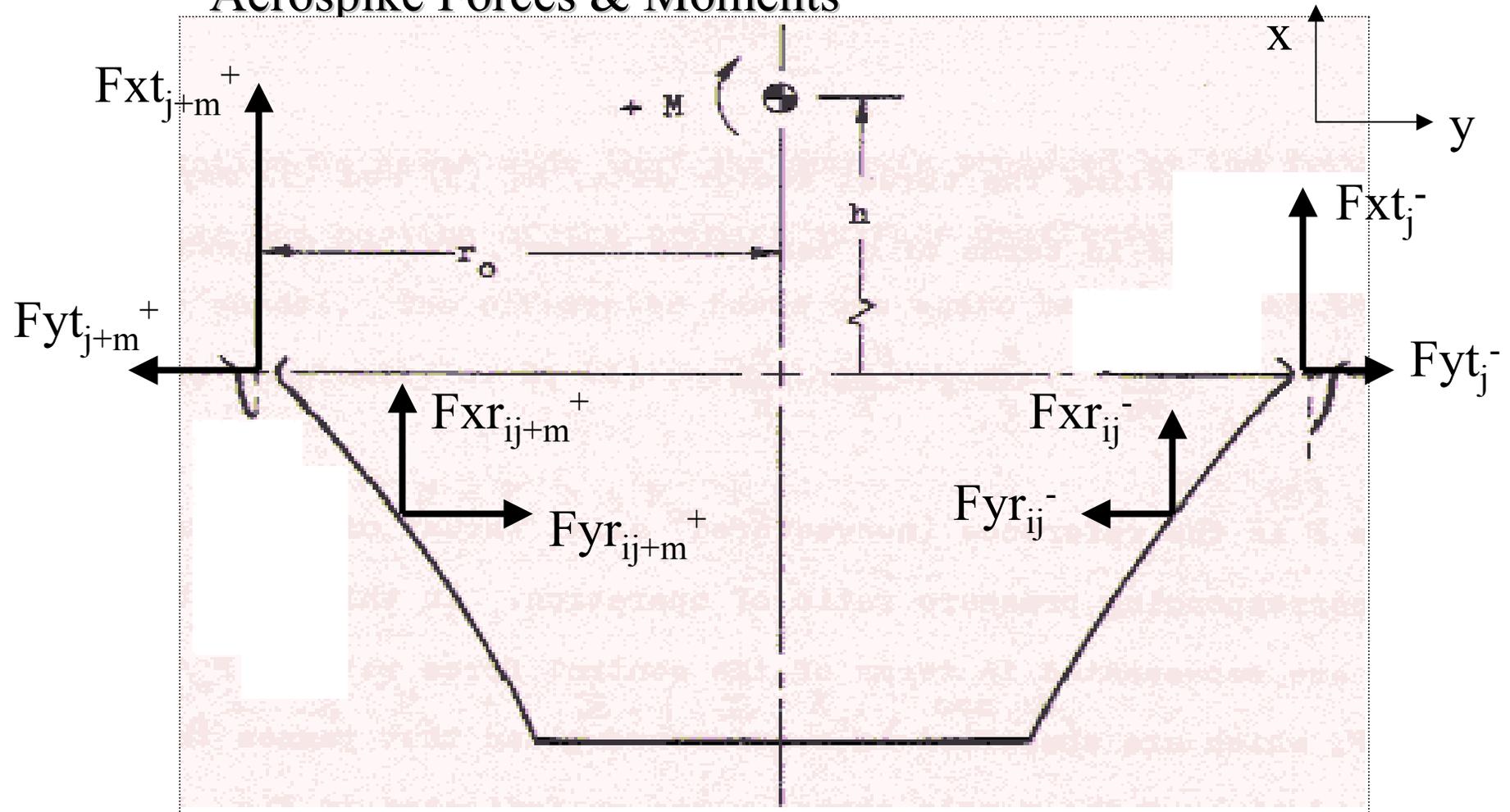
- Objective: Estimate thrust vector control capability (TVC) of an annular aerospike via differential throttling.
- Approach
  - Use ADAPT to define the forces acting on an aerospike.
  - Processed ADAPT output to parametrically assesses TVC capabilities in terms of an equivalent gimbal angle of a Bell Nozzle.
    - vehicle geometry, CG/Cowl Radius
    - spike length, % truncation
    - nozzle pressure ratio, effect of altitude
    - throttle setting, +/- 30%, +/-15% of  $P_c$



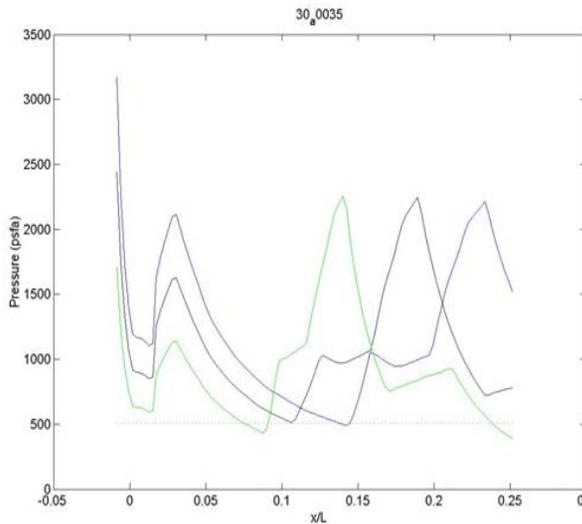
Modular thrusters allow differential throttling as a means for TVC.



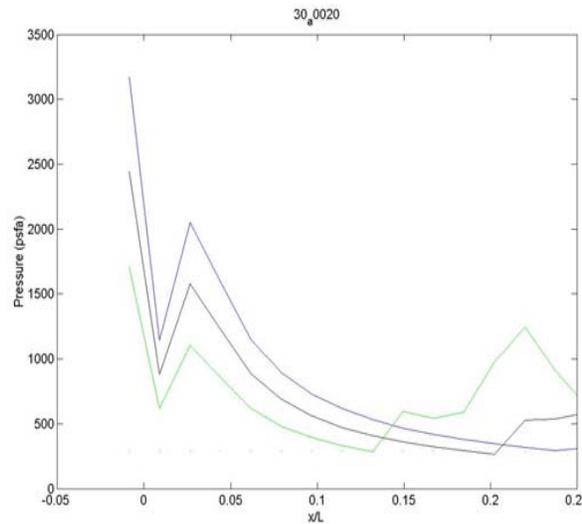
## Aerospike Forces & Moments



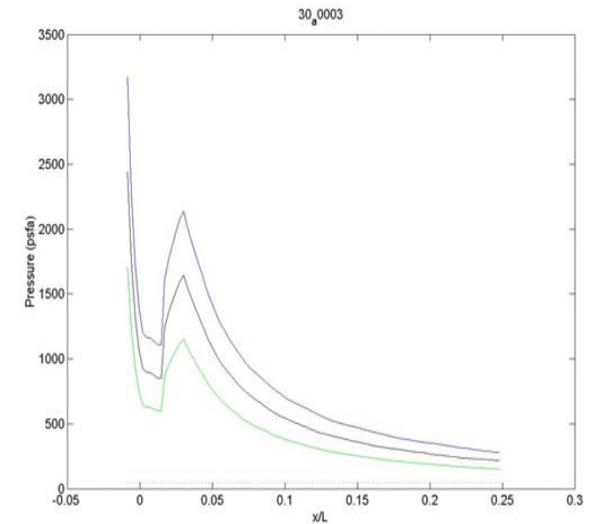
$$M = \sum_{j=1}^{j \max} \left[ (Fxt \times r_o) + (Fyt \times h) + \sum_{i=1}^{i \max} \left[ (Fxr_i \times r_i) + (Fyr_i \times h_i) \right] \right]$$



NPR=86



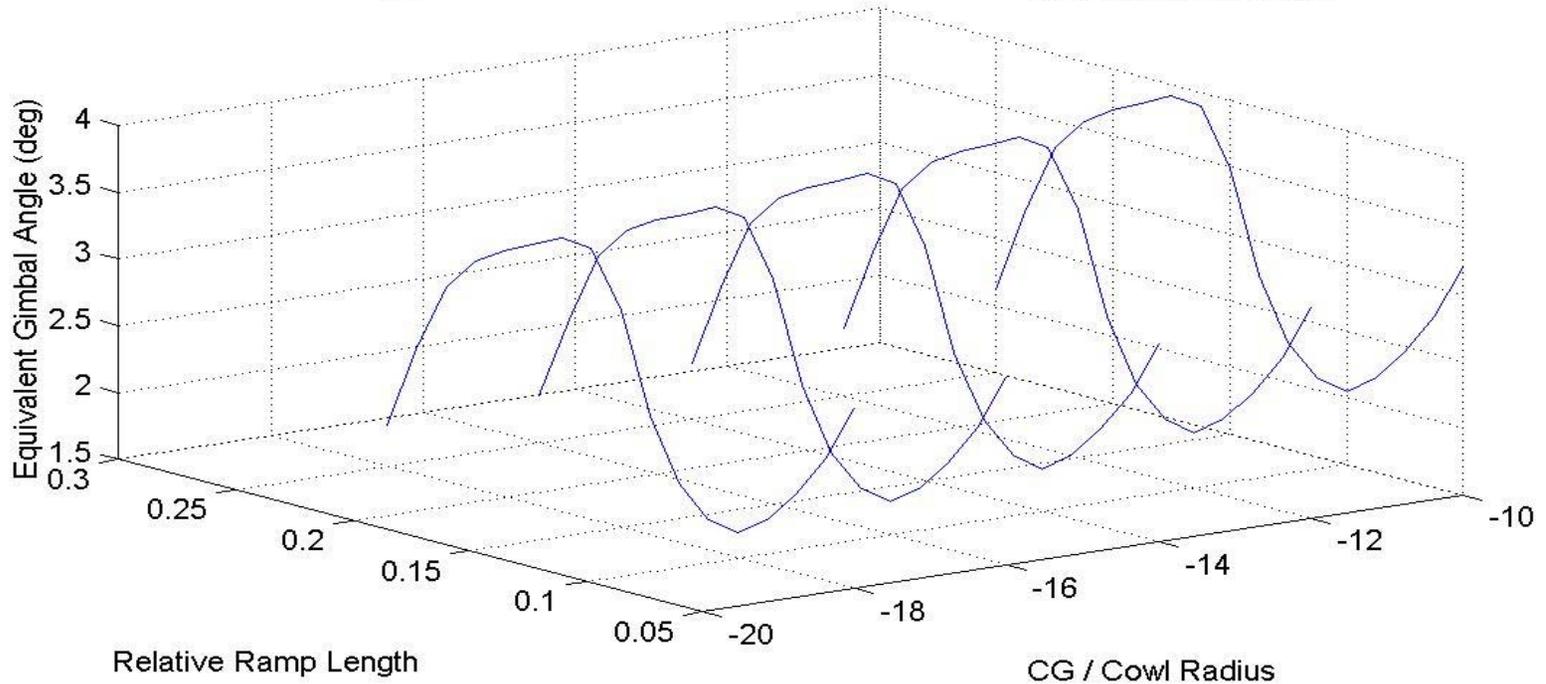
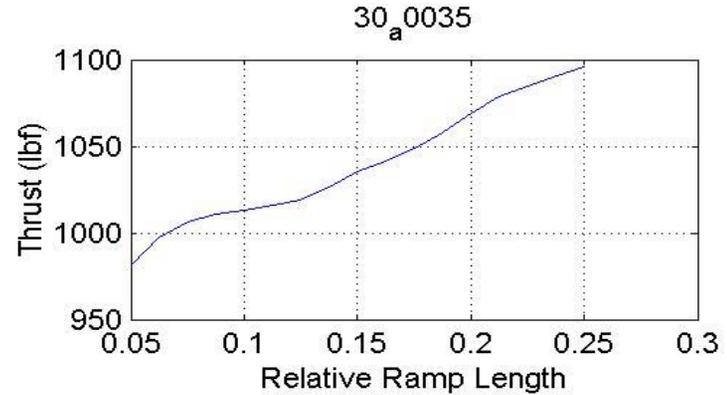
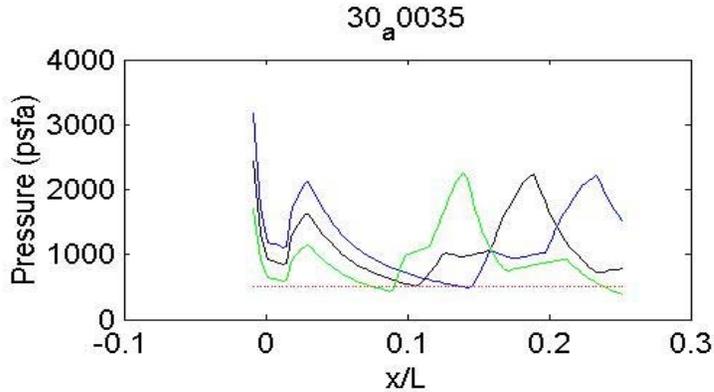
NPR=150



NPR\*=1000

- Green curve represents ramp pressure on throttled down quadrant. Positive contribution to overall moment.
- Black curve represents ramp pressure on nominal ramp quadrants. No effect on overall moment.
- Blue curve represents ramp pressure on throttled up quadrant. Negative effect on overall moment.

## Sample Output, NPR=86

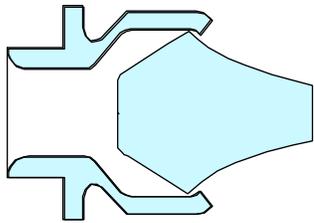


## Analytical TVC Model Conclusions

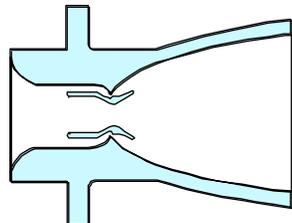
- Lateral forces, particularly the thruster's, dominate the solution
- The ramp's lateral force opposes the desired moment
- Ramp recompressions should factor into ramp length selection
- Differential throttling  $\pm 30\%$  on annular aerospike yields 1 to 4 degrees of equivalent gimbale angle.
- Axial Thrust Performance of an Aerospike warrants further study of TVC methods

- Related Work

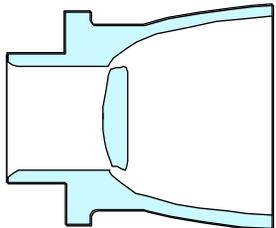
- A Cold Flow Test is About to Start With a Set of ACN All Designed to the Same NPR.



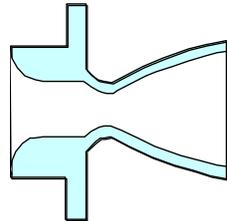
Plug: AR=22.3, 35% full plug length



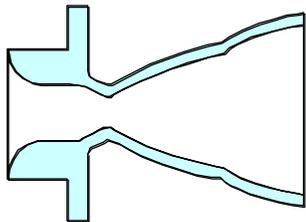
Dual-Expander: AR=22.08/40.25



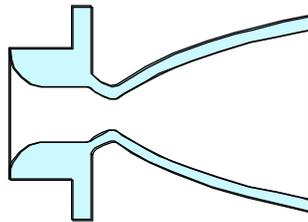
Expansion-Deflection: AR=18.2



Small Reference Bell: AR=12.2



Dual Bell: AR=12.2/27.1



Large Reference Bell: AR=27.1

