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A Coupled CFD/FEM Structural Analysis to Determine Deformed Shapes of the RSRM Inhibitors

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Abstract

Recent trends towards an increase in the stiffness of the NBR insulation material used in the construction of RSRM propellant inhibitors prompted questions about possible effects on RSRM performance. The specific objectives of the CFD task included: 1) the definition of pressure loads to calculate the deformed shape of stiffer inhibitors, 2) the calculation of higher port velocities over the inhibitors to determine shifts in the vortex shedding or edge tone frequencies and 3) the quantification of higher slag impingement and collection rates on the inhibitors and in the submerged nose nozzle cavity.

A coupled CFD/Finite element structural analysis was required to calculate the deformed inhibitor geometry. Since the NBR inhibitor material erodes at a different rate than the motor propellant burns, an inhibitor stub which protrudes above the propellant into the port cavity is created during motor operation. The impinging port flow causes the inhibitor stub to bend in the downstream flow direction. Since a stiffer NBR inhibitor material would cause the inhibitor to bend less, it was necessary to know the difference in the bending of the original NBR material compared to the stiffer NBR material. The CELMINT CFD computer code was used to perform the fluid dynamic calculations of the motor flow field. The structural bending effect of the pressure loads from the CFD code was analyzed by ED28. Initially, the CELMINT code was used to determine the flow field and inhibitor pressure loads for unbent motor inhibitors. This pressure loading on the inhibitors was used by ED28 to generate the bending which would occur in the inhibitor. The computed bent inhibitor geometry was then used again by the CFD code to compute a new pressure loading on the inhibitors. This iterative computation between the CFD code and the structural analysis code was continued until convergence in the inhibitor bent geometry was achieved.

The CFD solution was then used to assess the effect of higher flow velocities and edge tone frequencies from the reduced inhibitor bending on the maximum oscillating pressure amplitudes that occur during resonance between the edge tones and the motor longitudinal modes. Also, a comparison of the difference in slag accumulation between the two NBR materials was also made to determine if the stiffer material increases slag collection in the field joints and the submerged nozzle cavity.

The coupled CFD/FEM structural analysis was successful in defining the effect of inhibitor stiffness on inhibitor geometry and the shift in edge tone frequencies. Also, the two-phase CFD analysis showed that there was a small increase in the rate of slag accumulation at the aft inhibitor; however, motor trajectory analyses of slag debris shed from the inhibitors showed that the debris would pass out the motor nozzle and therefore create no additional slag accumulation in the slag pool around the nozzle.

A COUPLED CFD/FEM STRUCTURAL ANALYSIS TO DETERMINE DEFORMED SHAPES OF THE RSRM INHIBITORS

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Background

- In October, 1994, Thiokol reported the use of NBR material in RSRM's with properties significantly different from the historical database.
- A 30% to 40% increase in modulus was reported.
- This increased stiffness had the potential to affect the amplitude of chamber pressure oscillations in the SRM:
  - --By changing the inhibitor structural response
  - --By indirectly changing the flow/acoustic interaction
- The slag accumulation in the field joints and submerged nozzle region might also be increased thereby increasing the potential for pressure and thrust perturbations.

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Objectives of Coupled CFD/FEM and Two-Phase CFD Analyses

- Determine deformed geometry of NBR inhibitors at the forward, center and aft joints for both nominal and stiff NBR materials using a coupled CFD/FEM analysis.
- Determine effect of inhibitor properties/geometry on inhibitor hole velocities to evaluate effect on hole edge tone (vortex shedding) frequencies.
- Determine effect of inhibitor properties/geometry on slag accumulation on both the inhibitor surfaces and underneath the nozzle nose.

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Coupled CFD/FEM Analysis Approach

1) Perform single-phase gas CFD analysis of entire RSRM port at 80 second burn time using straight inhibitor lengths from erosion analysis.

2) Perform FEM structural analysis on inhibitors to determine deformations using surface pressure distributions from CFD analysis.

3) Perform CFD analysis using deformed inhibitor geometries from step 2).

4) Repeat steps 2) and 3) until convergence of inhibitor geometry is achieved.

5) Provide velocity profile at each inhibitor location for both nominal and stiff inhibitors as input to flow/acoustic interaction analysis.

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Two-Phase Flow CFD Methodology
CELMINT Code
(Combined Eulerian Lagrangian Multi-Dimensional Implicit Nonlinear Time-Dependent)

- **Navier-Stokes Solution**
  - Fully implicit, density-based, conservative, ensemble-averaged Navier-Stokes code
  - Low and high Reynolds number and wall injection $\kappa-\varepsilon$ models
  - Equilibrium and finite-rate chemistry for multi-species flows

- **Two-phase Flow Models**
  - Coupled Eulerian-Lagrangian for solid and liquid phases
  - Hermsen aluminum burn rate model for particle combustion
  - Specification of particle properties (density, size distribution)
  - Particle break-up based on Weber number
  - Agglomeration based on collisions between discrete phase particles and continuous phase smoke particles
  - Programmable for various particle capture criteria

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Propellant Thermochemical Properties and Motor Operating Conditions
RSRM 80 Second Burn Time

Propellant	TP-H1148
Pressure	625 psia
Total Temperature	6093° R
Molecular Weight	28.04
Dynamic Viscosity	6.189×10^{-5} bm/ft-sec
Ratio of Specific Heats	1.138
Flow Rate, Forward Segment	1555.9 lbm/sec
Flow Rate, Center Segment 1	2587.5 lbm/sec
Flow Rate, Center Segment 2	2578.6 lbm/sec
Flow Rate, Aft Segment	2849.0 lbm/sec
Flow Rate, Total	9571.0 lbm/sec
Throat Diameter	55.42 inches

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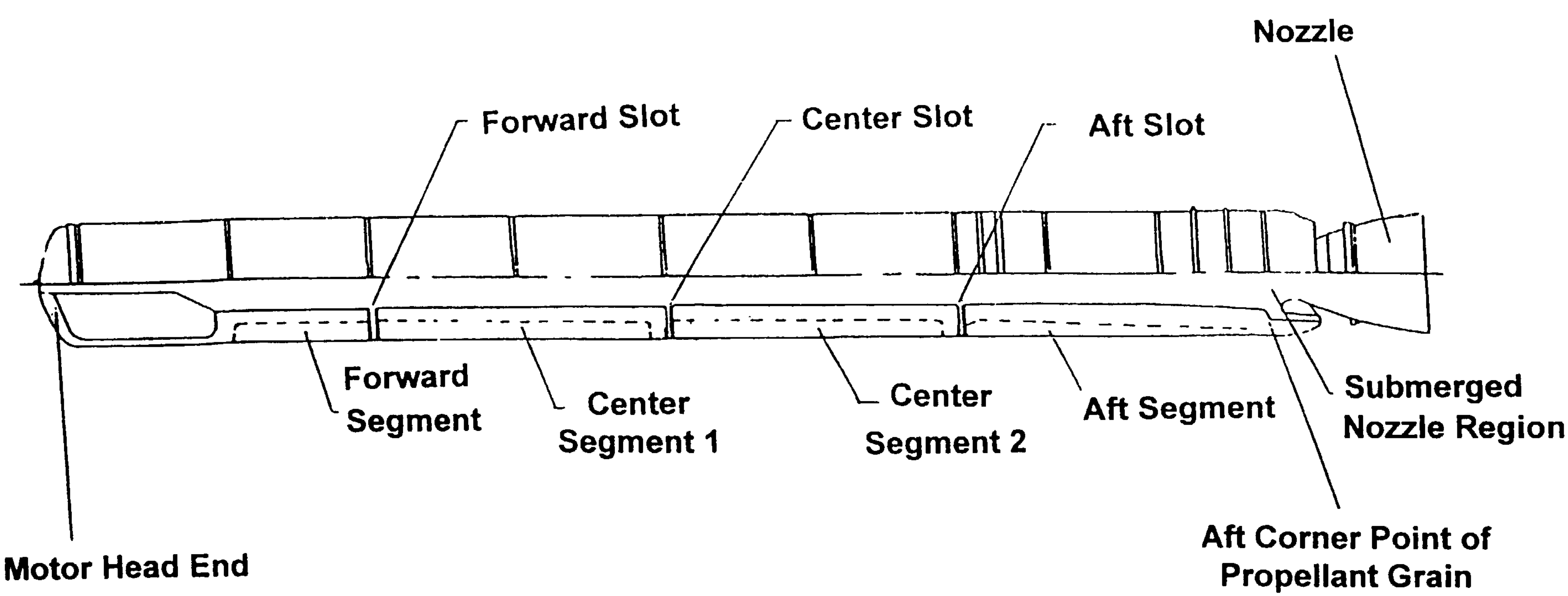
RSRM Motor Geometry



(Dashed Line Shows The 67 Second Burn Back)

Computational Grid Resolution

Port	400X50
Field Joints	30X20
Inhibitor Stub	4X20
Submerged Region	70X20
Overall Grid	488X70

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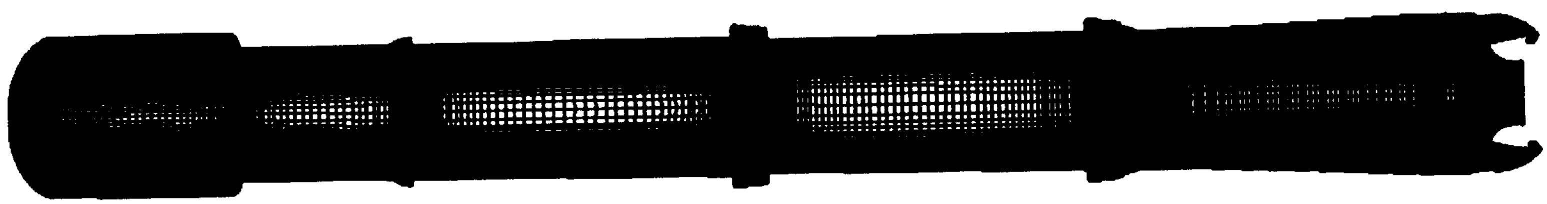
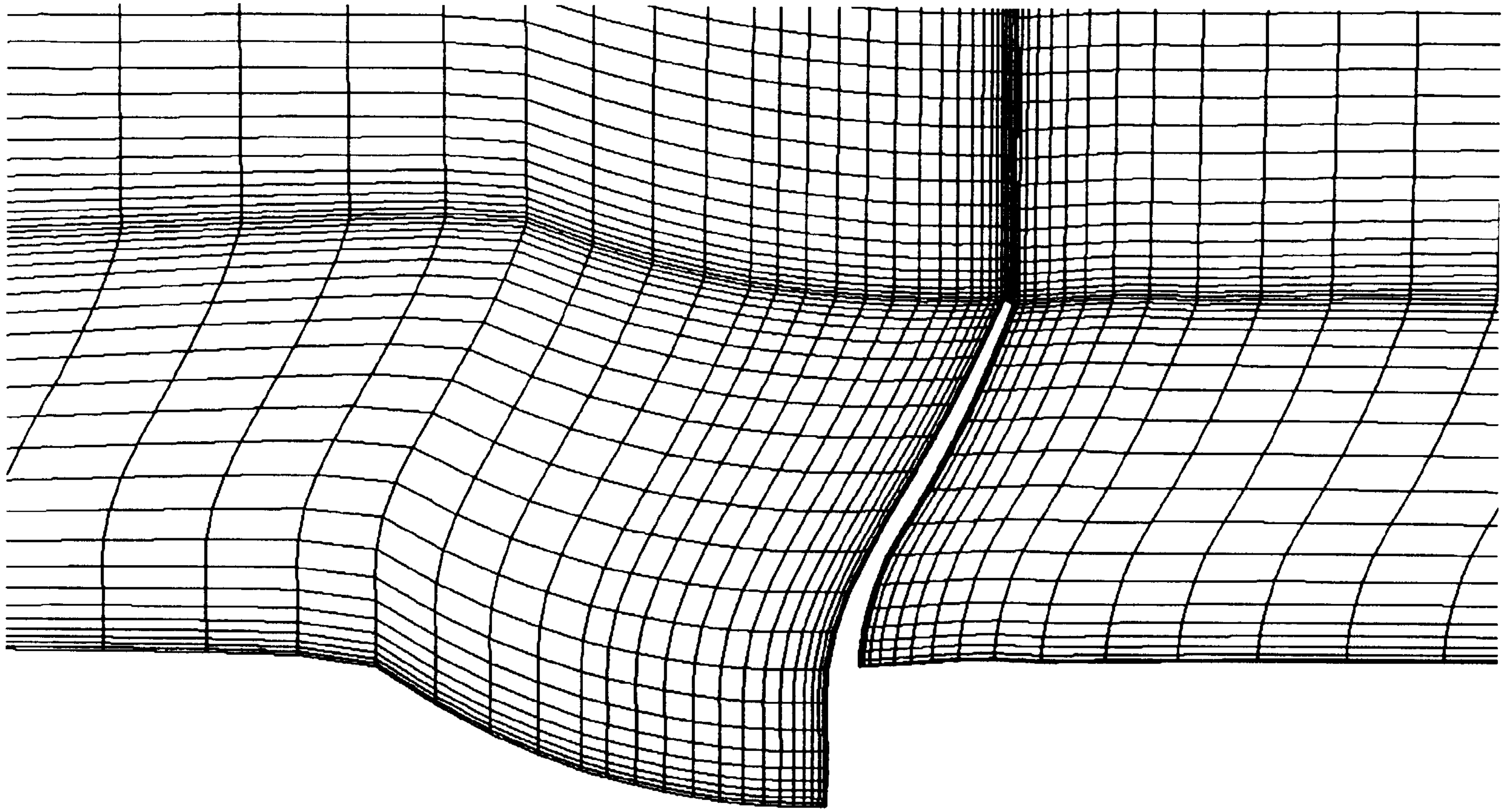


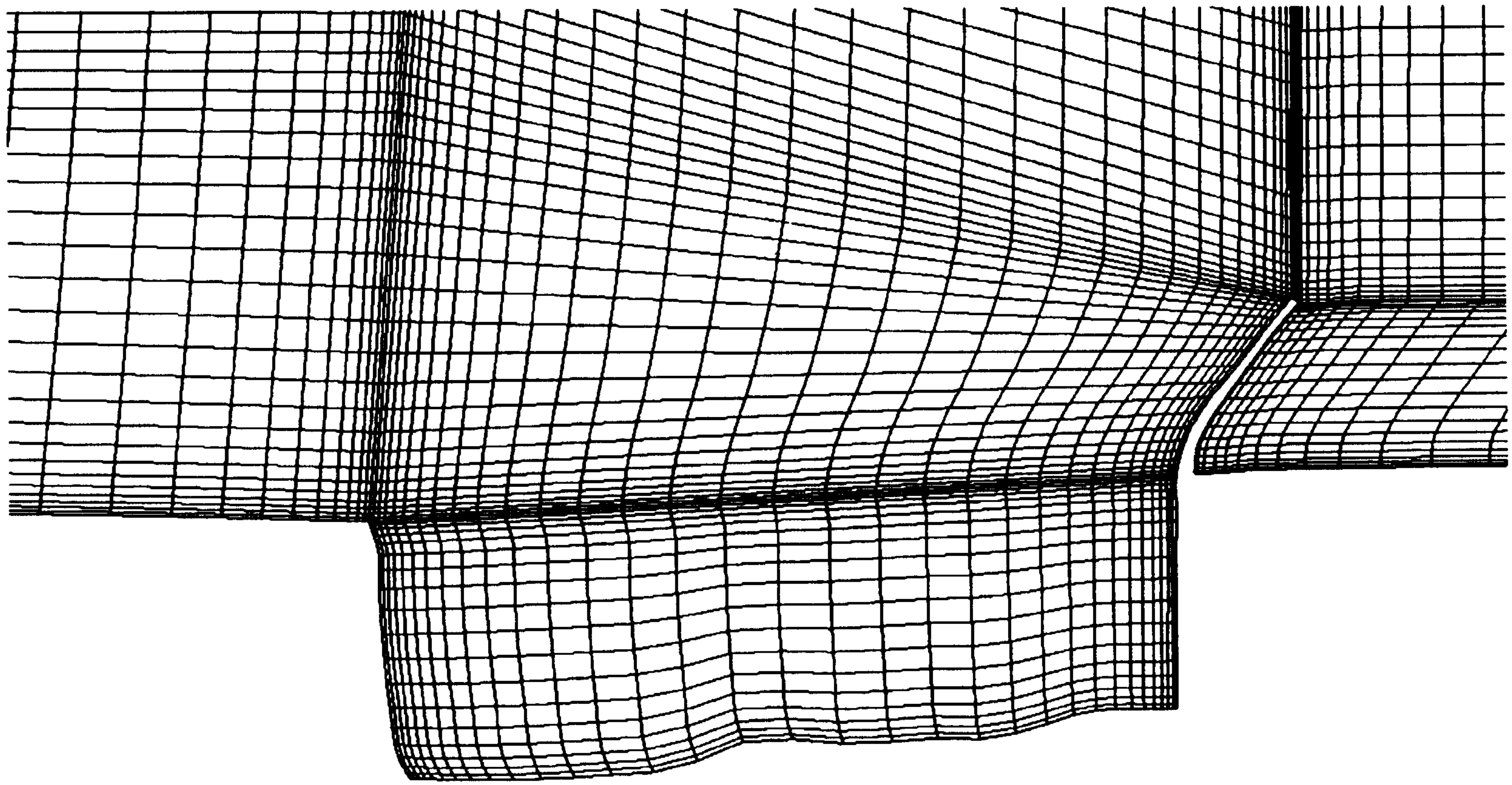
Computational Grid, Full Motor

RSRM 80 Second Stiff NBR Inhibitor



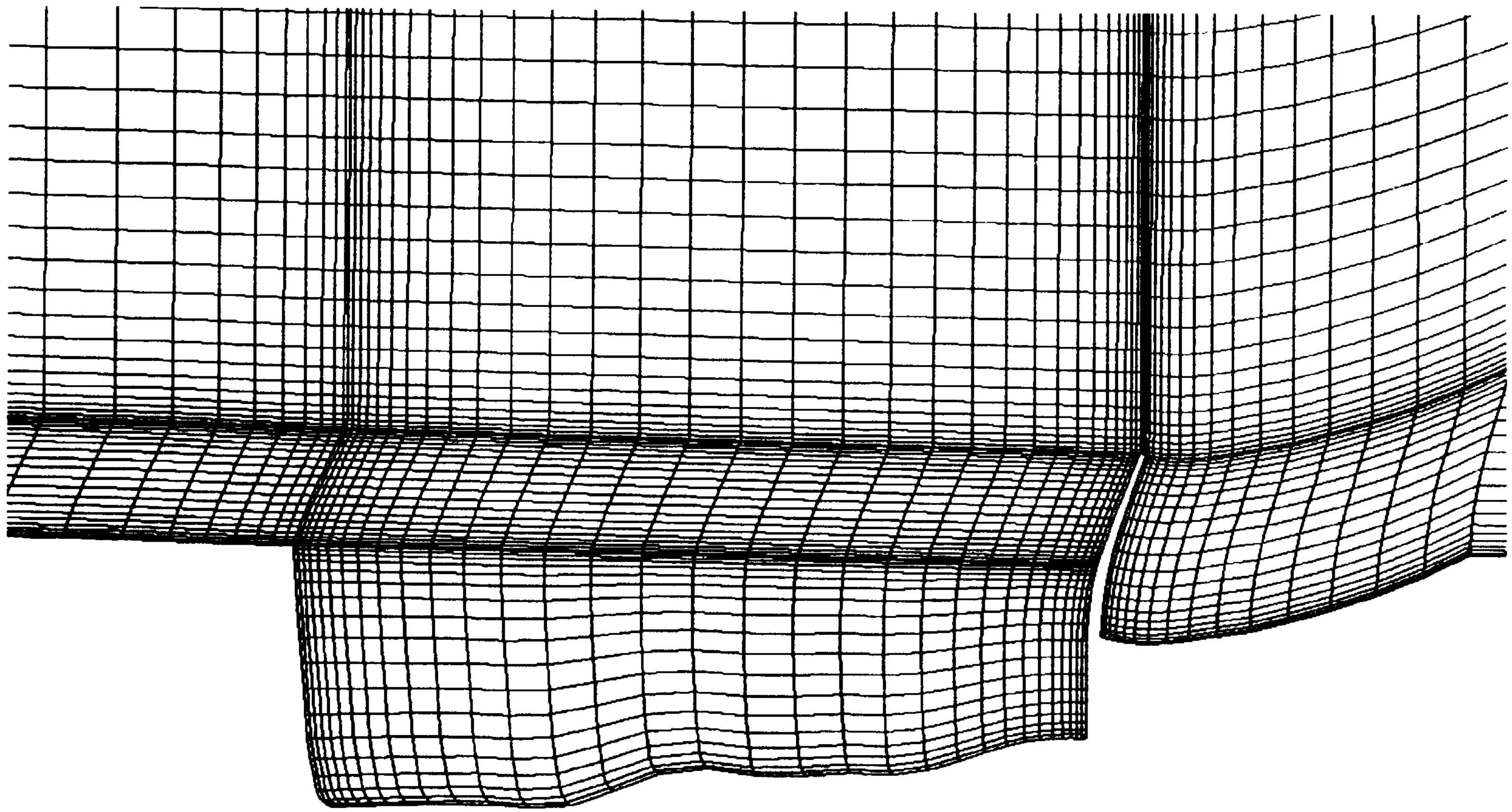
Computational Grid, Forward Slot

RSRM 80 Second Stiff NBR Inhibitor



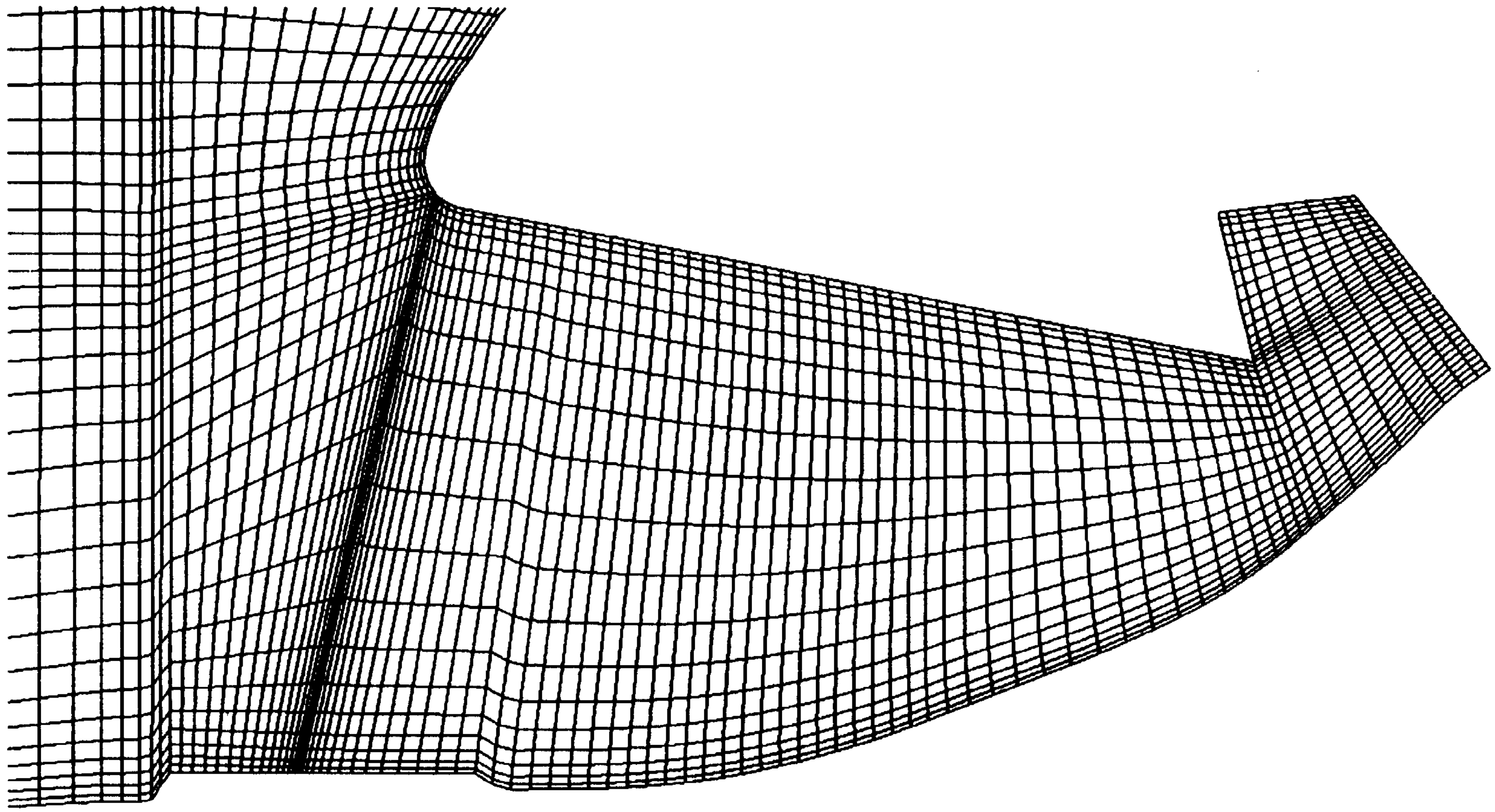
Computational Grid, Center Slot

RSRM 80 Second Stiff NBR Inhibitor



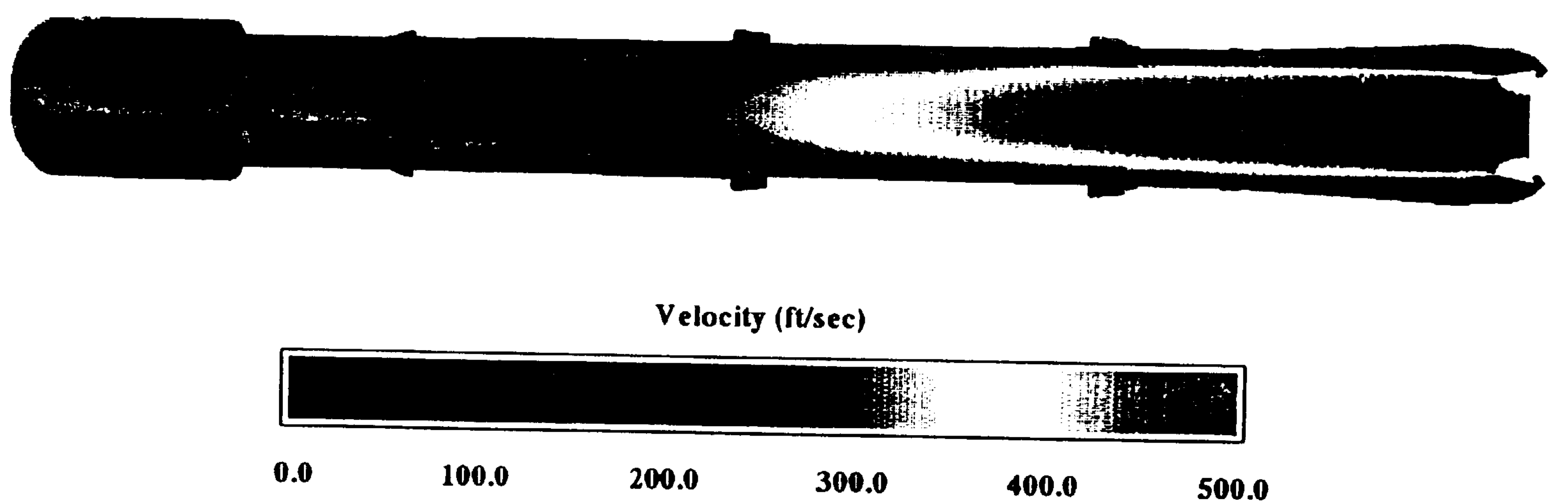
Computational Grid, Aft Slot

RSRM 80 Second Stiff NBR Inhibitor



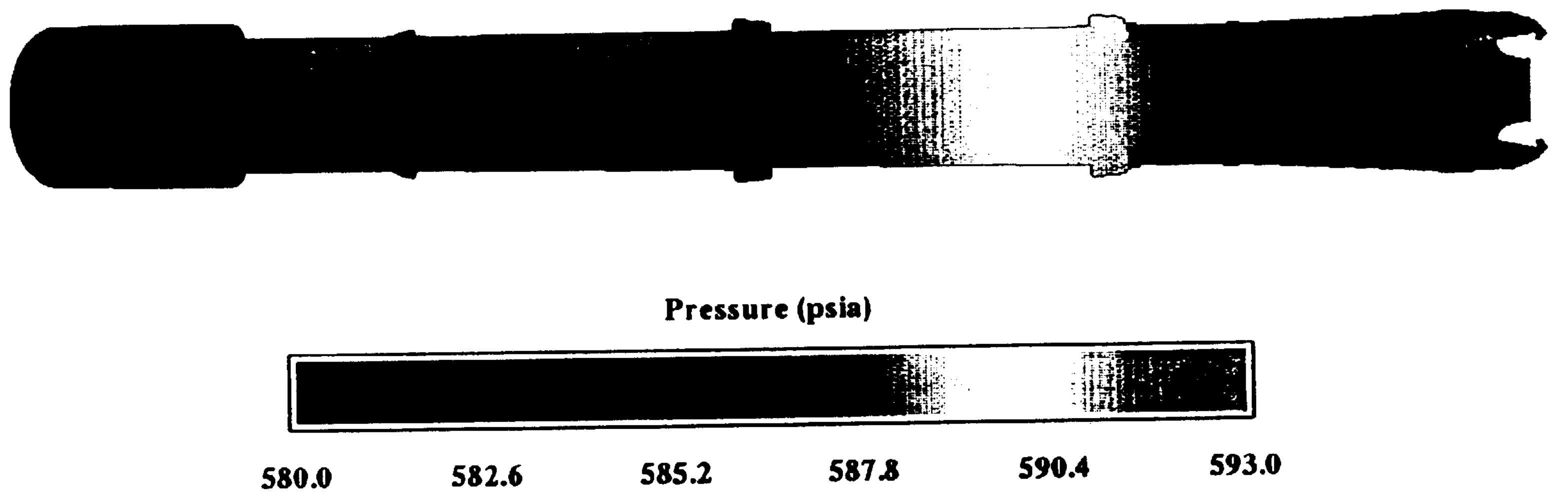
Computational Grid, Submerged Nozzle

RSRM 80 Second Stiff NBR Inhibitor



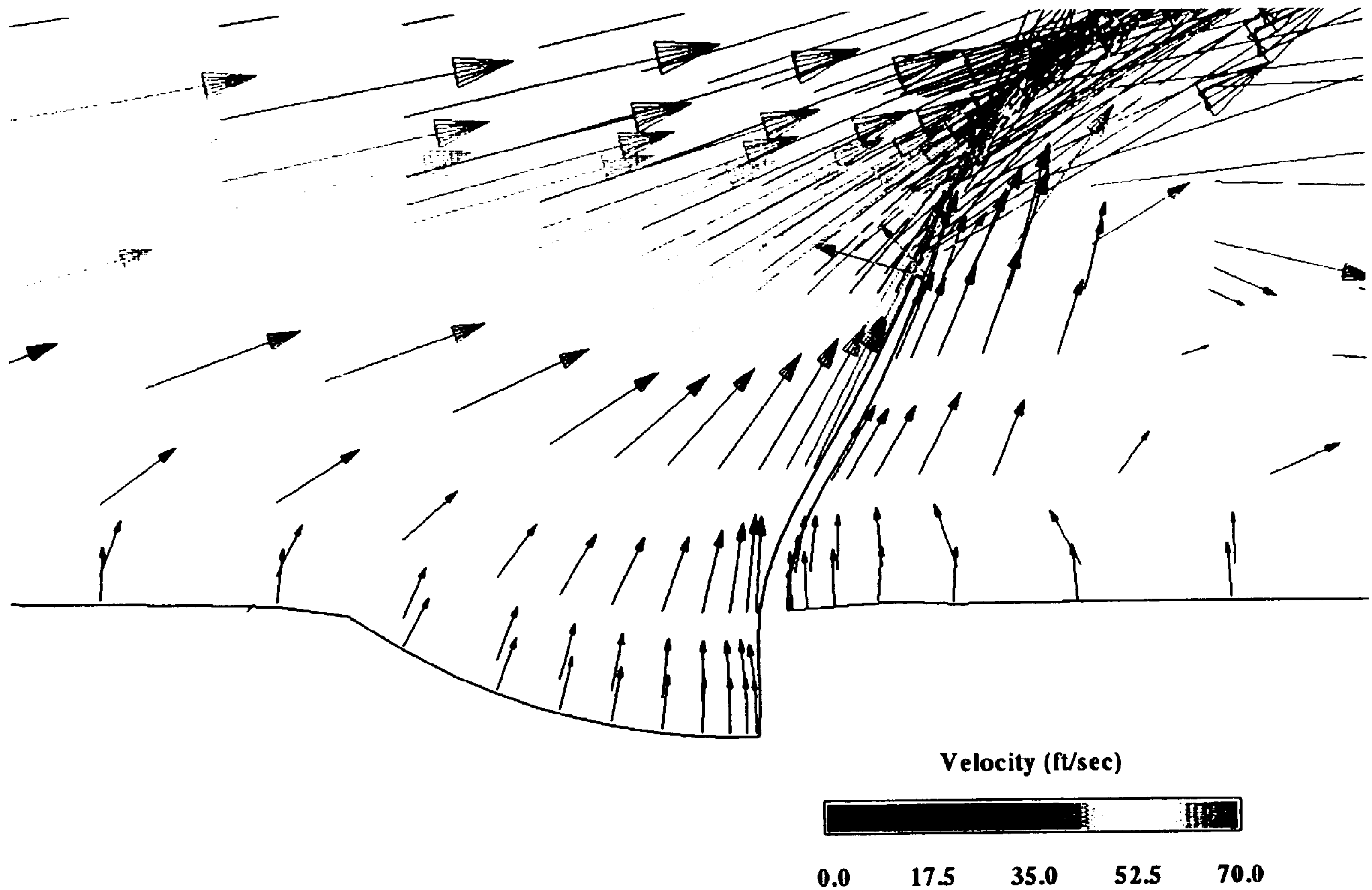
Flowfield Velocity Magnitude

RSRM 80 Second Stiff NBR Inhibitor

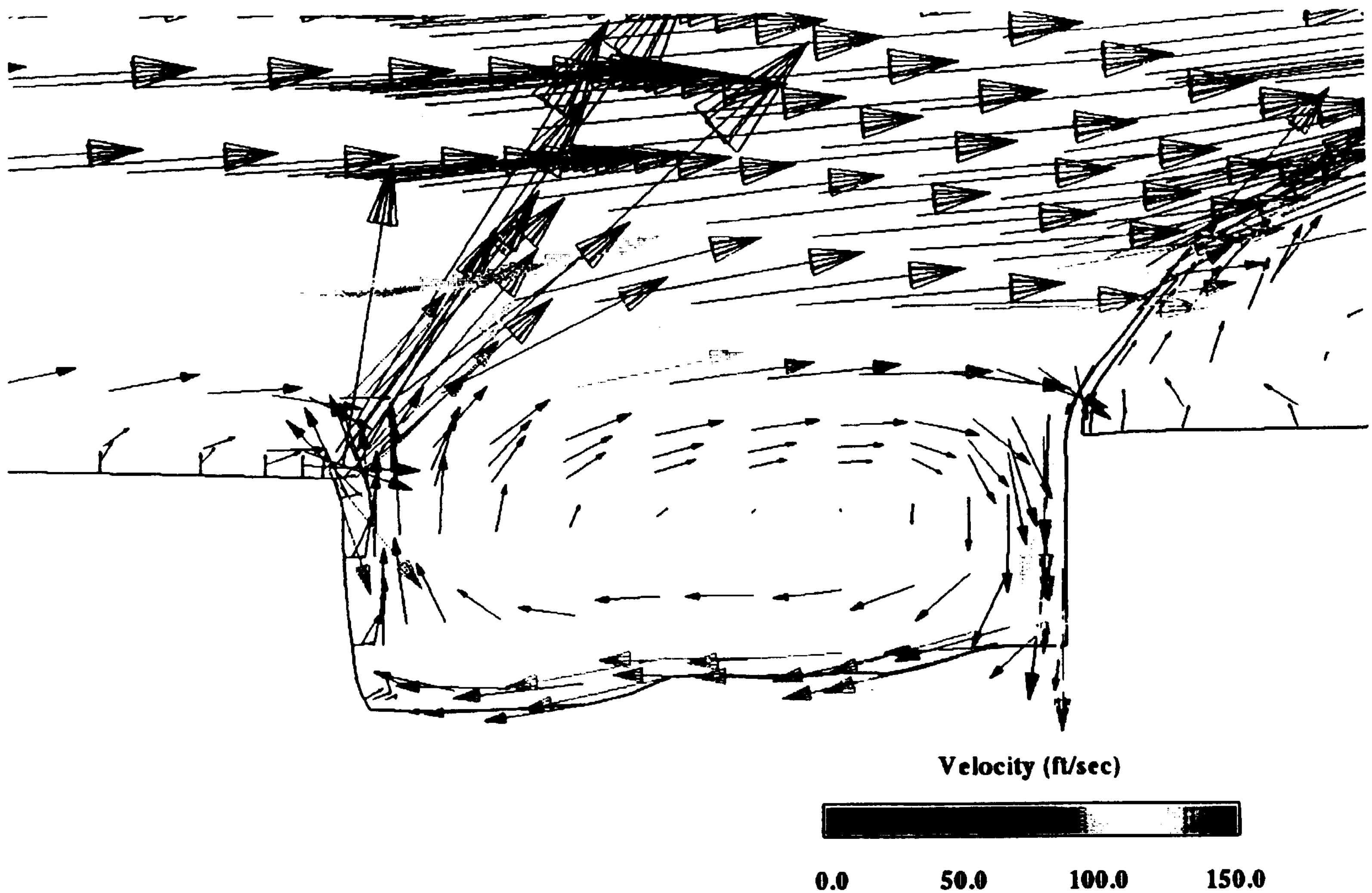


Flowfield Static Pressure

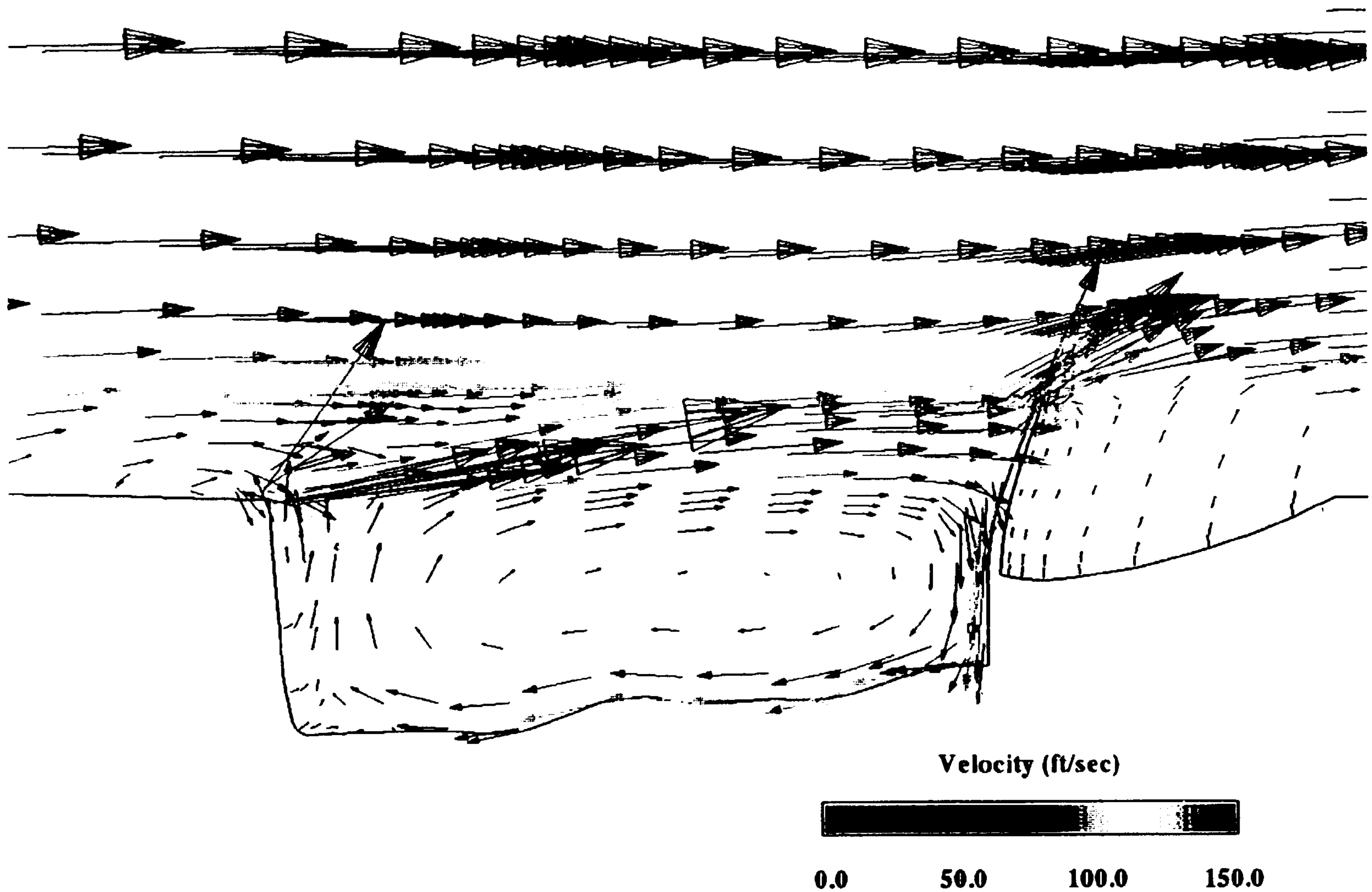
RSRM 80 Second Stiff NBR Inhibitor



Velocity Vectors, Forward Slot
RSRM 80 Second Stiff NBR Inhibitor

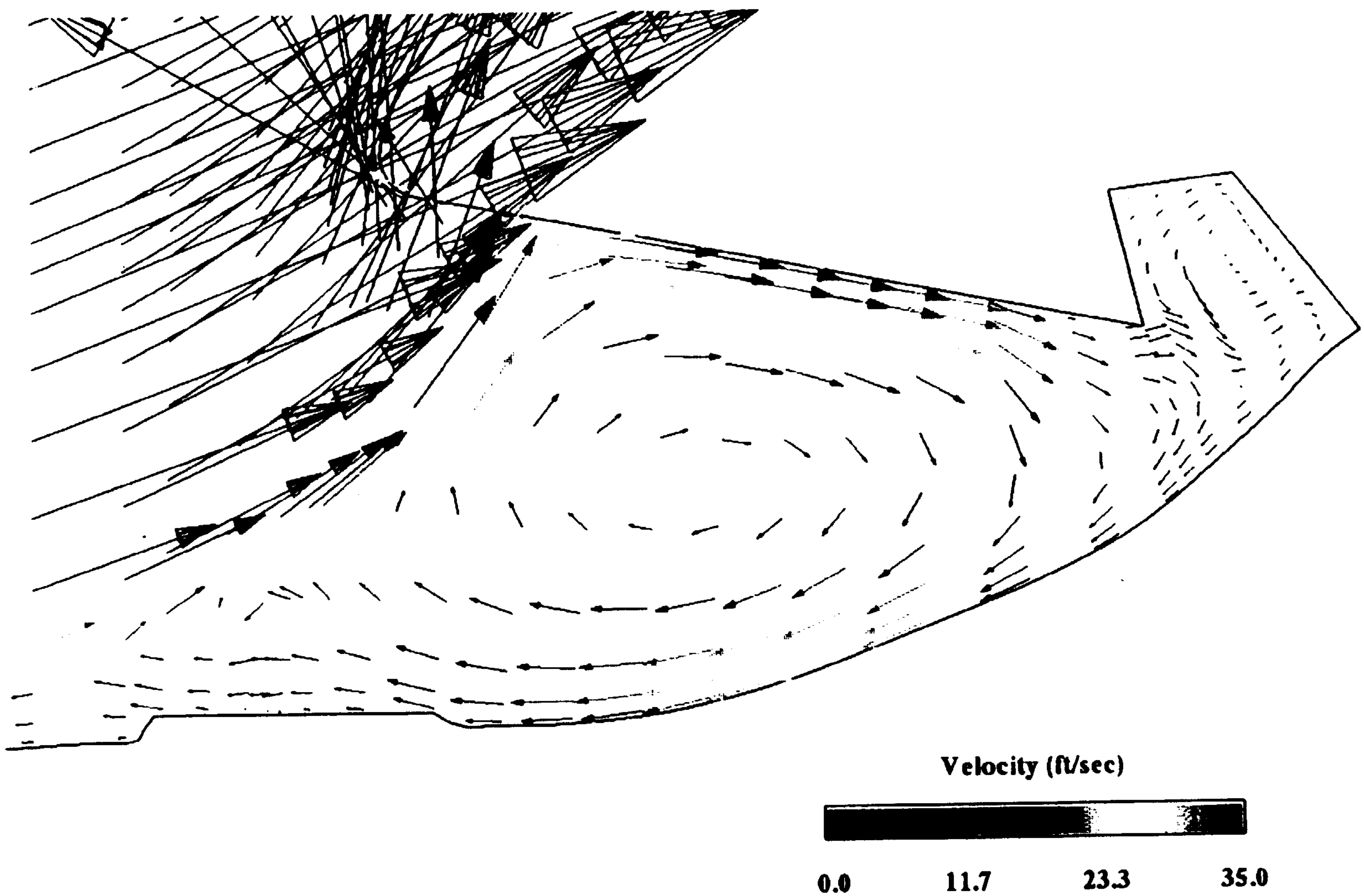


Velocity Vectors, Center Slot
RSRM 80 Second Stiff NBR Inhibitor



Velocity Vectors, Aft Slot

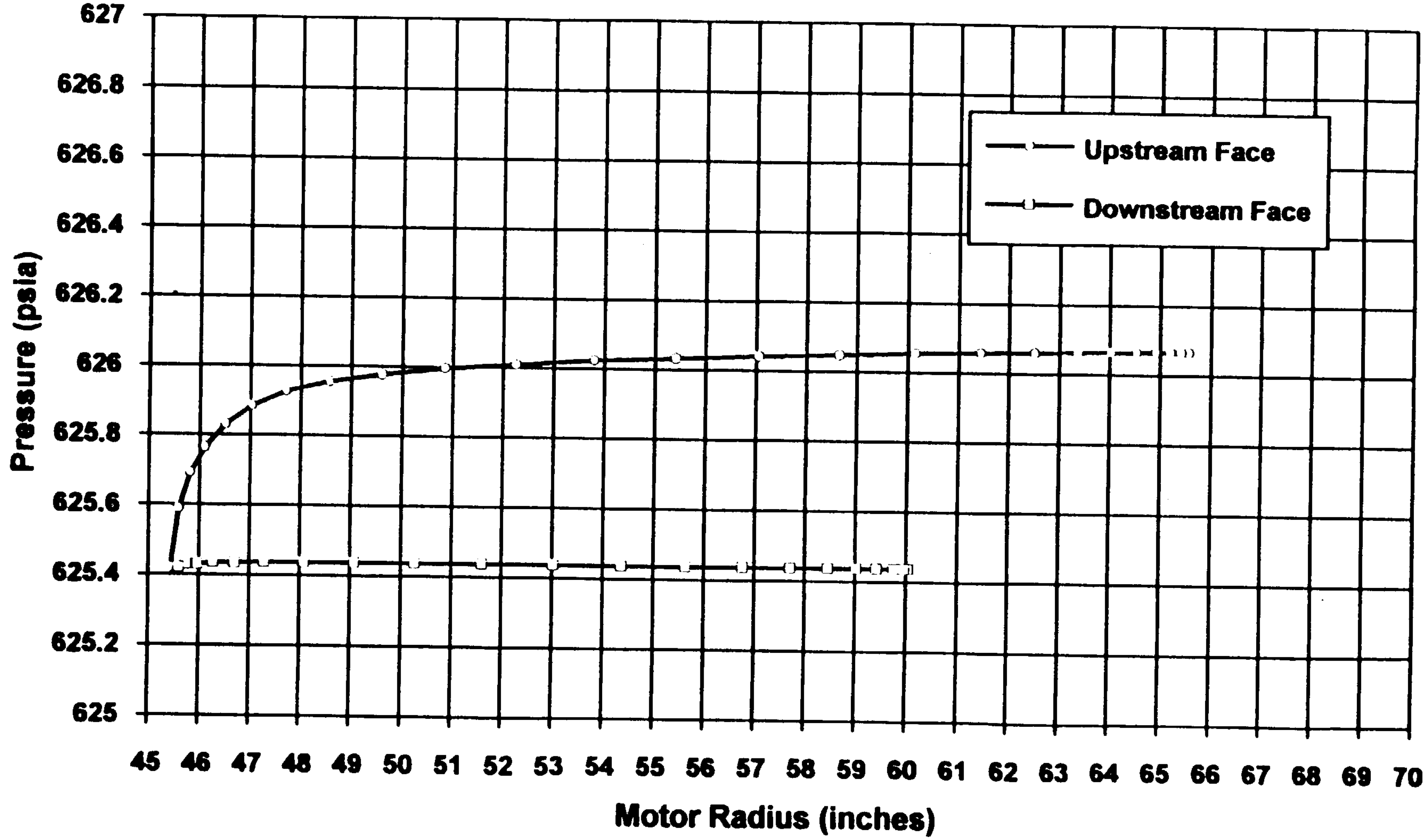
RSRM 80 Second Stiff NBR Inhibitor



Velocity Vectors, Submerged Nozzle

RSRM 80 Second Stiff NBR Inhibitor

Forward Inhibitor Radial Pressure Distribution
RSRM 80 Seconds Burn Time
Stiff NBR



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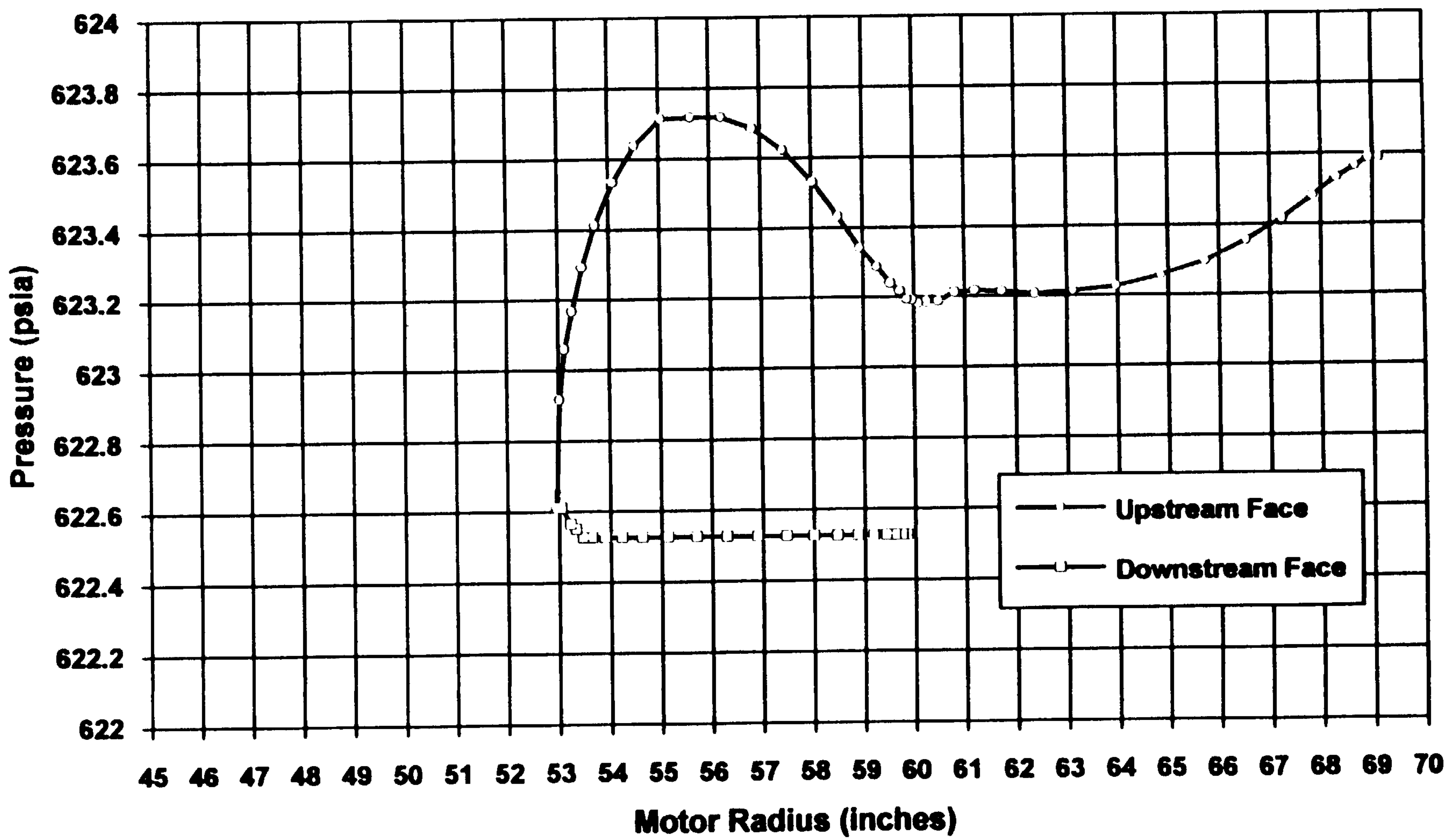
Center Inhibitor Radial Pressure Distribution RSRM 80 Seconds Burn Time Stiff NBR



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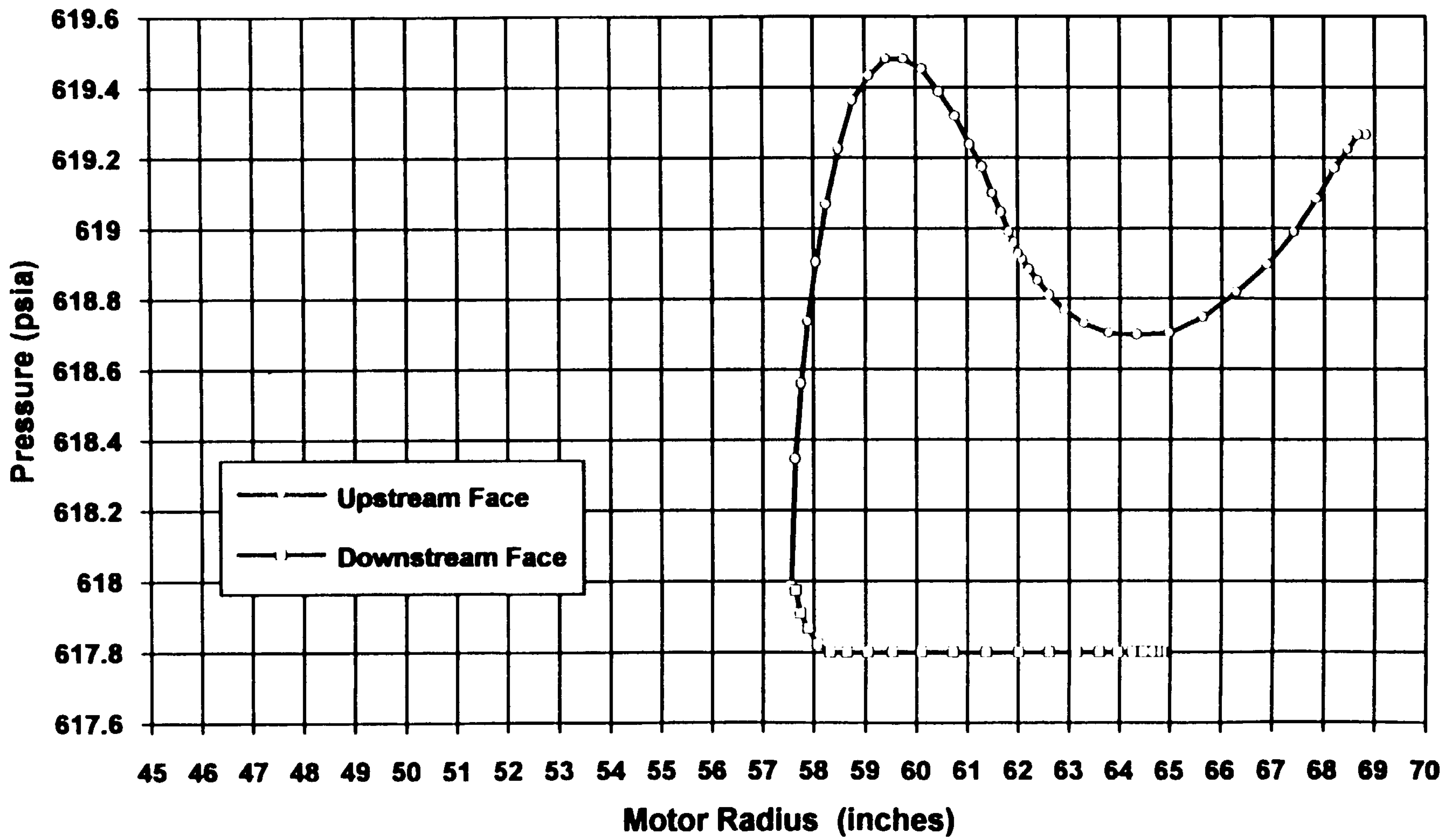
Aft Inhibitor Radial Pressure Distribution
RSRM 80 Seconds Burn Time
Stiff NBR



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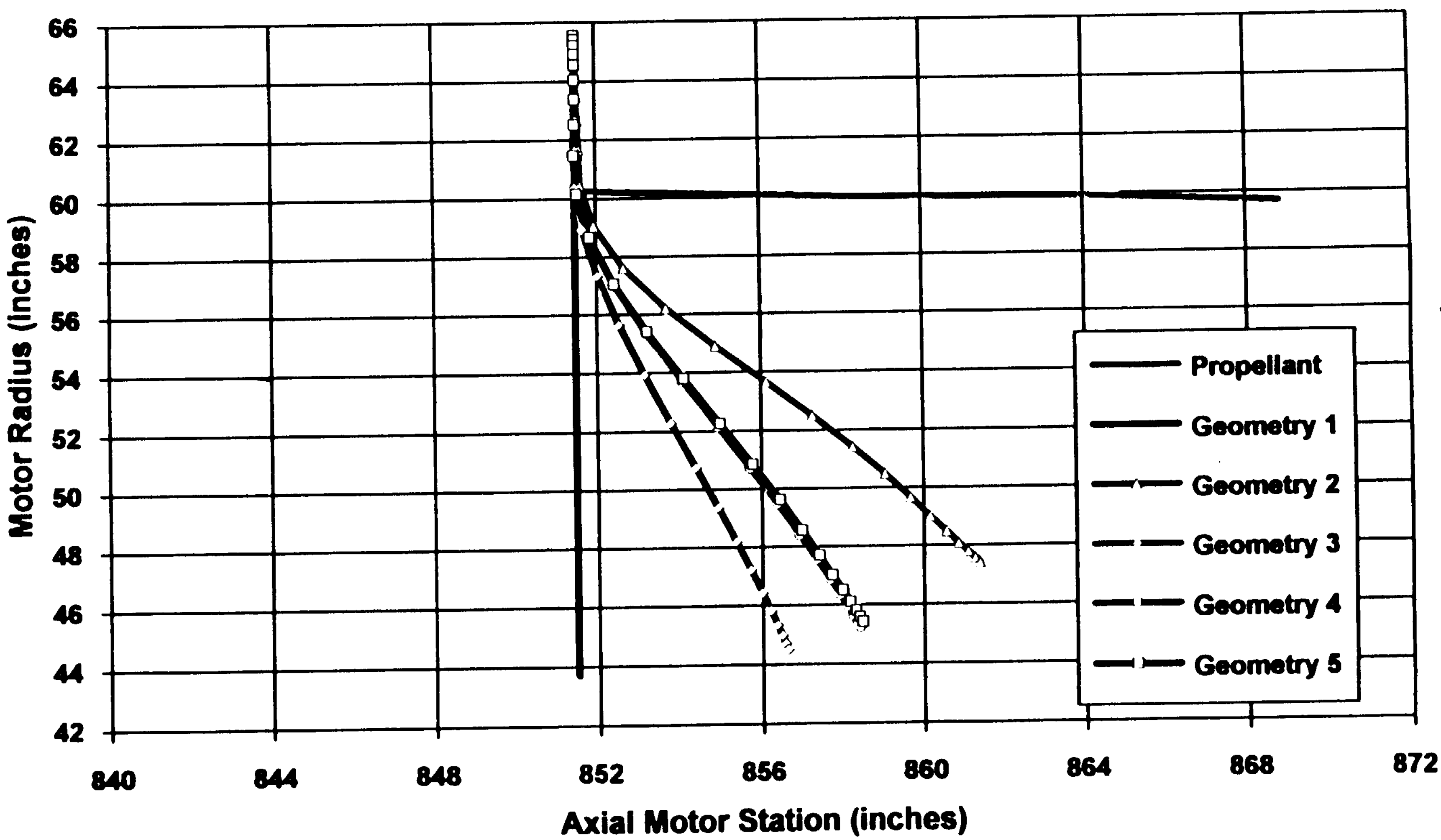
Forward Inhibitor Deformation Iterations
Stiff NBR
RSRM 80 Seconds Burn Time



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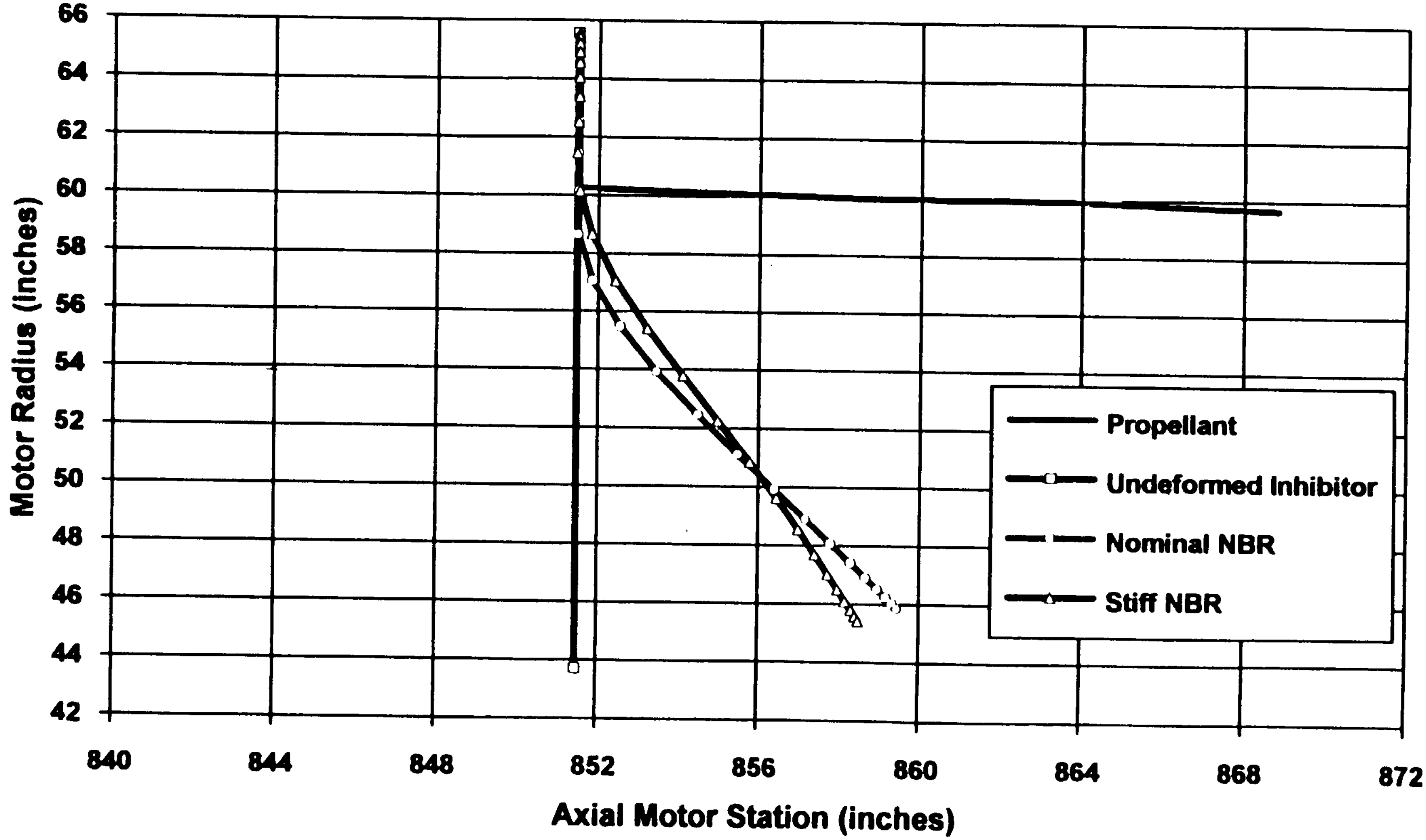
Forward Inhibitor Deformations
Nominal and Stiff NBR
RSRM 80 Seconds Burn Time



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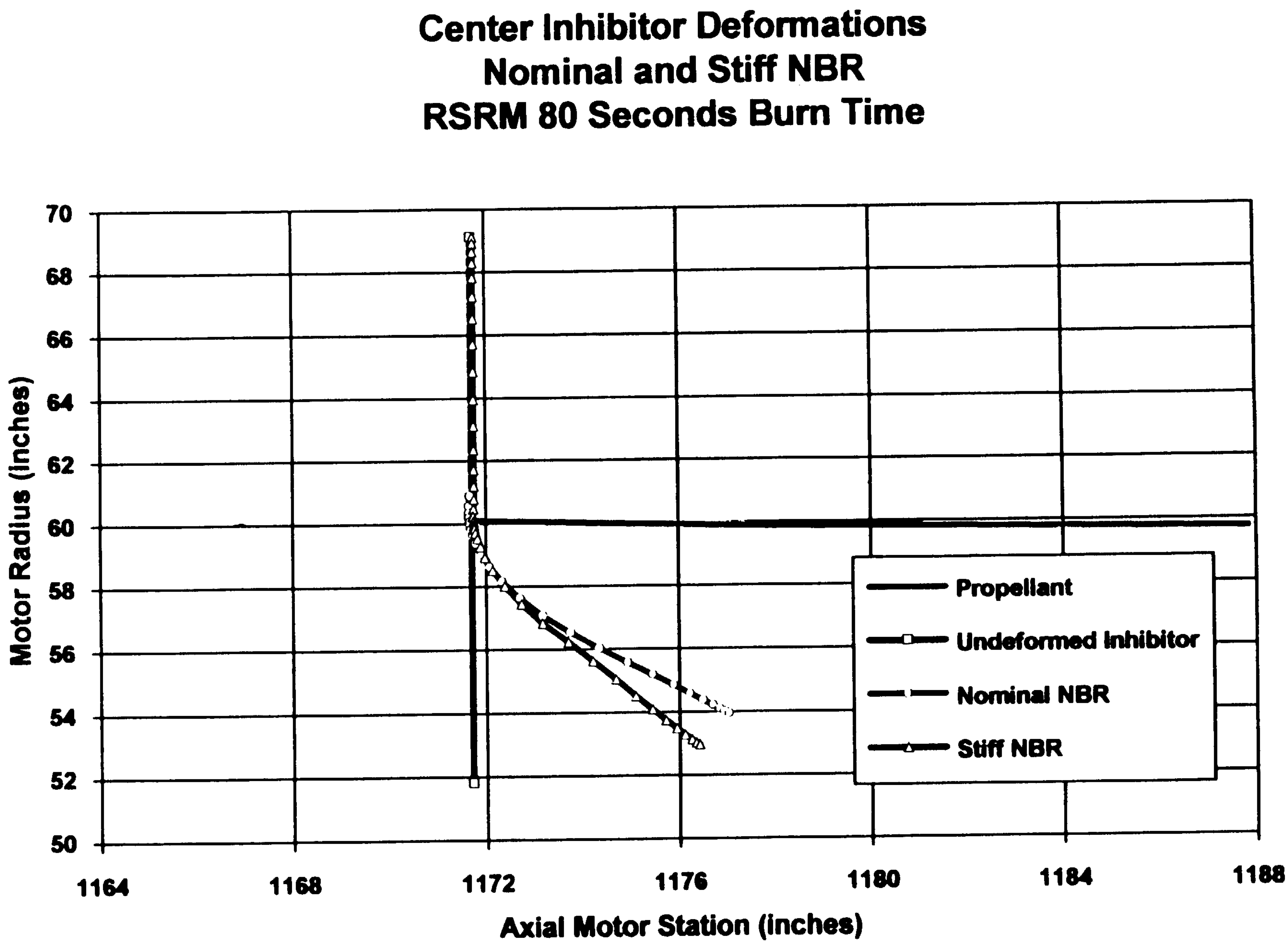
Center Inhibitor Deformations
Nominal and Stiff NBR
RSRM 80 Seconds Burn Time
Motor Radius (inches)
70
68
66
64
62
60
58
56
54
52
50
1164
1168
1172
1176
1180
1184
1188
Axial Motor Station (inches)
Propellant
Undeformed Inhibitor
Nominal NBR
Stiff NBR

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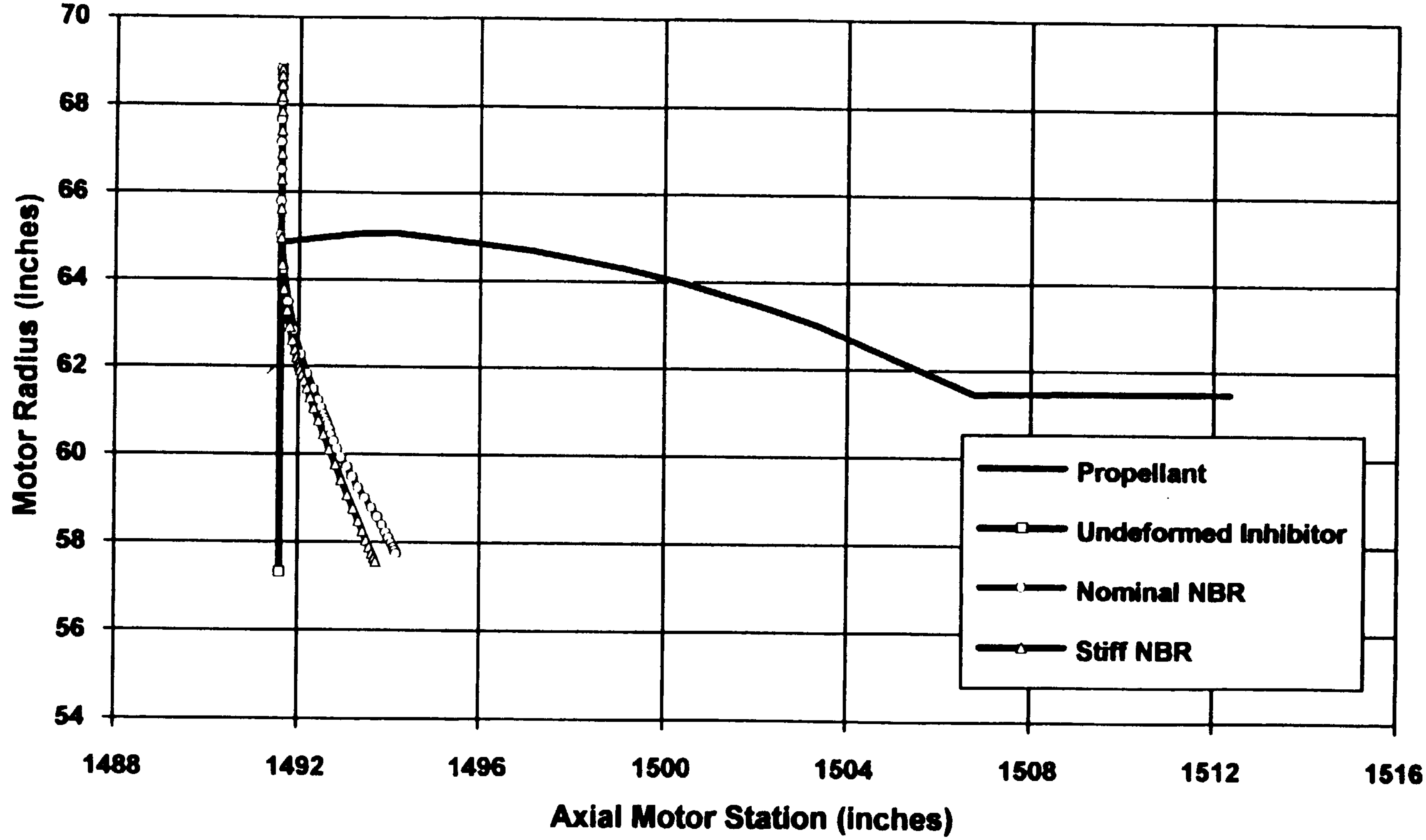
Aft Inhibitor Deformations
Nominal and Stiff NBR
RSRM 80 Seconds Burn Time



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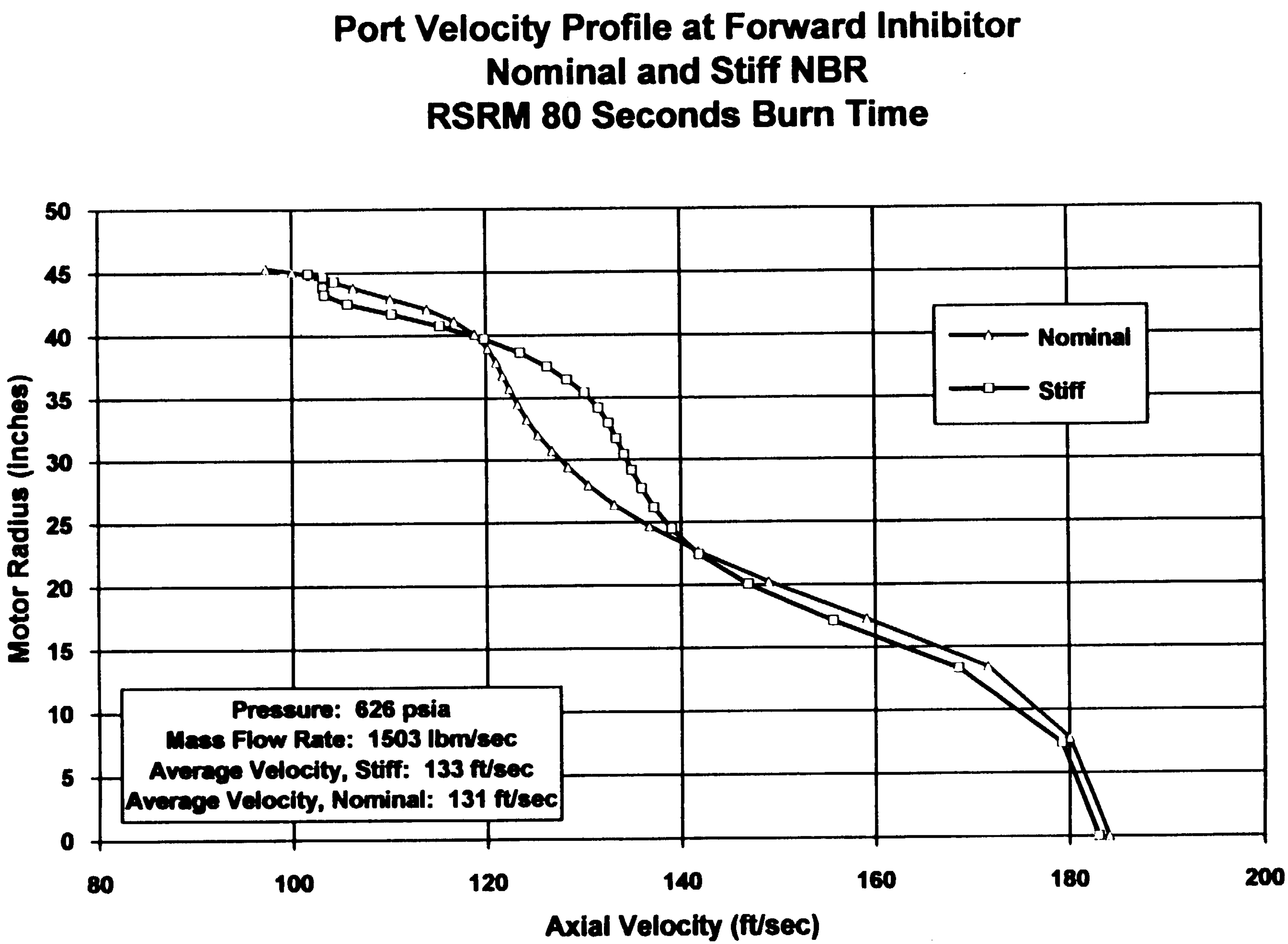
Port Velocity Profile at Forward Inhibitor
Nominal and Stiff NBR
RSRM 80 Seconds Burn Time
Motor Radius (inches)
Axial Velocity (ft/sec)
Nominal
Stiff
Pressure: 626 psia
Mass Flow Rate: 1503 lbm/sec
Average Velocity, Stiff: 133 ft/sec
Average Velocity, Nominal: 131 ft/sec
0
5
10
15
20
25
30
35
40
45
50
80
100
120
140
160
180
200

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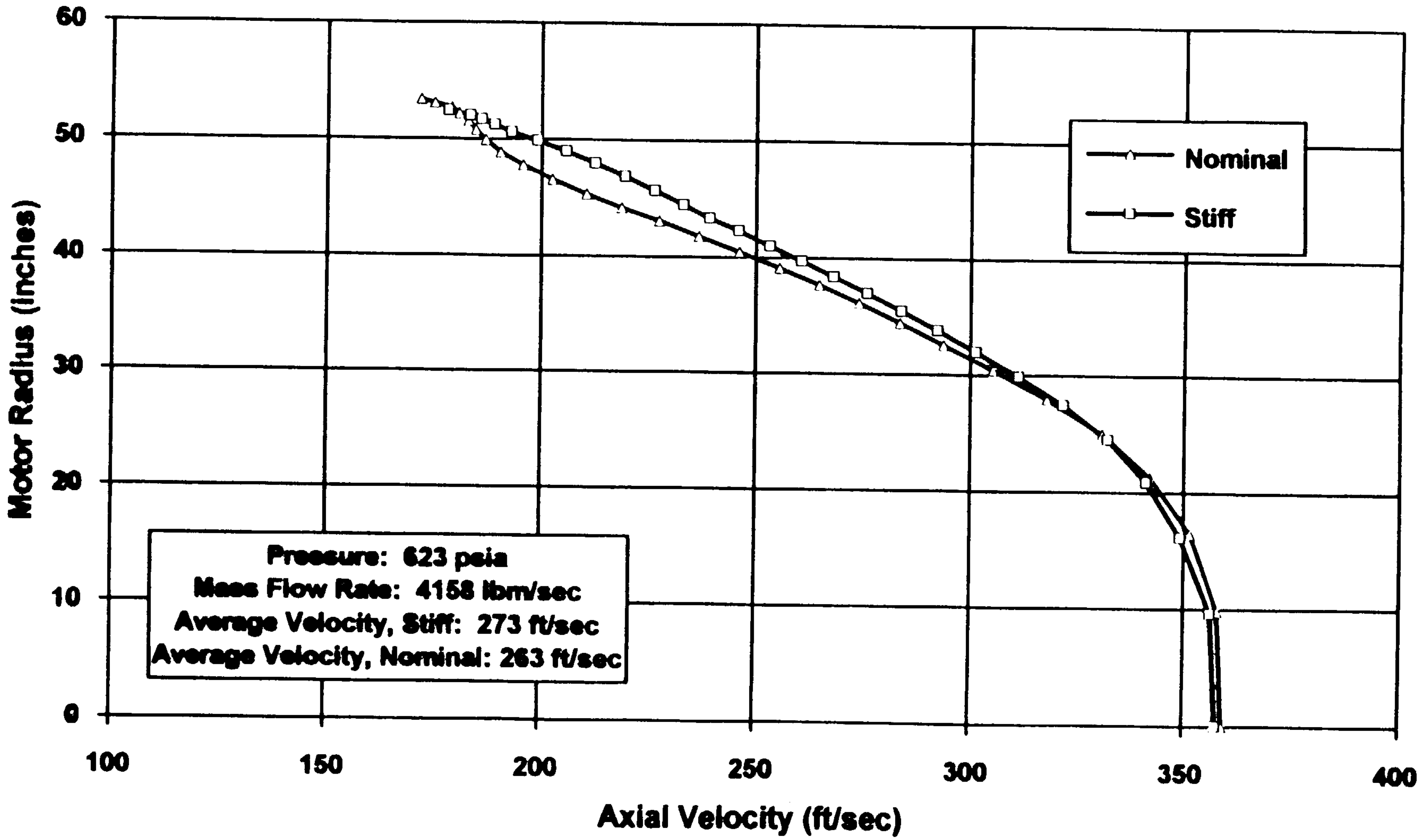
Port Velocity Profile at Center Inhibitor
Nominal and Stiff NBR
RSRM 80 Seconds Burn Time



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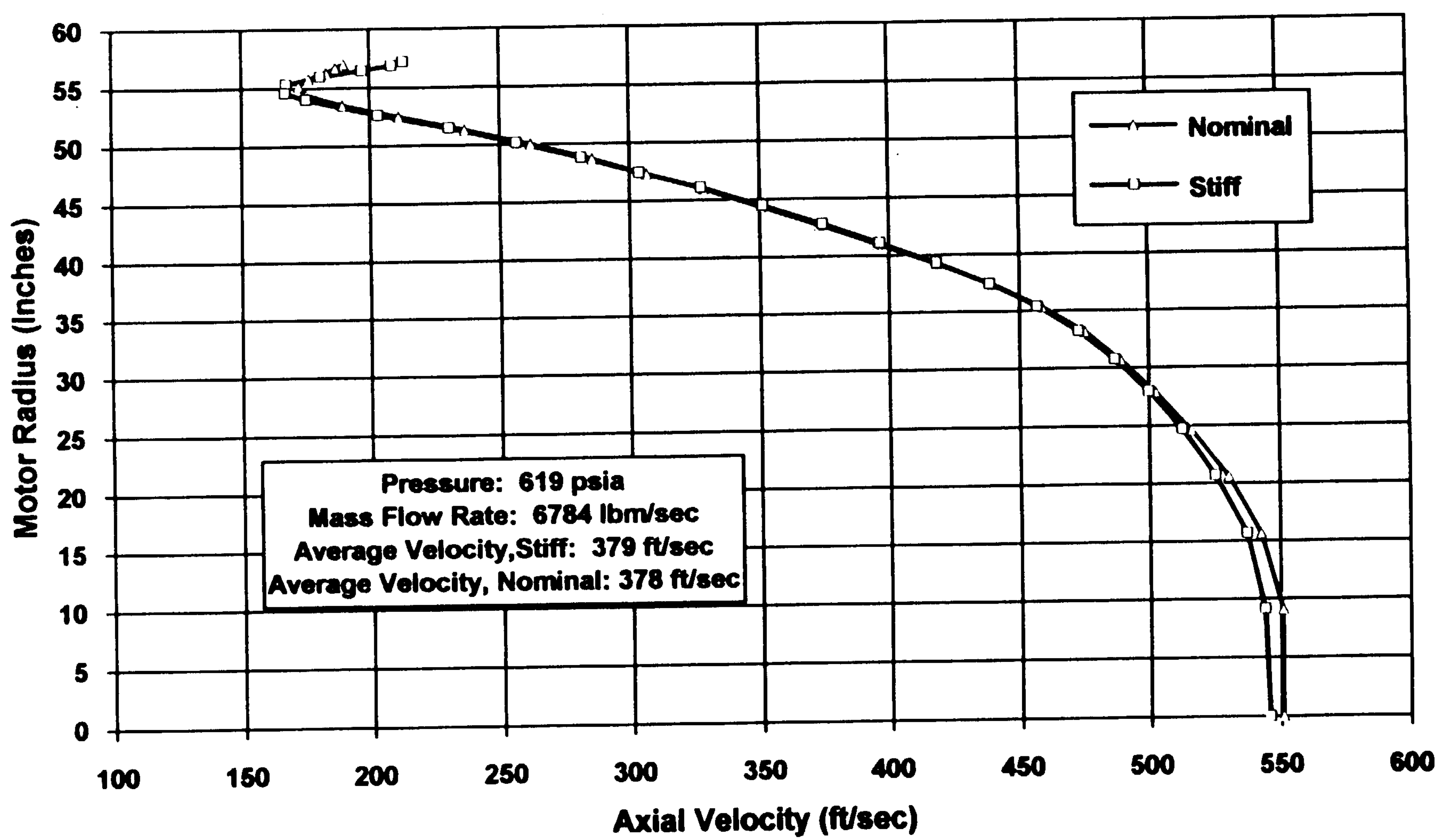
Port Velocity Profile at Aft Inhibitor
Nominal and Stiff NBR
RSRM 80 Seconds Burn Time



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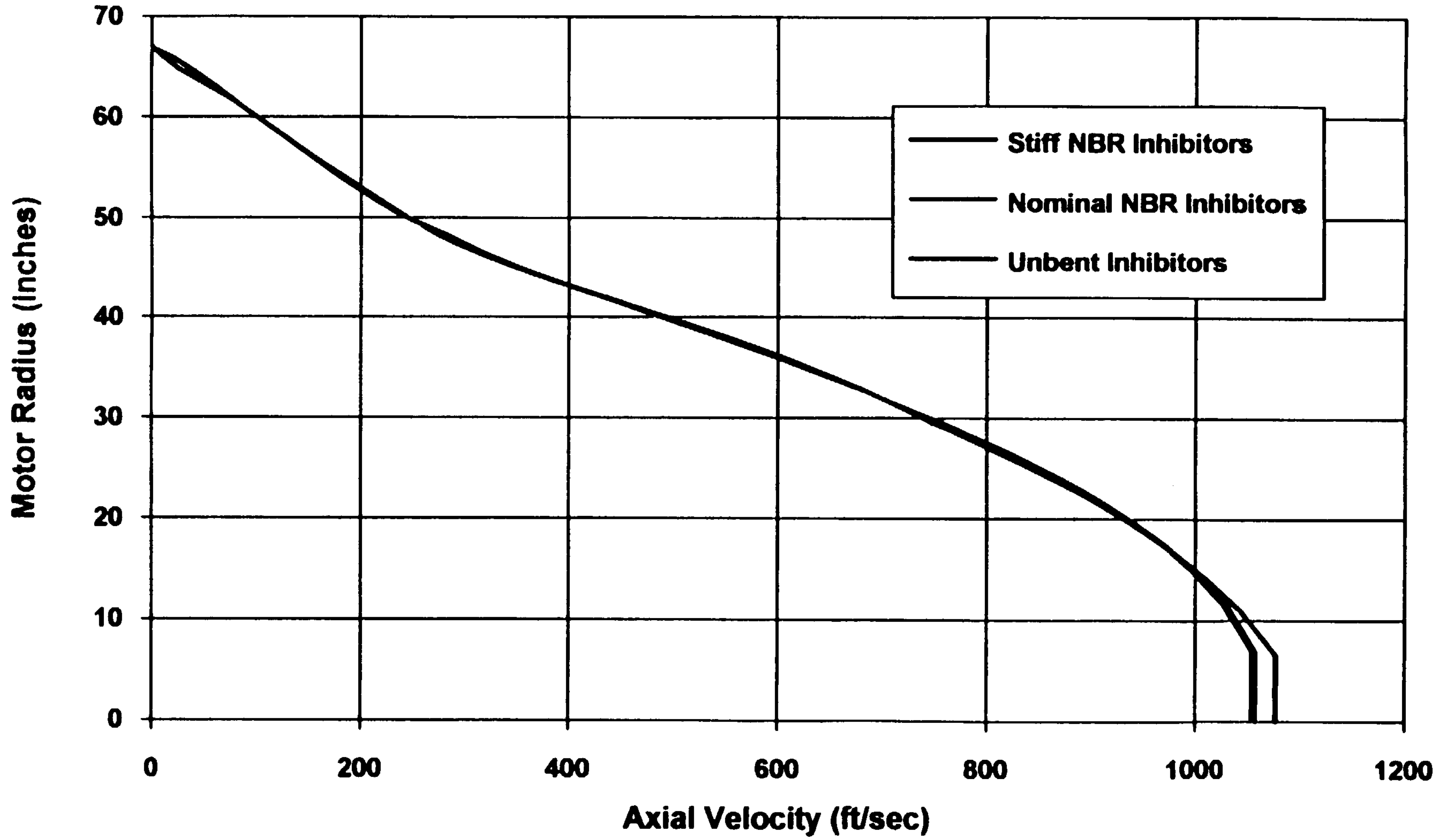
Comparison of the Motor Port Velocity Profiles Immediately Upstream of Nozzle Nose
RSRM 80 Seconds Burn Time



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Coupled CFD/FEM Analysis Conclusions

- The coupled CFD/FEM inhibitor structural analysis was successfully iterated to convergence to determined the deformed geometry of inhibitors at the forward, center and aft joints.

- The velocity through the inhibitor hole for the stiff inhibitors is somewhat higher which would increase the hole true frequency and delay tuning with the acoustic mode until a later burn time.

- The velocity profile at the nozzle entrance just upstream of the nose is not affected by the inhibitor stiffness/geometry and thus nozzle internal aerotorque would not be impacted.

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Two-Phase CFD Analysis Approach

- Perform two-phase CFD analysis of RSRM port at 80 second burn time using final deformed inhibitor geometries for both nominal and stiff inhibitors.
- Calculate slag captured on both nominal and stiff inhibitors at all three field joints.
- Perform trajectory analysis for slag debris shed from inhibitor tips for all above cases to determine whether it passes through nozzle or accumulates underneath nozzle nose.

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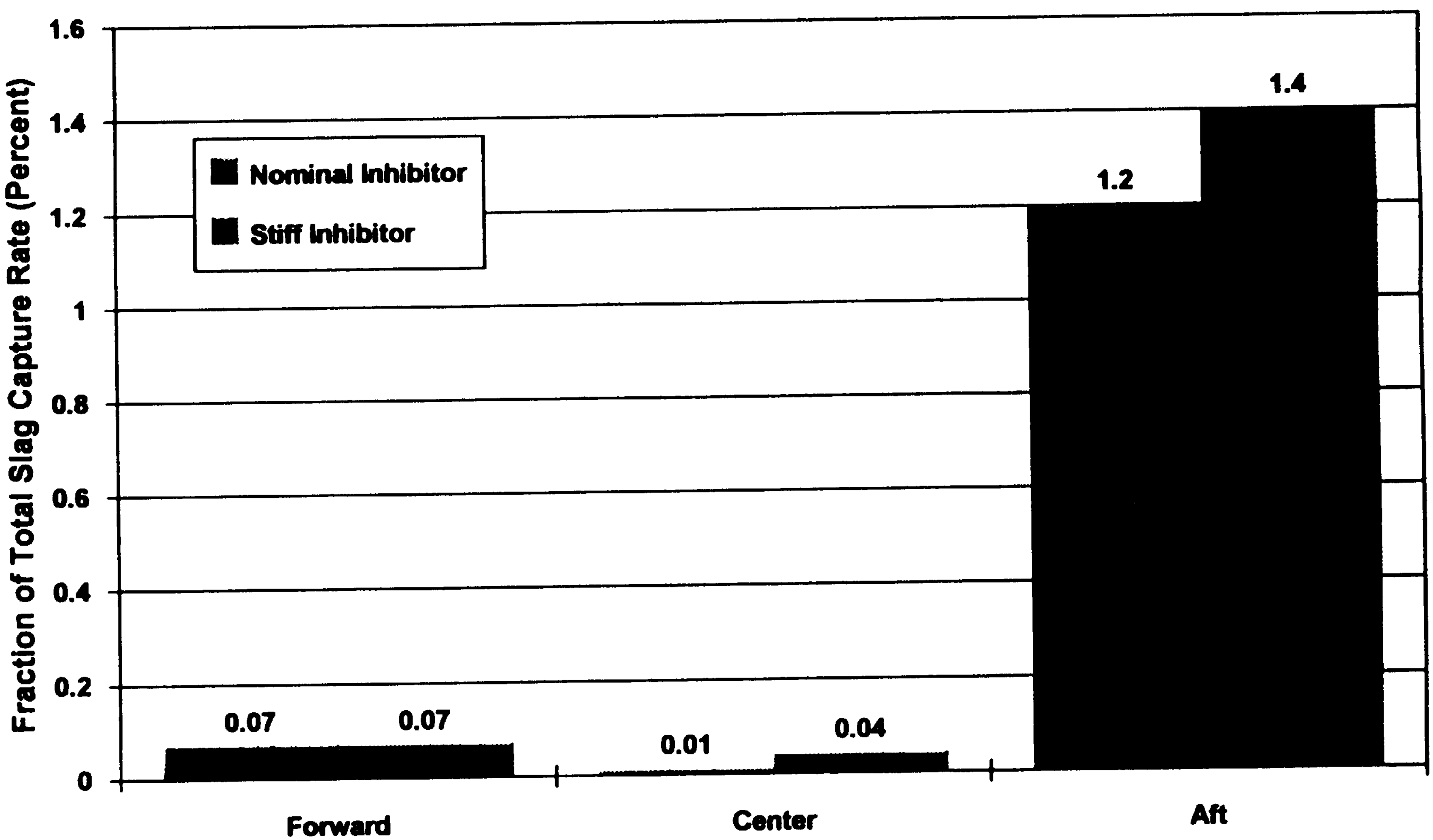
RSRM Inhibitor Slag Accumulation
Nominal and Stiff NBR Inhibitors
80 Second Burn Time



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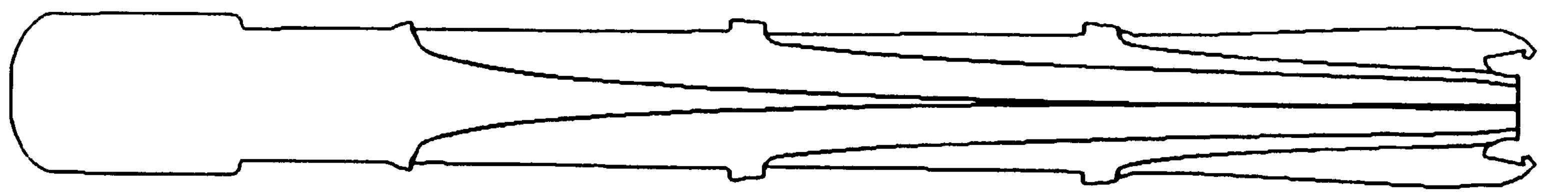
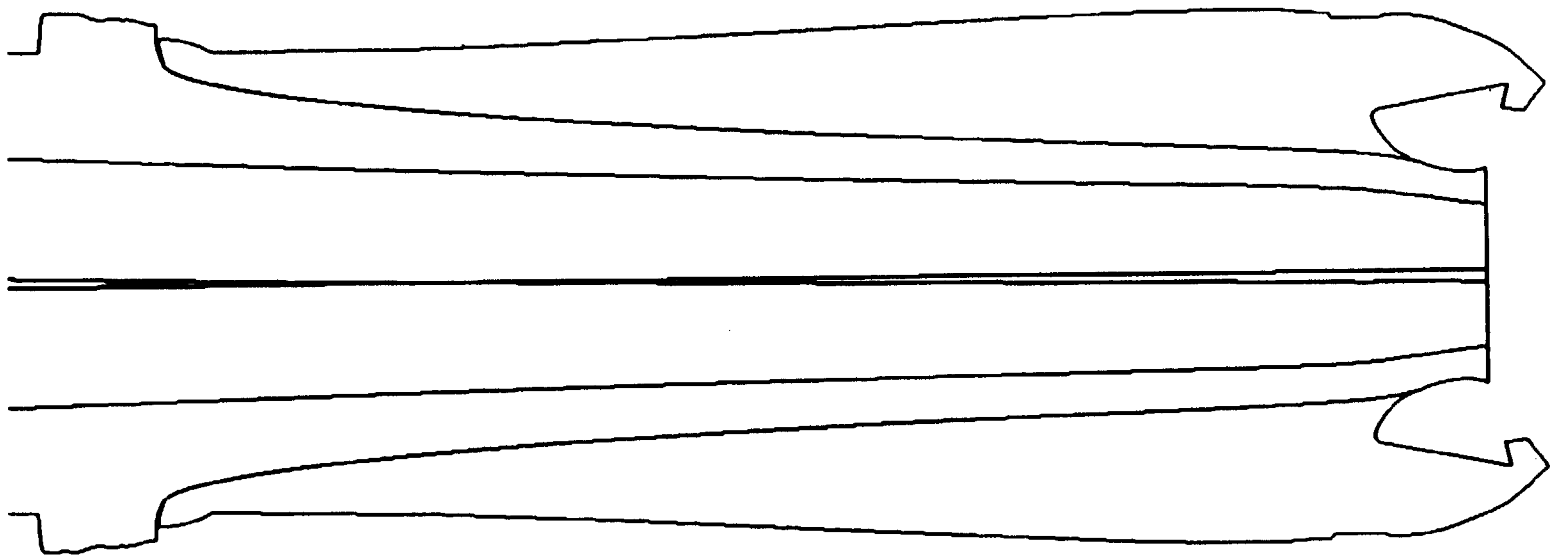


Slag Debris Trajectories

RSRM 80 Second Stiff NBR Inhibitor

Debris Diameter: 0.2 Inches



Slag Debris Trajectories

RSRM 80 Second Stiff NBR Inhibitor

Debris Diameter: 0.2 Inches

Slag Debris Trajectory Results
Nominal and Stiff NBR Inhibitors

Release Location	Debris Diameter			
	0.2 inches	0.4 inches	0.8 inches	1.6 inches
		Nominal NBR		
Forward	Exits Nozzle	Exits Nozzle	Exits Nozzle	Exits Nozzle
Center	Exits Nozzle	Exits Nozzle	Exits Nozzle	Exits Nozzle
Aft	Exits Nozzle	Exits Nozzle	Exits Nozzle	Nozzle Nose
		Stiff NBR		
Forward	Exits Nozzle	Exits Nozzle	Exits Nozzle	Exits Nozzle
Center	Exits Nozzle	Exits Nozzle	Exits Nozzle	Exits Nozzle
Aft	Nozzle Nose	Nozzle Nose	Nozzle Nose	Nozzle Nose

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Two-Phase CFD Analysis Conclusions

- The rate of slag accumulation for both the nominal and stiff inhibitors at all joints is a very small percentage of the total motor slag accumulation rate.
- The rate of slag accumulation on the center inhibitor is approximately four times greater for the stiff NBR compared to the nominal NBR.
- Slag debris shed from the nominal inhibitors at all three joints exits the nozzle throat plane.
- Slag debris shed from the stiff inhibitors at the forward and center joints exits the nozzle throat plane. Slag from the aft joint stiff inhibitor impacts the nozzle entrance ramp.
- No excess slag collected on the stiff inhibitors is transported underneath the nozzle nose to add to the normal slag pool.

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