Status of Nozzle Aerodynamic Technology at MSFC

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

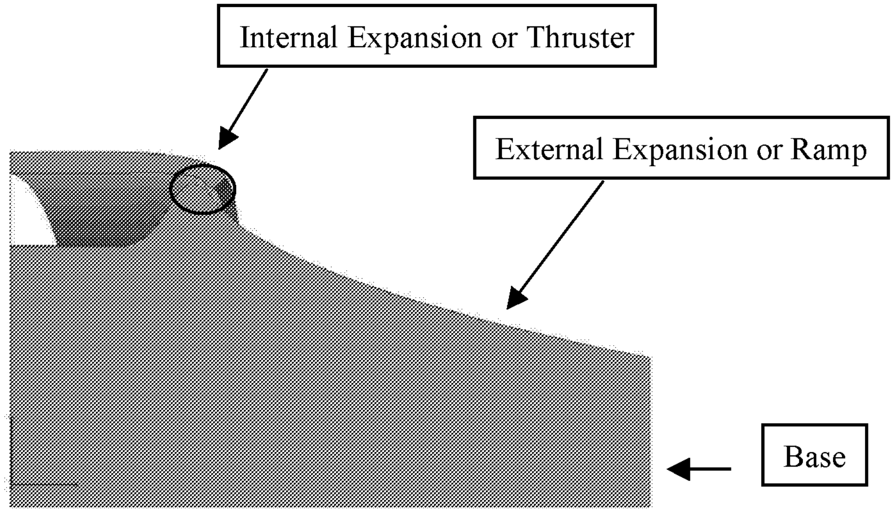
Thermal and Fluid Workshop
September, 2001
Huntsville, AL.

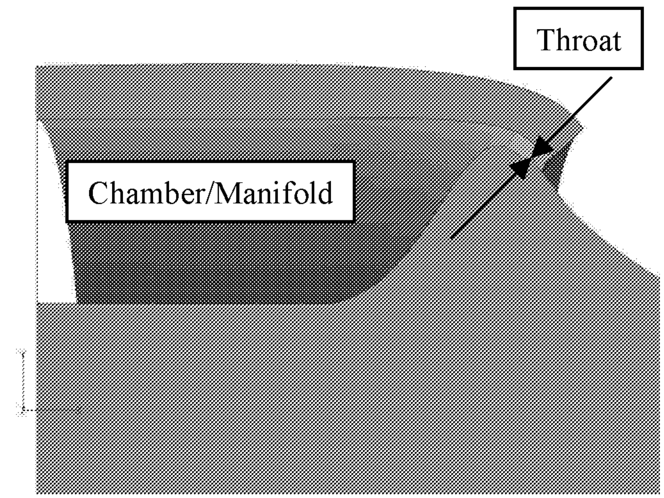
- Overview
  - Objectives
  - Analytical Tool Development
  - Cold Flow Nozzle Test Hardware
  - Analytical TVC Model
  - Related Work

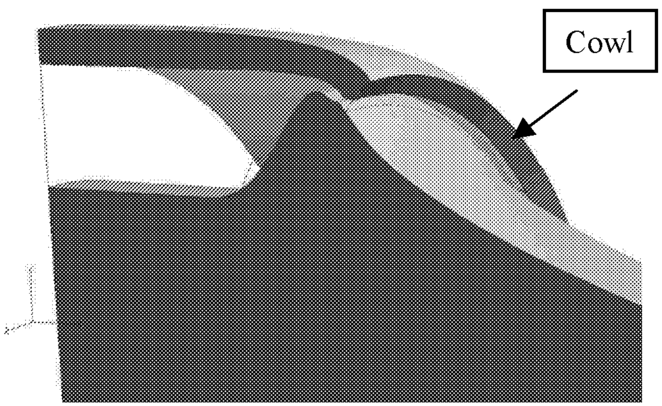
- Objectives
  - Of this Presentation: Provide Insight Into MSFC In-house Nozzle Aerodynamic Technology; Design, Analysis & Testing
  - CDDF 'Altitude Compensating Nozzle Technology'
    - Develop In-house ACN Aerodynamic Design Capability
    - Build In-house Experience for all aspects of ACN via End-to-End Nozzle Test Program
    - Obtain Experimental Data for Annular Aerospike: Thrust η, 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

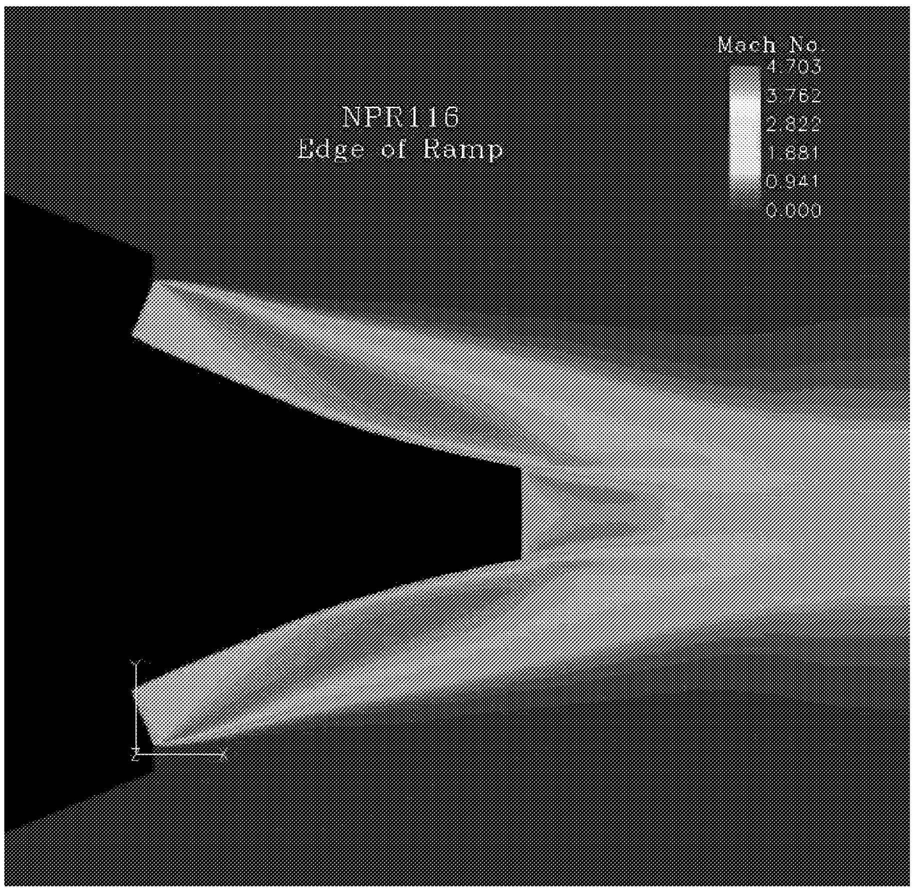




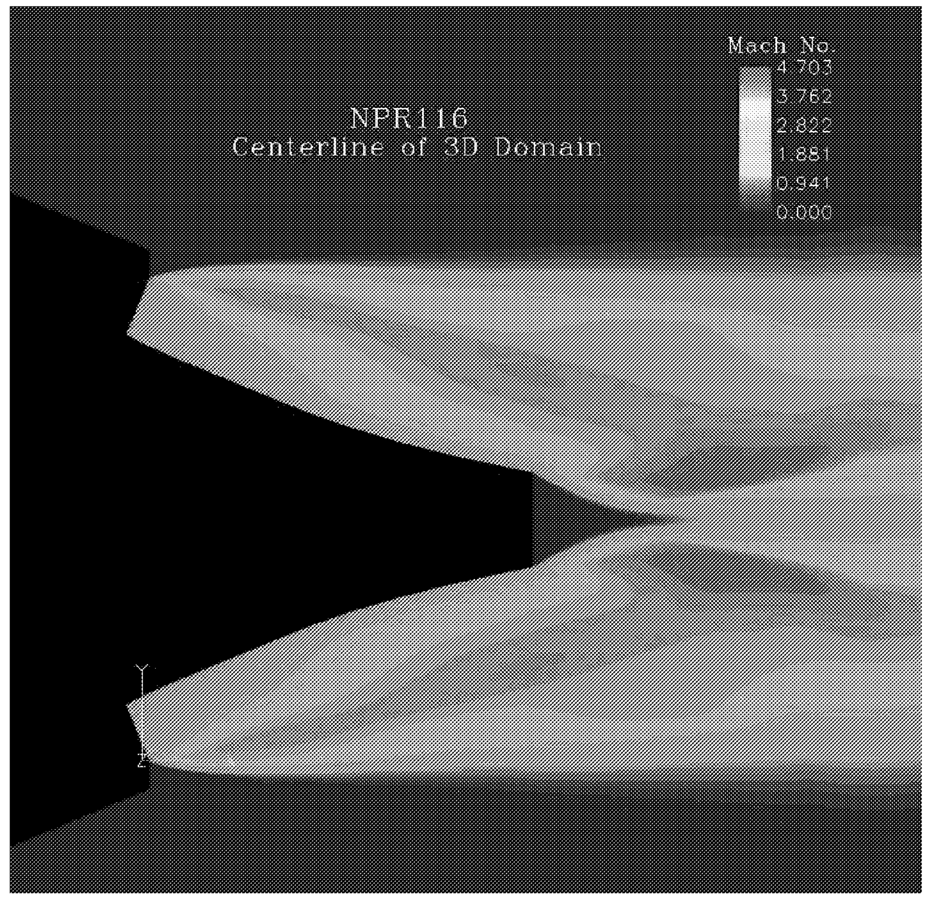


Aerospike Nozzle Terminology

Low Altitude or NPR

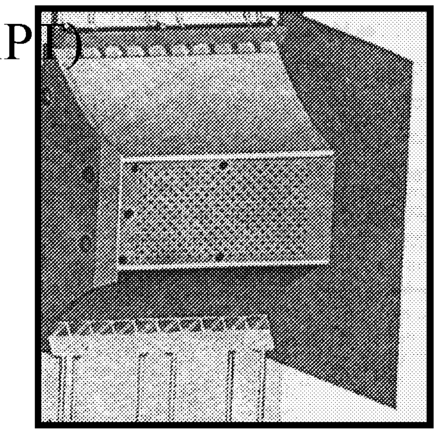


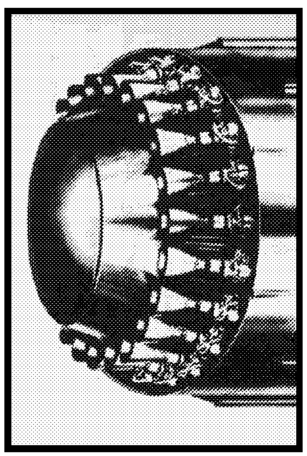
High Altitude or NPR

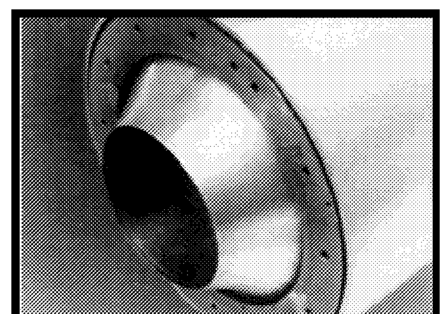


Status of Nozzle Aerodynamic Technology At MSFC

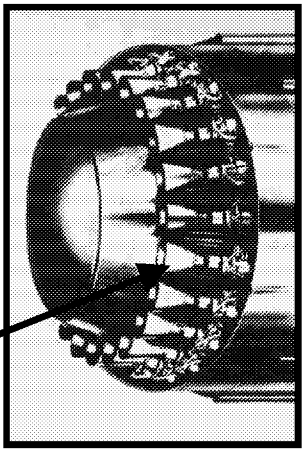
- Analytical Tool Development
  - Chose Aerospike Nozzles as the ACN to Start With
  - To support future propulsion selection we needed a parametric design and performance tool for ACN
  - Aerospike Design And Performance Tool (ADAPT)
    - Developed by Bud Smith/Plumetech
    - Parametrics
      - Aerospike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

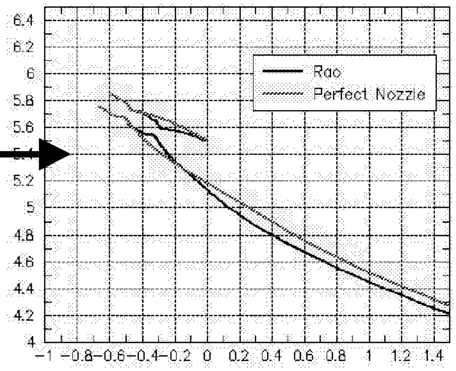






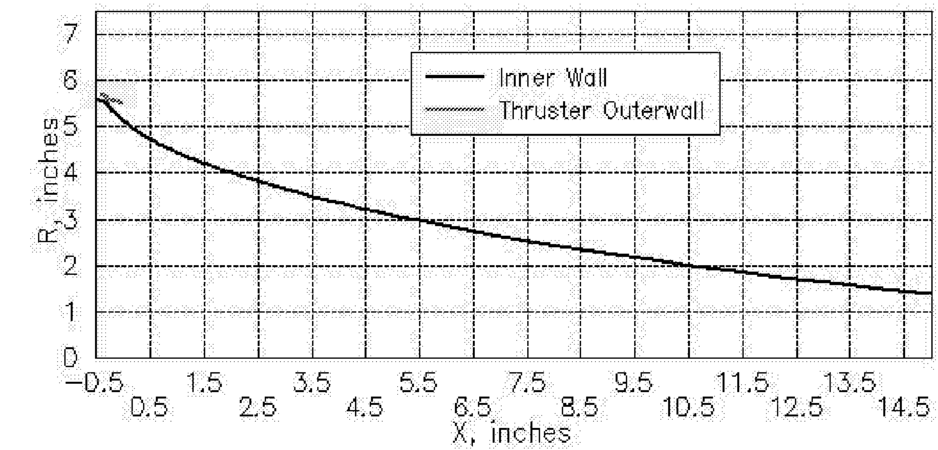
- Analytical Tool Development
  - Chose Aerospike Nozzles as the ACN to Start With
  - To support future propulsion selection we needed a parametric design and performance tool for ACN
  - Aerospike Design And Performance Tool (ADAPT)
    - Developed by Bud Smith/Plumetech
    - Parametrics
      - Aerospike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

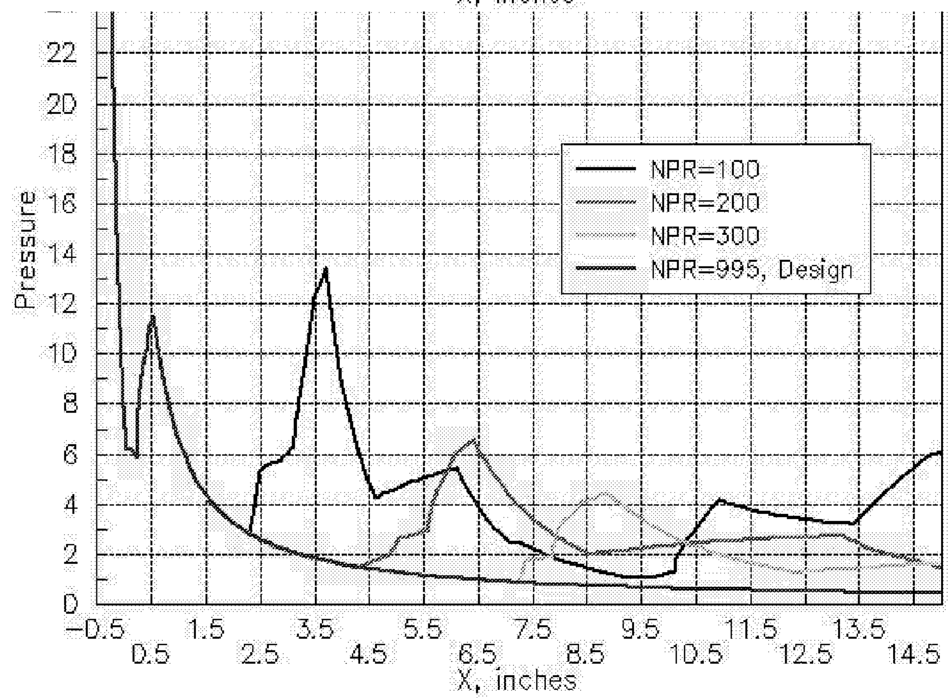




- Analytical Tool Development, cont.
    - Parametrics, cont.
        - Sizing and Design Point
            - » Radius, Area Ratio or NPR_{design}(10)
            - » Mass Flow or Throat Area
            - » P_c, P_{a_des}(10), Expansion Split(10)
        - Working Fluid; Air, Lox/RP, Lox/H2, Others
        - 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
Performance					
Thruster					
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
Cluster					
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 **Truncation of 25.00 Percent**(X = 4.31 INCHES)

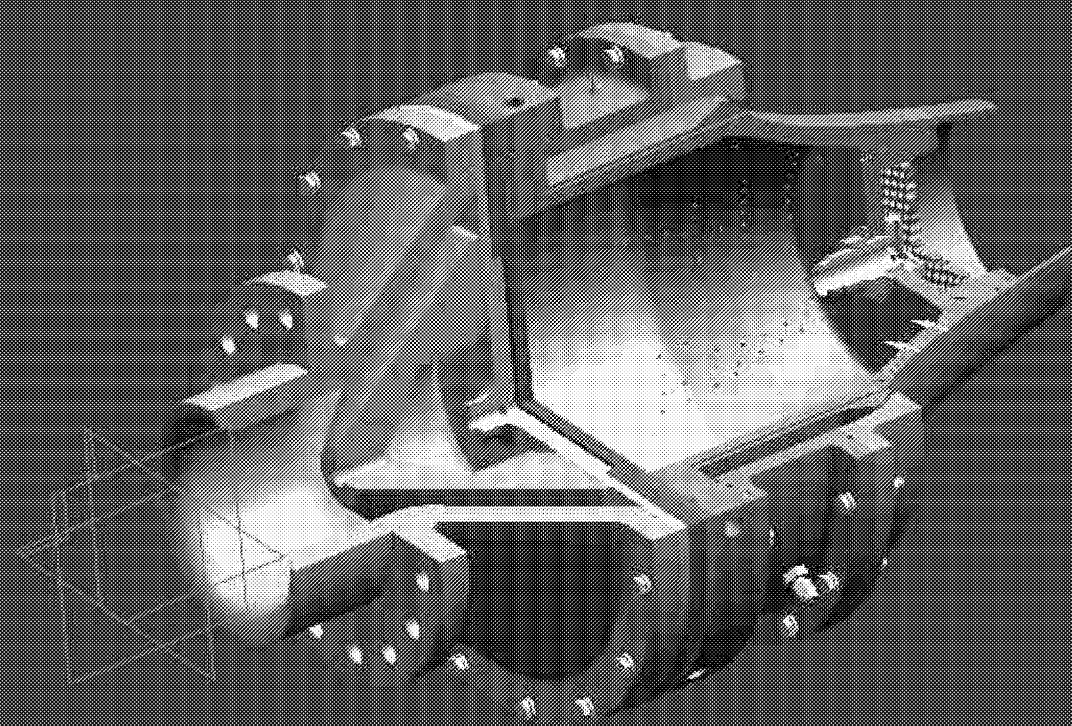
Case Number	010100	010101	010102	010103	010
Ambient Pressure - psia	0.3014	6.0300	3.0150	1.5080	1.0
Pressure Ratio - Pc/Pa	995.3800	49.7512	99.5025	198.9390	298.5
Performance					
Cluster					
Delivered Thrust - lbf	1215.5	1093.5	1134.4	1143.7	117
Delivered Isp - sec	85.552	76.968	79.848	80.500	82.
Boundary 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-Defection

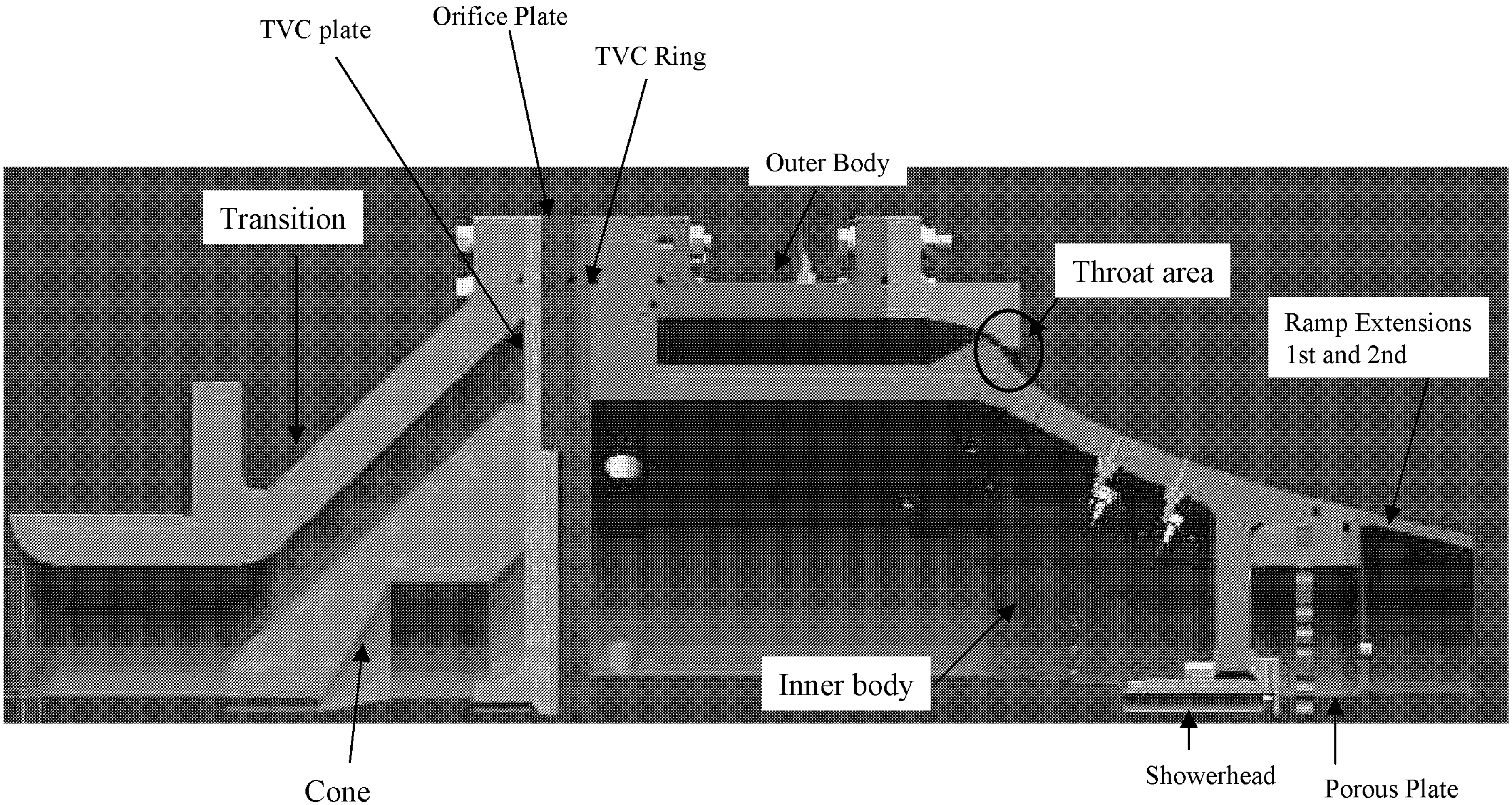
- Cold Flow Test Hardware Design
  - Objective of Test Article
    - Validation of ADAPT Design & Performance Methods
    - Exercise Skills from End-to-End. Learn by Doing
      - Aero Design, Mechanical Design, Build, Cold Flow Test, Data Interpretation, Validation of Design Tools
    - Axial Thrust 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}=250psi
    - Throat = 0.072 in., R_e = 5.5 in.
    - Mass Flow ~11 lbm/s, Thrust ~ 1000lbf
    - TVC, +/- 10% and 20% Differential Throttling
  - Status: Mechanical Design is Nearly Complete, Testing in Jan. 2002

Status of Nozzle Aerodynamic Technology At MSFC

Cold Flow Nozzle Test Hardware
Annular Aerospike with TVC Capability

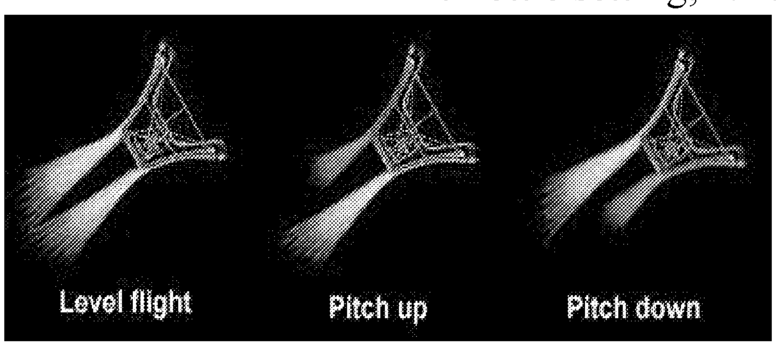


Cold Flow Nozzle Test Hardware
Annular Aerospike with TVC Capability

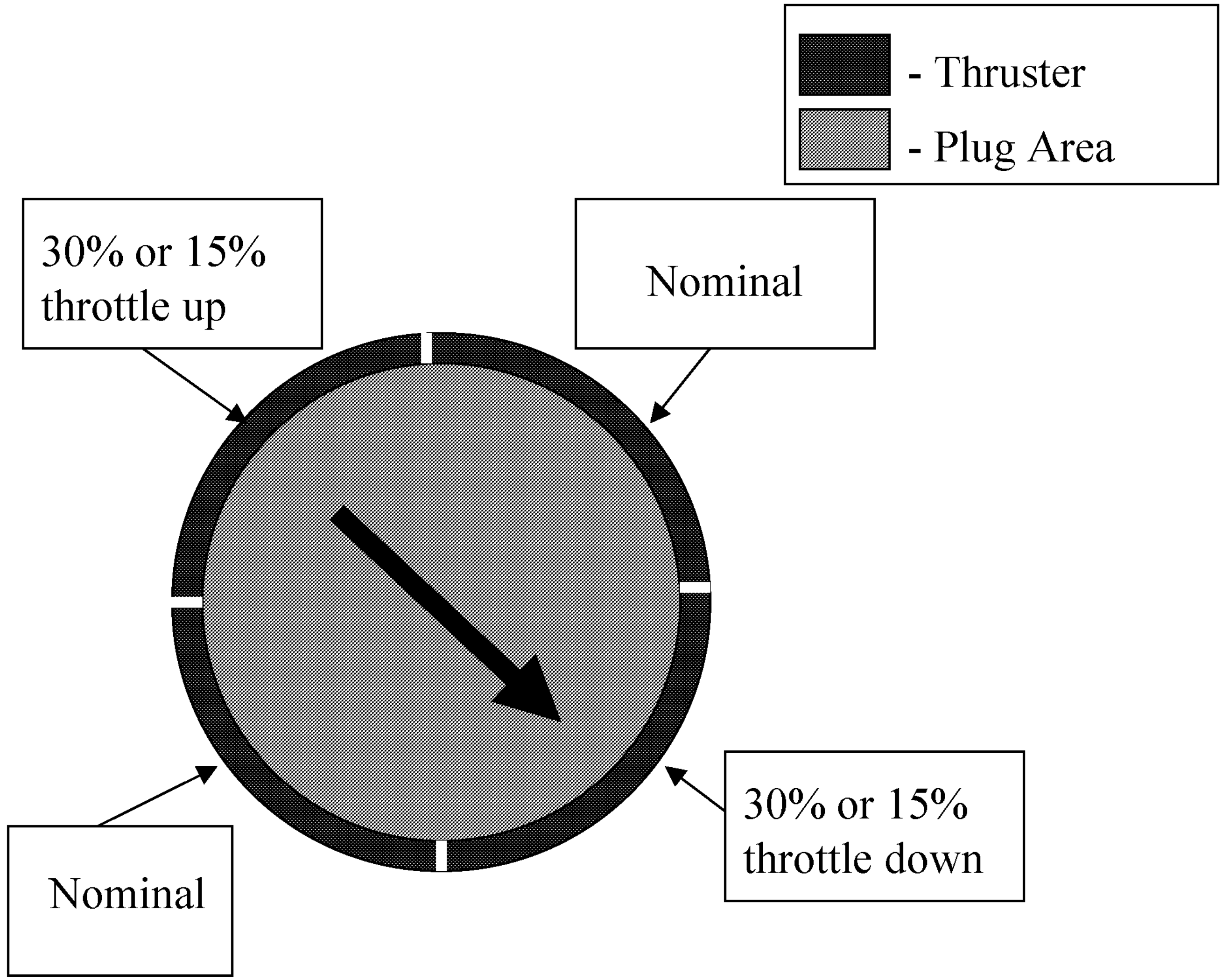


Note: the splitter plates are not shown

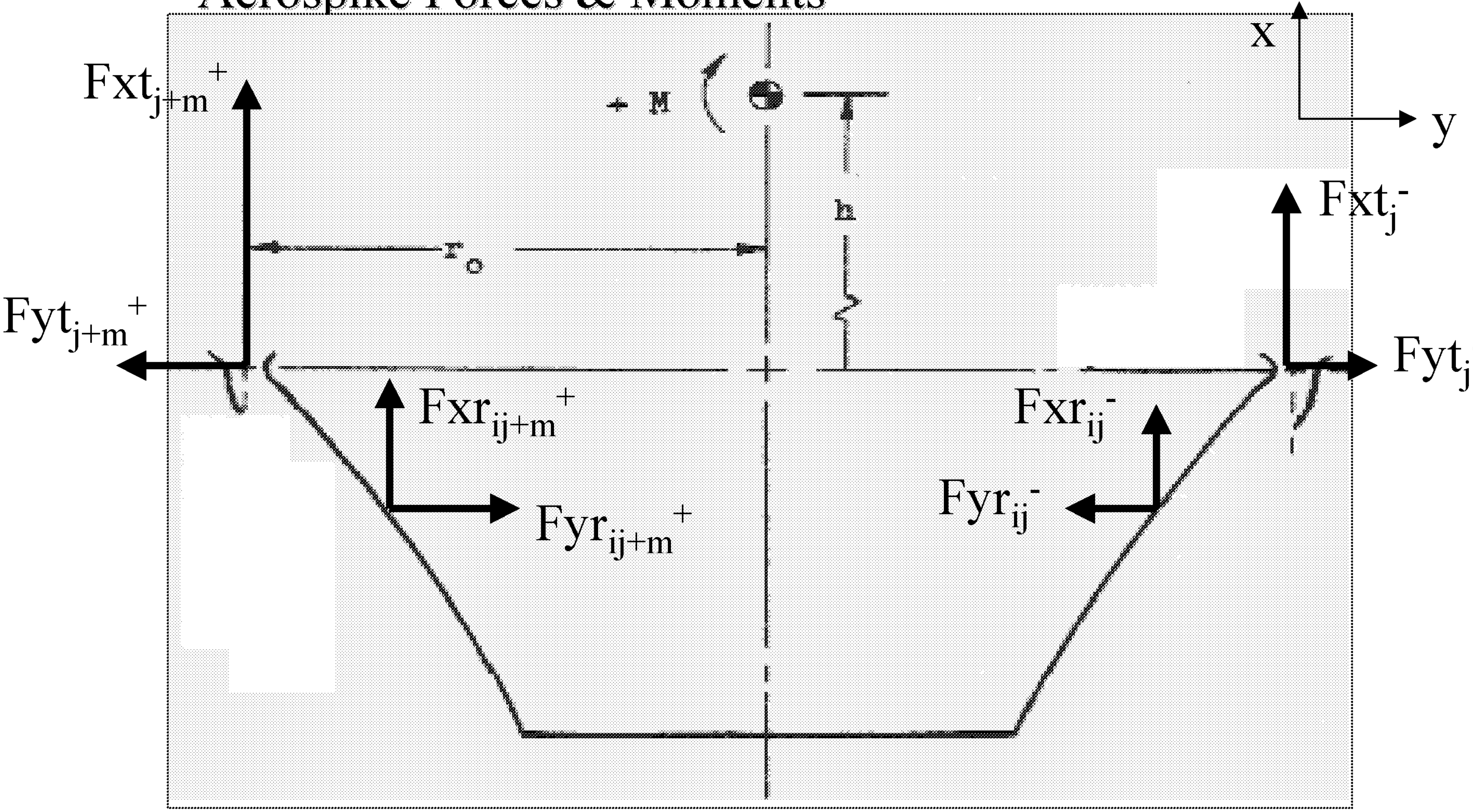
- Analytical TVC Model
  - Objective: Estimate thrust vector control capability (TVC) of an annular aerospike via differential throttling.
  - Approach
    - Use ADAPT to define the forces acting on an aerospike.
    - Processed ADAPT output to parametrically assesses TVC capabilities in terms of an 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



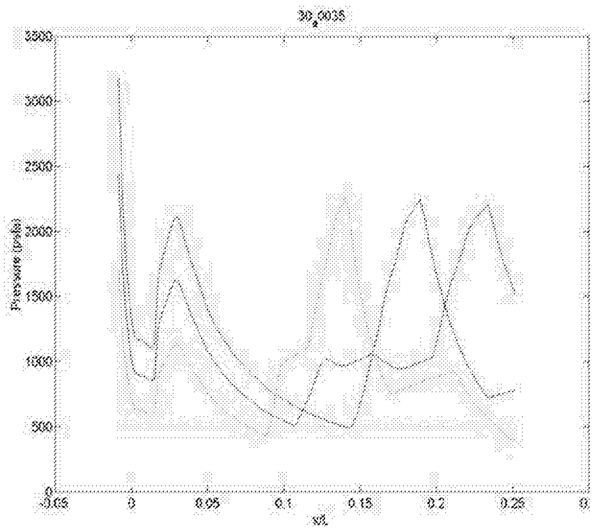
Modular thrusters allow differential throttling as a means for TVC.



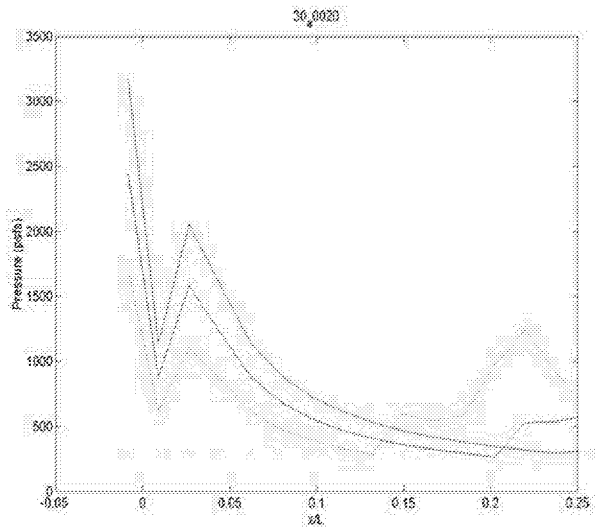
Aerospike Forces & Moments



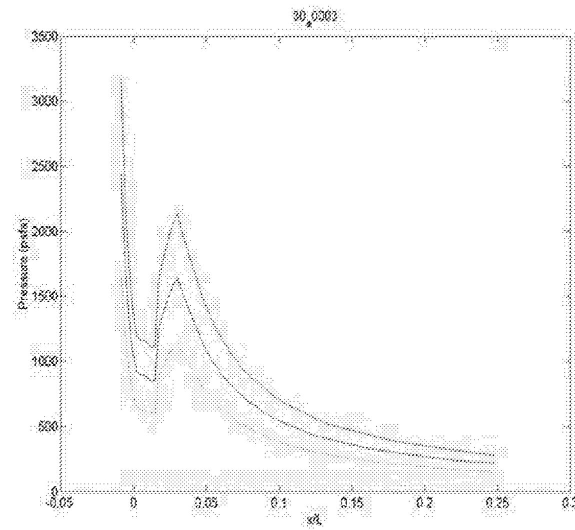
$$M = \sum_{j=1}^{j\max}\left[\left(Fxt \times r_o\right) + \left(Fyt \times h\right) + \sum_{i=1}^{i\max}\left[\left(Fxr_i \times r_i\right) + \left(Fyr_i \times h_i\right)\right]\right]$$



NPR=86



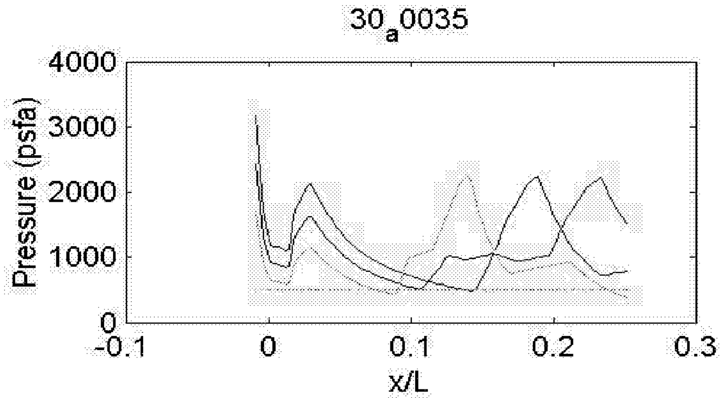
NPR=150

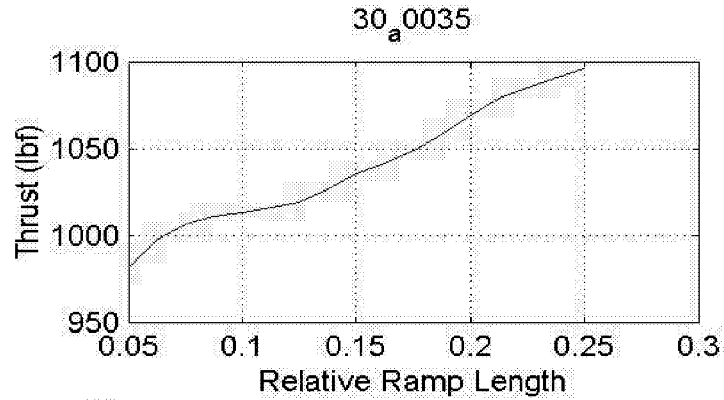


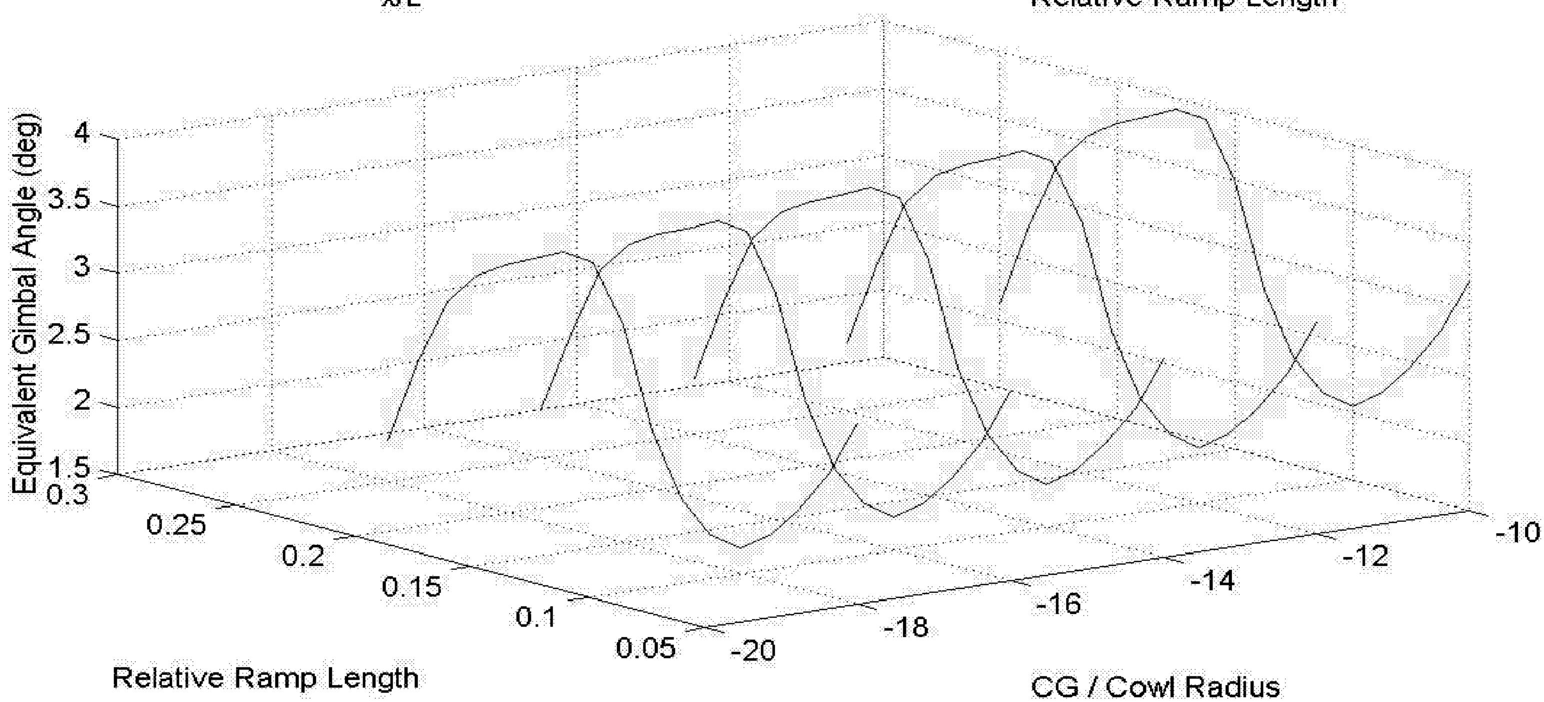
NPR*=1000

- 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







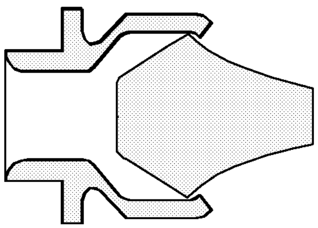
Analytical TVC Model
Conclusions

- 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 +/-30% on annular aerospikes yields 1 to 4 degrees of equivalent gimbal angle.
- Axial Thrust Performance of an Aerospike warrants further study of TVC methods

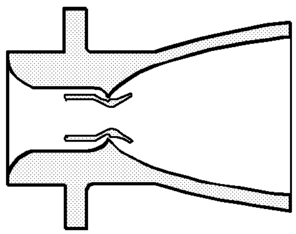
Status of Nozzle Aerodynamic Technology At MSFC

Space Transportation Directorate

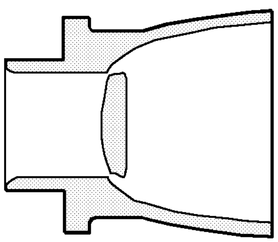
- Related Work
  - A Cold Flow Test is About to Start With a Set of ACN All Designed to the Same NPR.



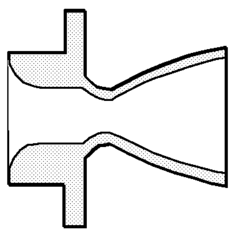
Plug: AR=22.3, 35% full plug length



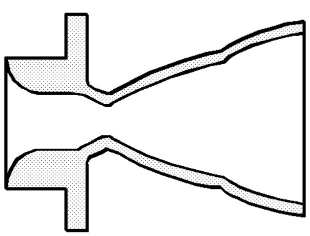
Dual-Expander: AR=22.08/40.25



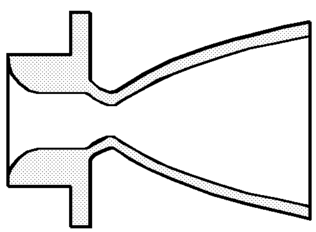
Expansion-Deflection: AR=18.2



Small Reference Bell: AR=12.2



Dual Bell: AR=12.2/27.1



Large Reference Bell: AR=27.1