Application of Two-Phase CFD to the Design and Analysis of a Subscale Motor Experiment to Evaluate Propellant Slag Production

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Abstract

The RSRM Pressure Perturbation Investigation Team concluded that the cause of recent pressure spikes during both static and flight motor burns was the expulsion of molten aluminum oxide slag from a pool which collects in the aft end of the motor around the submerged nozzle nose during the last half of motor operation. It is suspected that some motors produce more slag than others due to differences in aluminum oxide agglomerate particle sizes which may relate to subtle differences in propellant ingredient characteristics such as particle size distributions, contaminants, or processing variations.

In order to determine the effect of suspect propellant ingredient characteristics on the propensity for slag production in a real motor environment, a subscale motor experiment was designed to accomplish this objective. An existing 5 inch ballistic test motor was selected as the basic test vehicle due to low cost and quick turn around times. The standard converging/diverging nozzle was replaced with a submerged nozzle nose design to provide a positive trap for the slag which would increase both the quantity and repeatability of measured slag weights. CFD was used to assess a variety of submerged nose configurations to identify the design which possessed the best capability to reliably collect slag. CFD was also used to assure that the final selected nozzle design would result in flow field characteristics such as dividing streamline location, nose attach point, and separated flow structure which would have similitude with the RSRM submerged nozzle nose flow field. It was also decided to spin the 5 inch motor about its longitudinal axis to further enhance slag collection quantities. Again, CFD was used to select an appropriate spin rate along with other considerations, including the avoidance of burn rate enhancement from radial acceleration effects.

The CFD analyses were performed with the CELMINT code which is a two-phase Navier-Stokes coded employing an Eulerian/Lagrangian scheme, a low Reynolds number κ-ε turbulence model modified for wall injection, and both surface and distributed particle combustion models which include particle agglomeration and break-up. Aluminum oxide particle distributions were measured with RSRM propellant in a combustion bomb with particle quench capability. Predictions for slag weights and slag distribution patterns were compared with slag weight data from defined zones in the motor and nozzle. Various parameters were investigated to reconcile differences between CFD predictions and data. General comparisons were acceptable considering combustion bomb data on particle sizes was not available for each propellant sample. Confidence in using this methodology in the RSRM was enhanced by this successful subscale experiment.

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Background

- Flight and static test data for the Space Shuttle Reusable Solid Rocket Motors reveals roughness and small spikes in the pressure trace for some motors during the 65-75 second time period.

- An extensive investigation has determined that periodic expulsion of aluminum oxide slag is the cause of pressure perturbations.

- Excessive slag production by some motors is suspected as making these motors more susceptible to slag expulsion.

- Excessive slag production is related to propellant ingredient characteristics including but not limited to aluminum and ammonium perchlorate particle size distributions.

- A low cost, quick turn-around experimental method was needed to evaluate effects of subtle changes in propellant ingredient characteristics on the propensity for slag production.

Experimental Program Objective and Approach

Objective:

Develop and employ a subscale rocket test motor capable of measuring relative slag production of propellants with subtle changes in ingredient characteristics.

Approach:

- Use an existing Thiokol 5-inch diameter ballistic test motor and static test spin stand.

- Modify existing converging/diverging nozzle entrance geometry by incorporating submerged nose to enhance slag capture and retention.

- Select motor operating pressure to match full scale motor pressure. Select spin rate to enhance slag capture but avoid propellant burn rate augmentation.

- Use CFD to determine overall viability of experiment, to aid in design of motor components, to support selection of test conditions, and to analyze test results.

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Specific CFD Analysis Tasks

- Evaluate candidate nozzle entrance designs for slag capturing characteristics.

- Select submerged nose nozzle geometry that qualitatively simulates the primary flow pattern and features relative to nozzle nose attachment and recirculation pattern in the RSRM.

- Determine viability of experiment design before hardware manufacture by evaluating sensitivity of slag capture weights to small changes in aluminum oxide particle size distribution.

- Determine effect of spin rate on slag capture weights to support final selection of test spin rate.

- Perform post-test analysis of data including parametric studies as required to validate and calibrate two-phase CFD model.

- Use analysis results to upgrade two-phase CFD model for RSRM slag predictions.

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FIVE INCH SPIN MOTOR ASSEMBLY

Nozzle Body

Submerged Nose Nozzle

0.916

5.0

9.0

3.0

Propellant

Motor Case

Head End Closure

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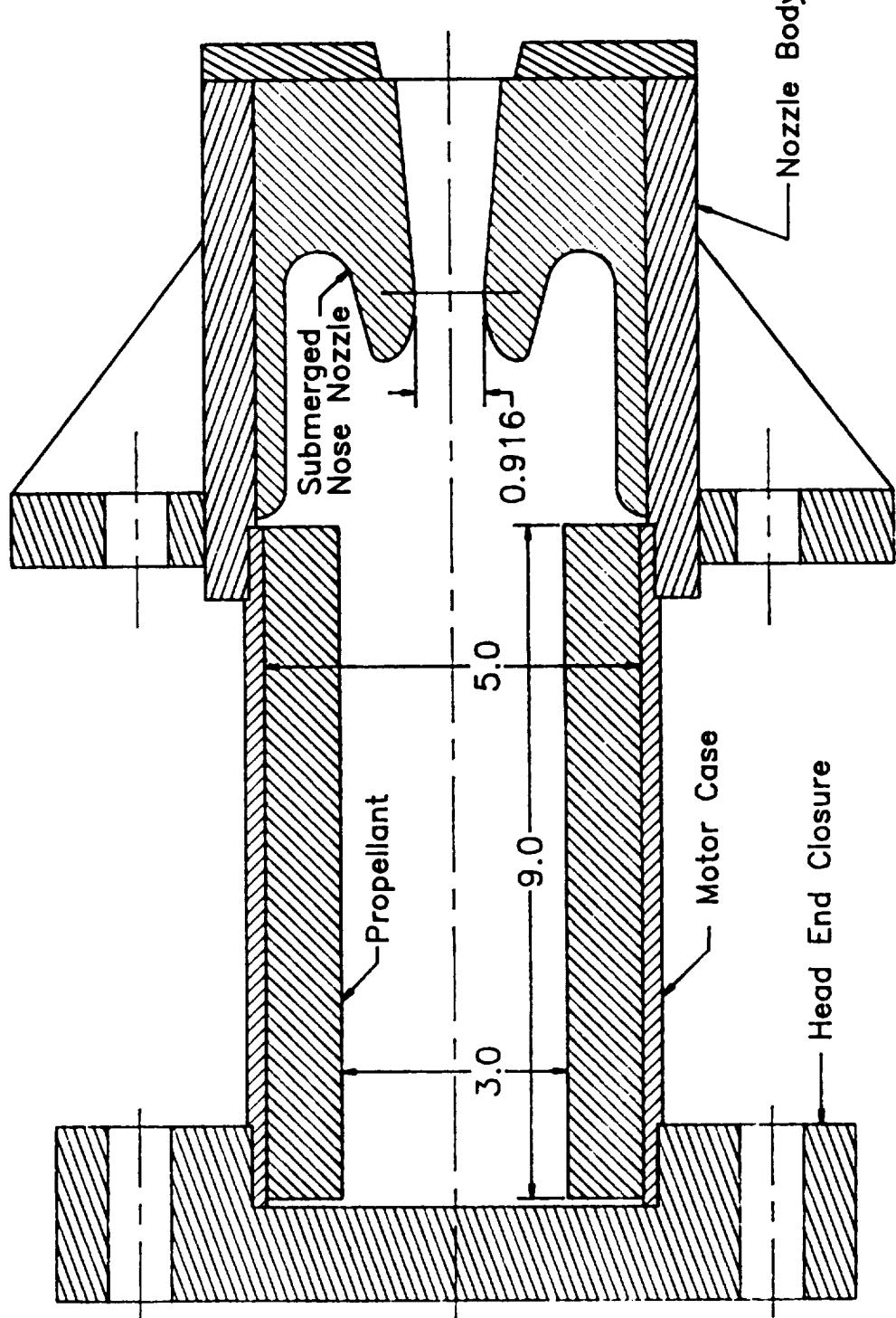
FIVE INCH SPIN MOTOR NOZZLE
SLAG ZONES

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B

C

D
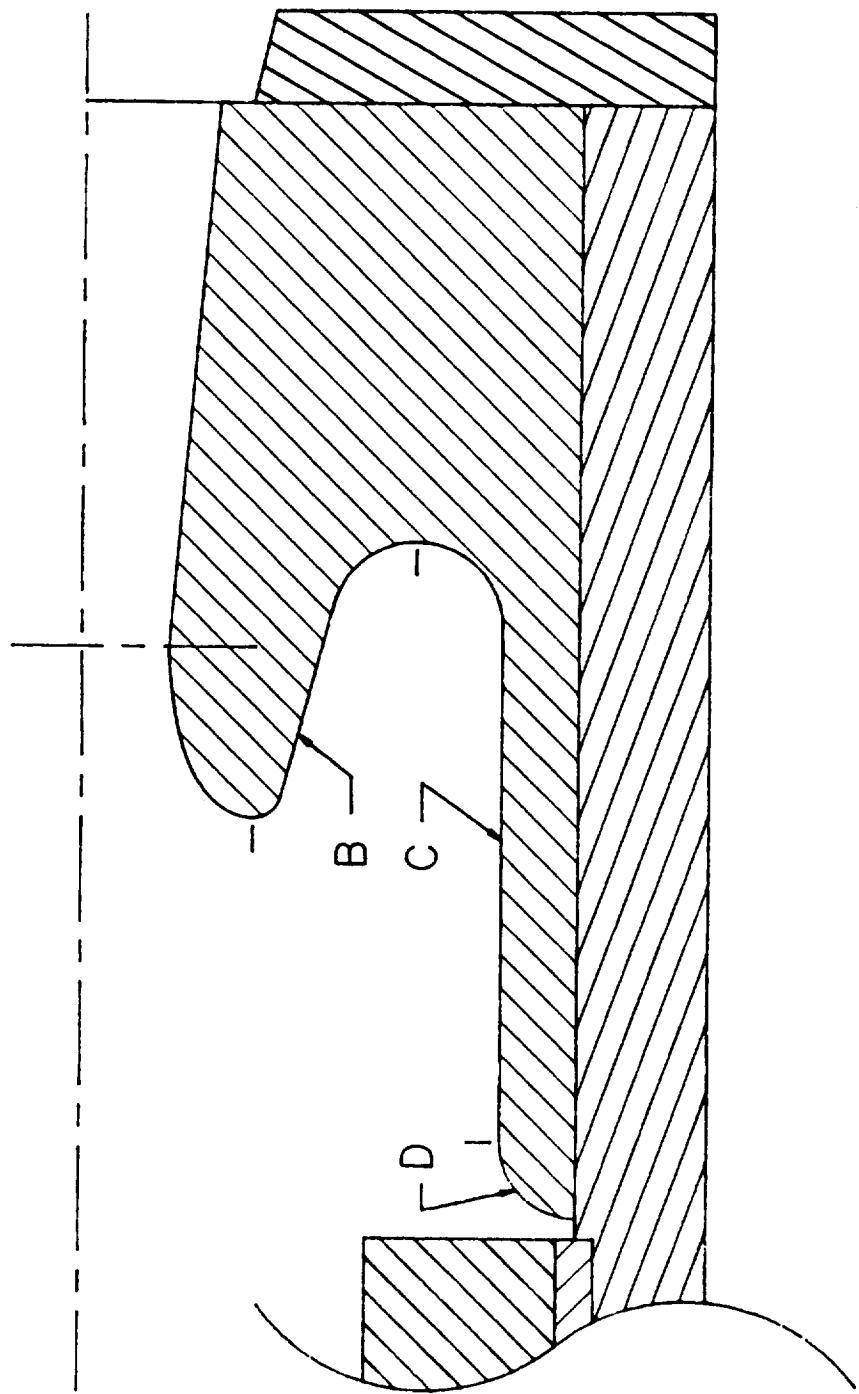
FIVE INCH SPIN MOTOR NOZZLE

SLAG SUBZONES

B1

B2

B3

B4

B5

B6

D
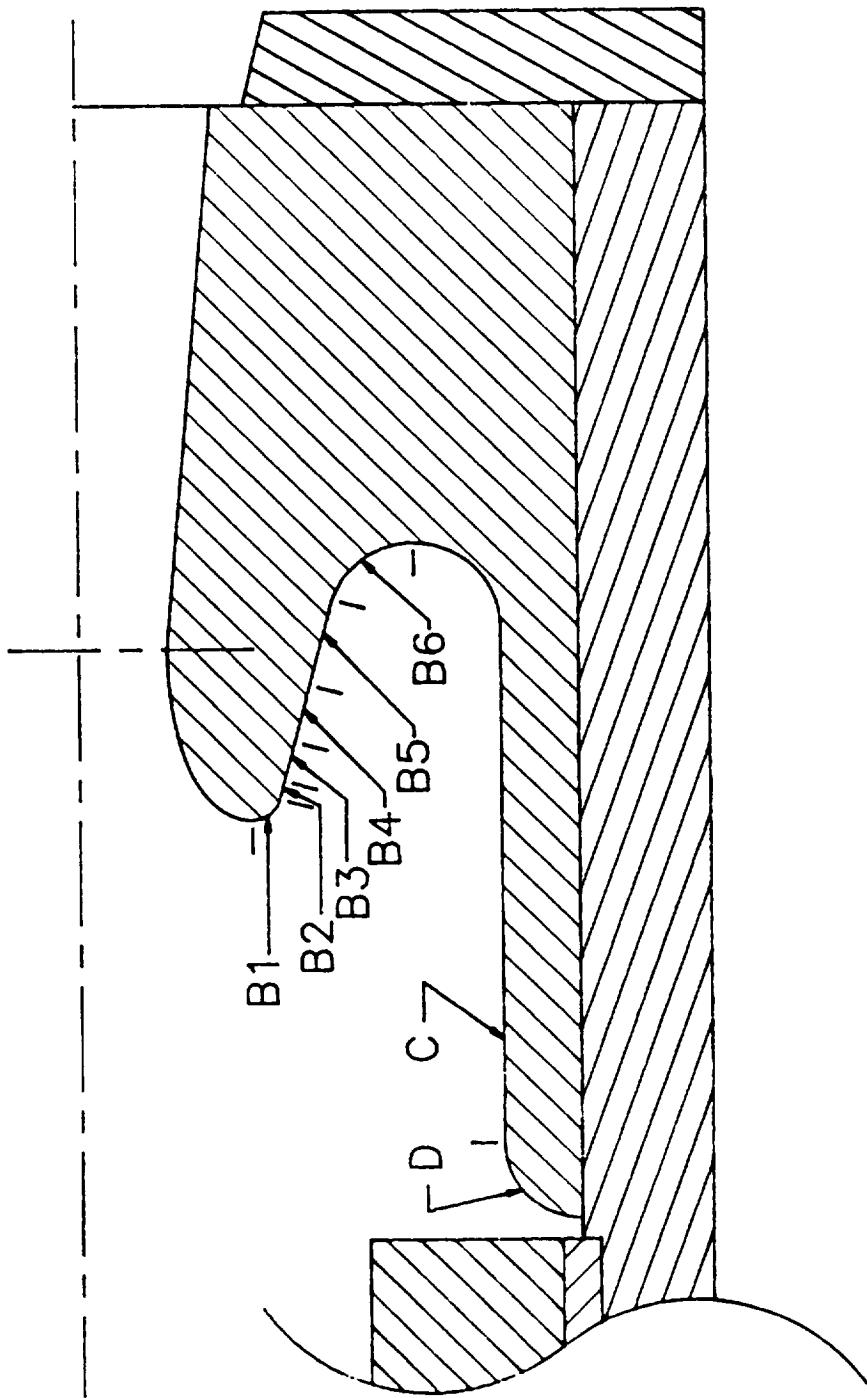
C
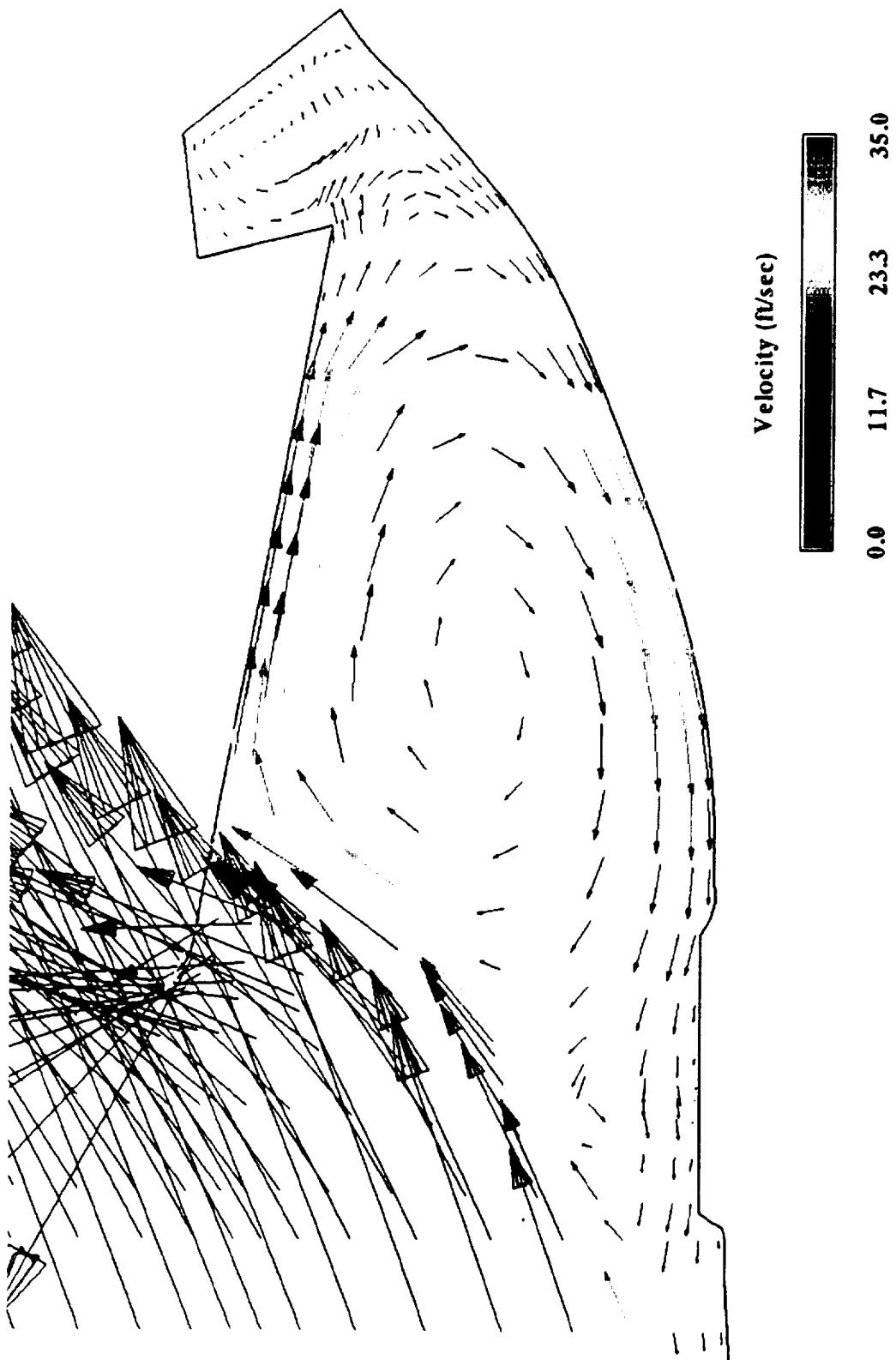
Velocity Vectors, Submerged Nozzle RSRM 80 Second Stiff NBR Inhibitor

Velocity (ft/sec)

0.0   11.7   23.3   35.0

1253
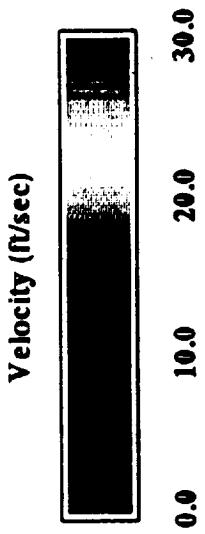
Velocity Vectors, Submerged Nozzle Spin Motor at 50% Web Time

Velocity (ft/sec)

0.0   10.0   20.0   30.0

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

Effect of Spin Rate on Nozzle Slag Accumulation
WECCO AP, Surface Combustion, 400RPM

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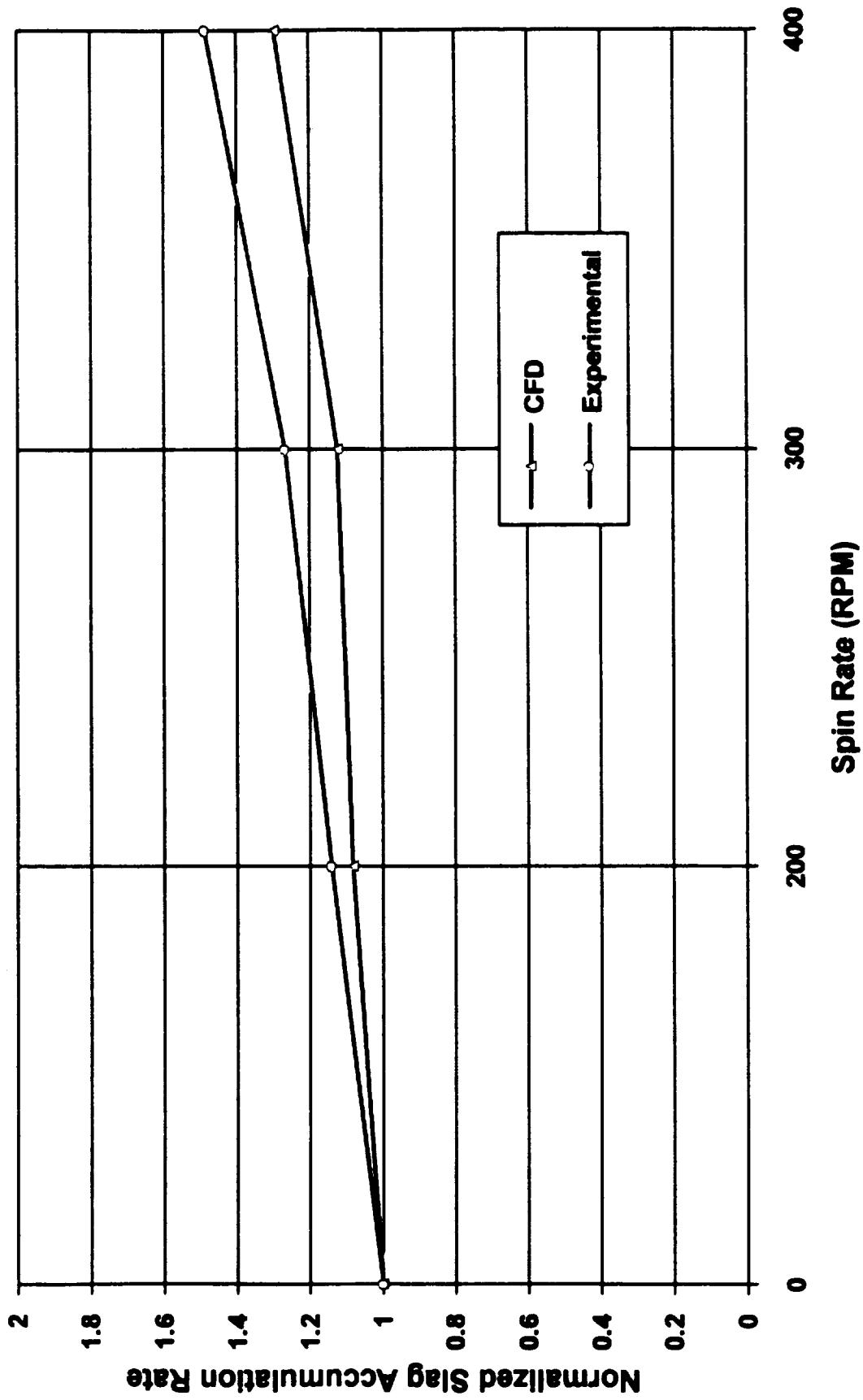
Computational Grid Resolution

Location	15% Web	50% Web	85% Web
Port	50X50	50X65	50X65
Nozzle Closure	105X85	110X95	115X80
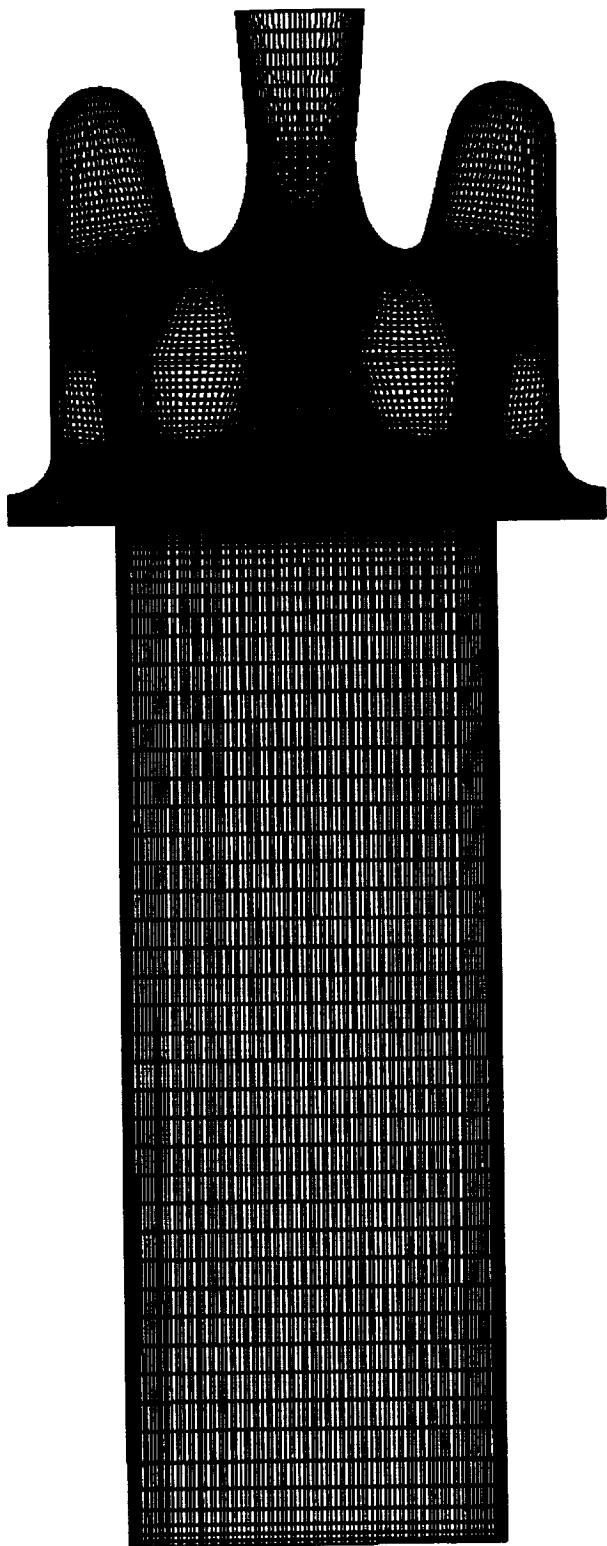
Computational Grid
Spin Motor At 15 % Web Time
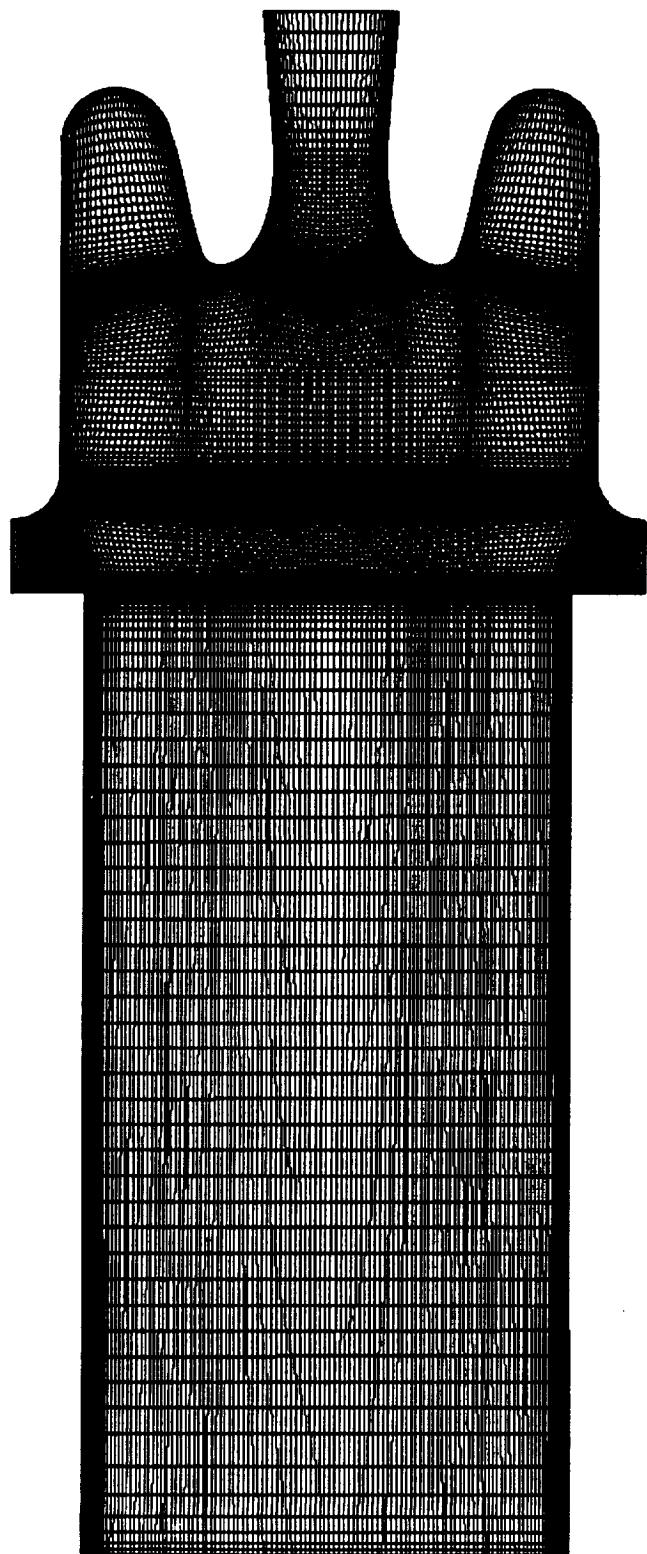
Computational Grid
Spin Motor At 50 % Web Time
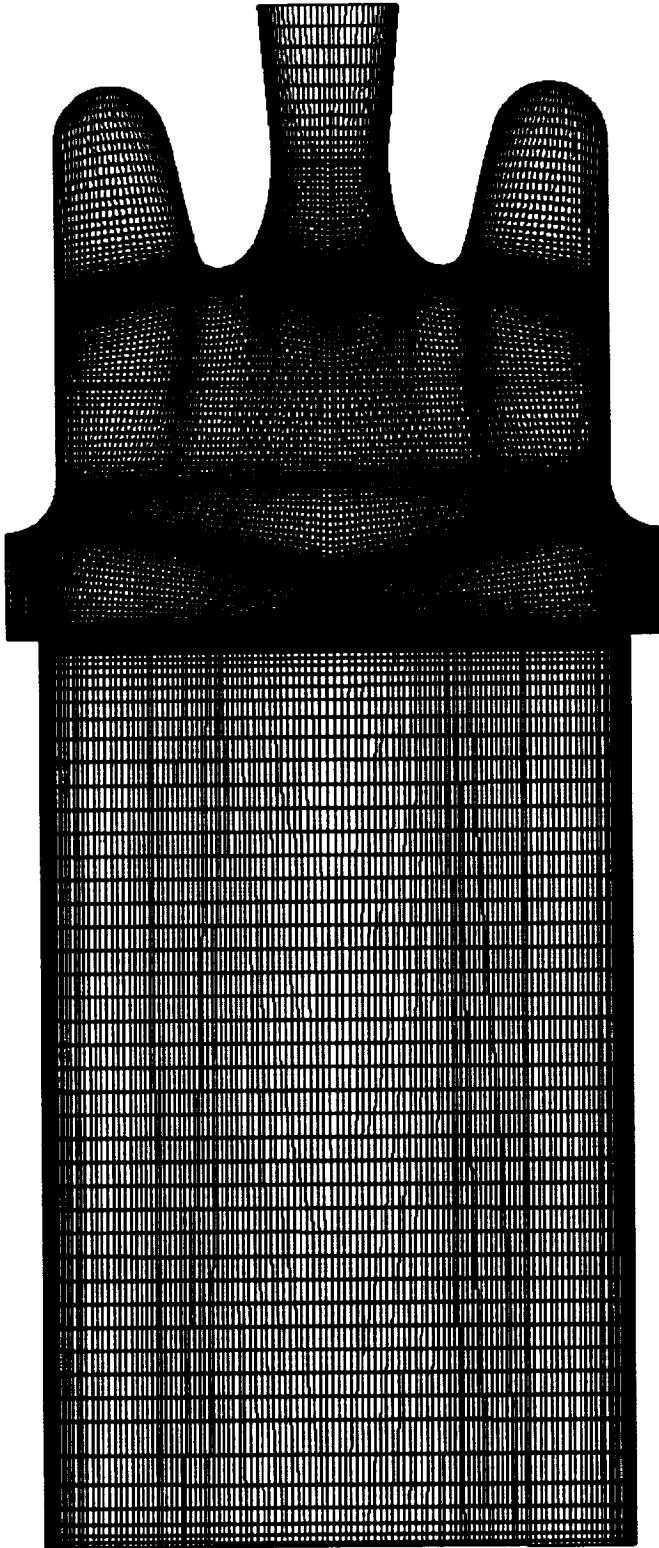
Computational Grid
Spin Motor At 85 % Web Time

RSRM Propellant Thermochemical and Nominal Particle Properties

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
Particle Distribution	Polynomial Fit to Wecco Quench Bomb Data
Particle Density	60lbm/ft^3
Ratio of Initial Particle/Gas Velocity	1.0
Aluminum Oxide Caps Fraction (Discrete Phase)	28.33%

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Spin Motor Operation Conditions

Parameter	15% Web	50% Web	85% Web
Chamber Pressure:	610.6 psia	628.8 psia	610.6 psia
Mass Flow Rate:	2.613 lbm/s	2.691 lbm/s	2.613 lbm/s
Propellant Burning Area:	115.47 in^2	114.67 in^2	112.35 in^2
Throat Diameter:	.916 inches		
Burn Time:	2.71 seconds		

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Experimental Data and Curve Fit Distribution Functions
WECCO Quench Bomb Data- 500 psi
3-inch Quench Distance

Legend:

○ WECCO Data

— Polynomial Distribution, Dm=113μm

—·— Log-Normal Distribution, Dm=96μm, σ=0.30

— — Log-Normal Distribution, Dm=80μm, σ=0.42

X-axis: Particle Diameter (microns)

Y-axis: Cumulative Mass Fraction

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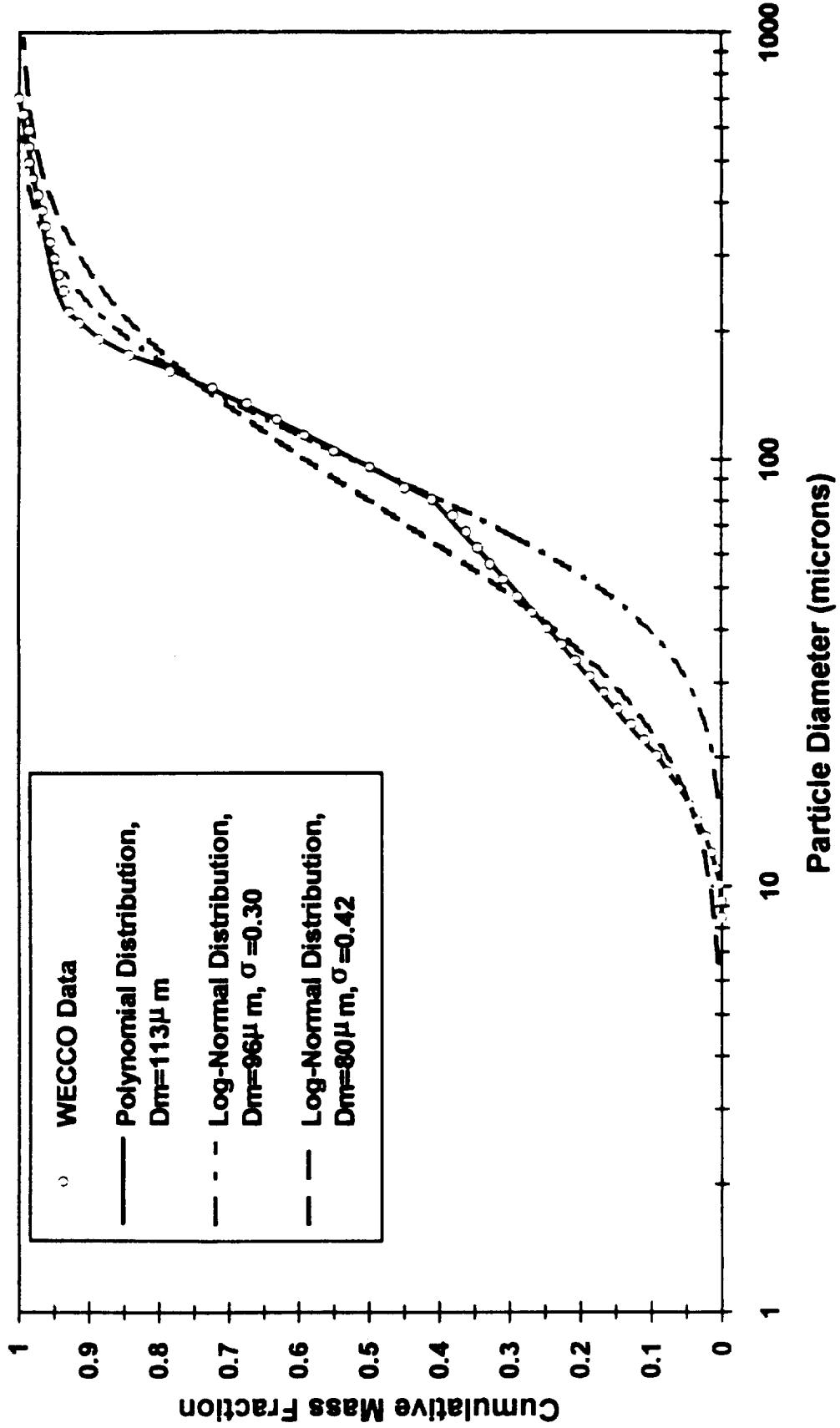
Experimental Data and Curve Fit Density Functions
WECCO Quench Bomb Data- 500 psi
3-inch Quench Distance

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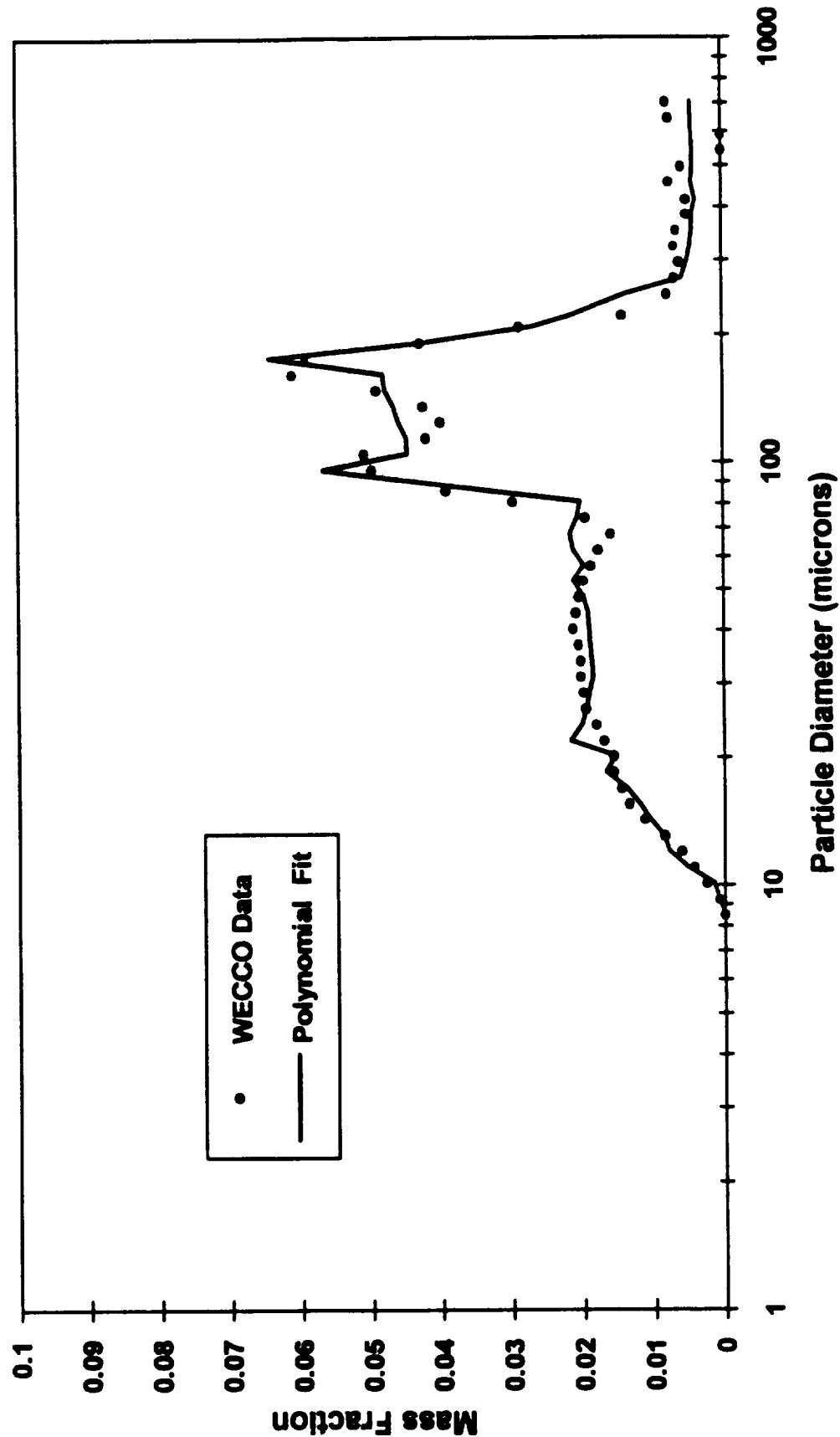
Experimental Data and Curve Fit Distribution Functions
## Kerr McGee Quench Bomb Data- 500 psi
3-inch Quench Distance

Legend:
- ○ Kerr McGee Data
- —— Polynomial Distribution, Dm=140 μ m
- – – – Log-Normal Distribution, Dm=90 μ m, σ =0.38

X-axis: Particle Diameter (microns)

Y-axis: Cumulative Mass Fraction

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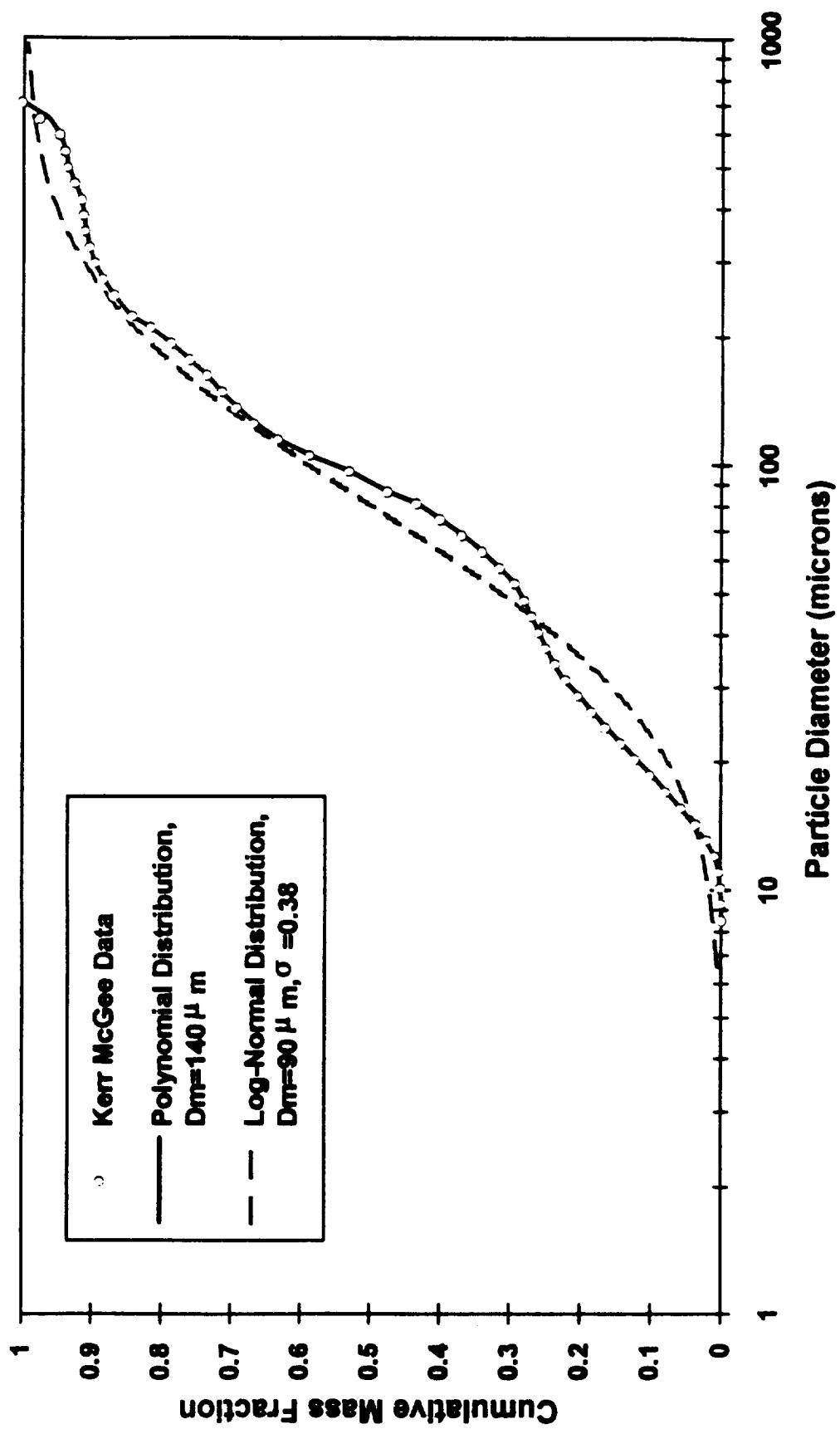
Experimental Data and Curve Fit Density Functions
Kerr McGee Quench Bomb Data- 500 psi
3-inch Quench Distance

ERC, Inc.
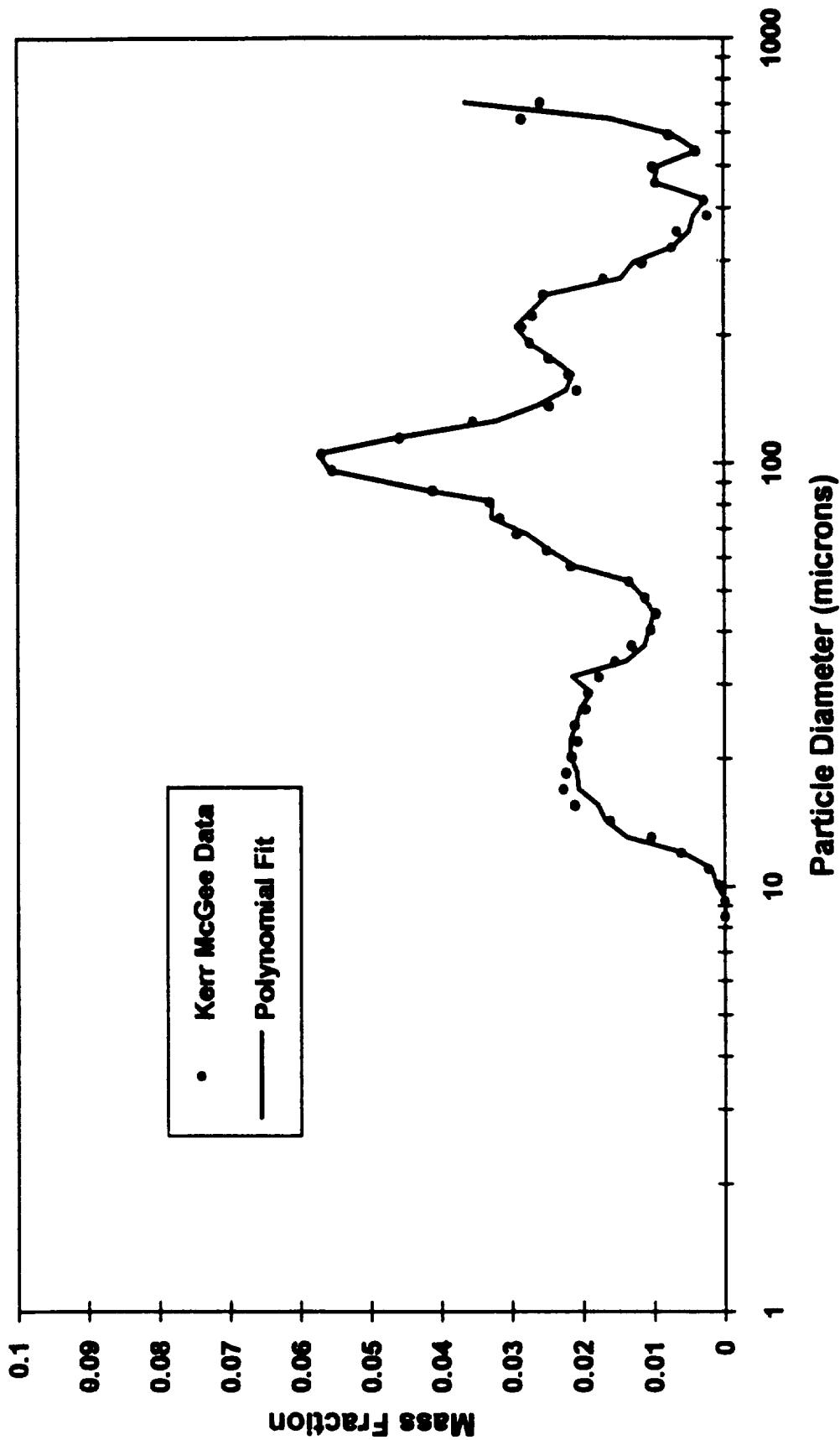
Effect of Particle Size Distribution on Slag Accumulation WECCO AP, Surface Combustion, 400 rpm

Percent Motor Web Time

Slag Accumulation (Grams)

Initial Particle/Gas Velocity Ratio = 0.85

Legend:
- Polynomial
- Log-Normal, Dm = 96 microns
- Log-Normal, Dm = 80 microns
- Experimental

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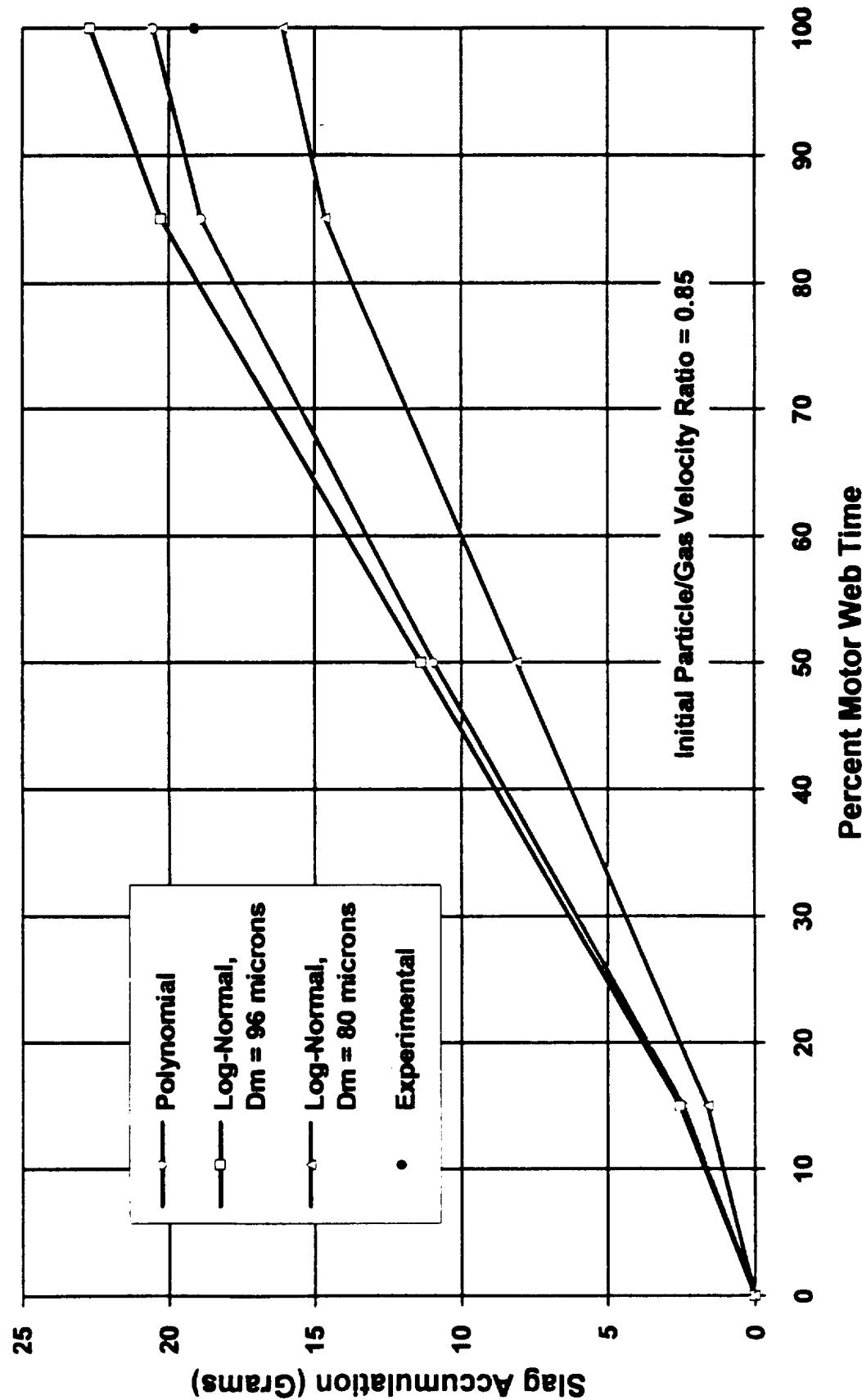
Nozzle Slag Accumulation
WECCO and Kerr McGee AP
Surface Combustion, 400 RPM

Slag Accumulation (grams)

Percent Motor Web Time

Legend:
— WECCO AP, Dm=113 µm
— Kerr McGee AP, Dm=140 µm

Velocity (ft/sec)

Velocity Magnitude
Spin Motor at 15% Web Time

Velocity (ft/sec)

Velocity Magnitude
Spin Motor at 50% Web Time

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Velocity Magnitude
Spin Motor at 85% Web Time

Velocity (ft/sec)

0.0   20.0   40.0   60.0   80.0   100.0

Velocity Field In The Submerged Nozzle Region

**Spin Motor At 15 % Web Time**
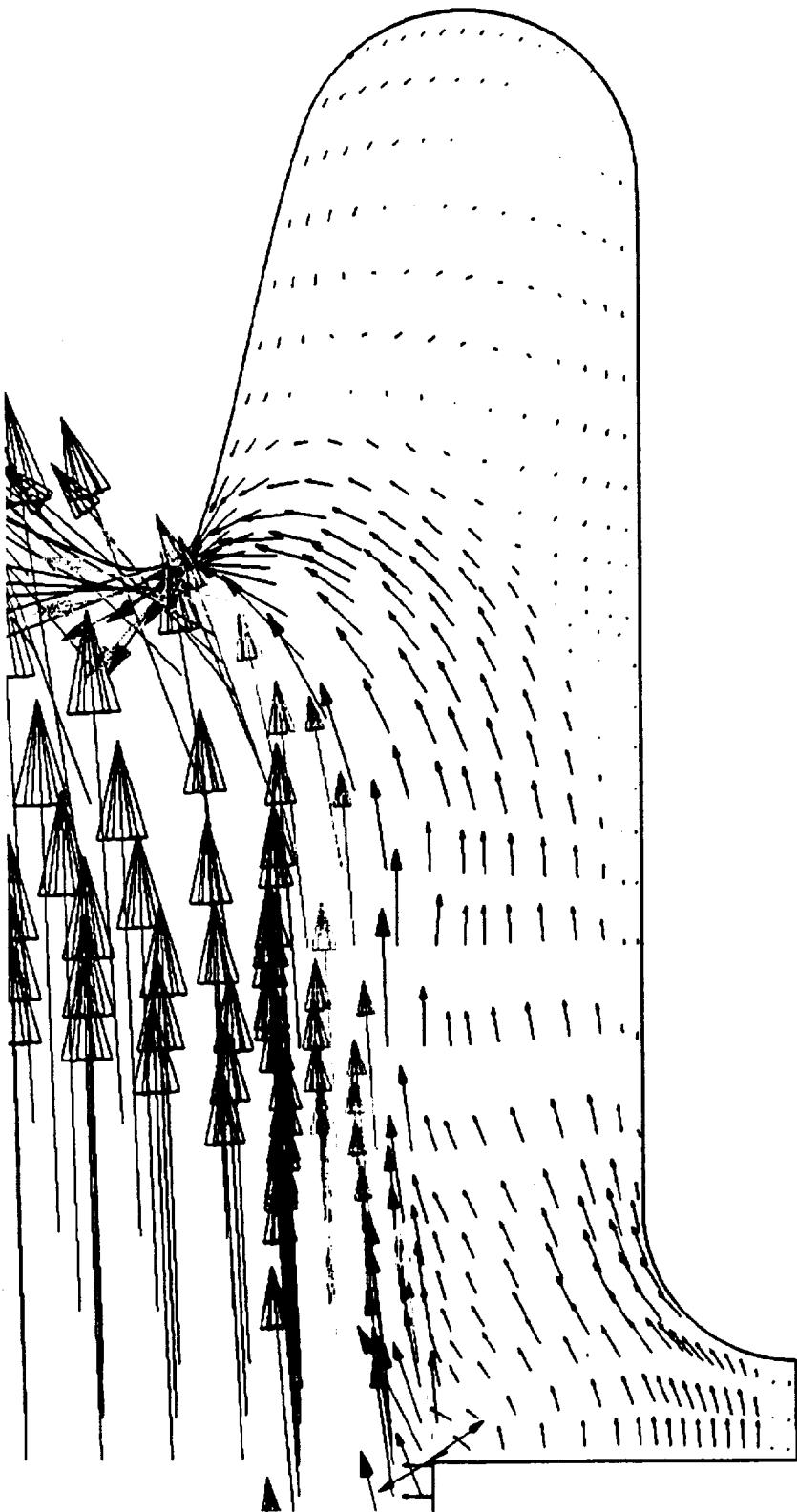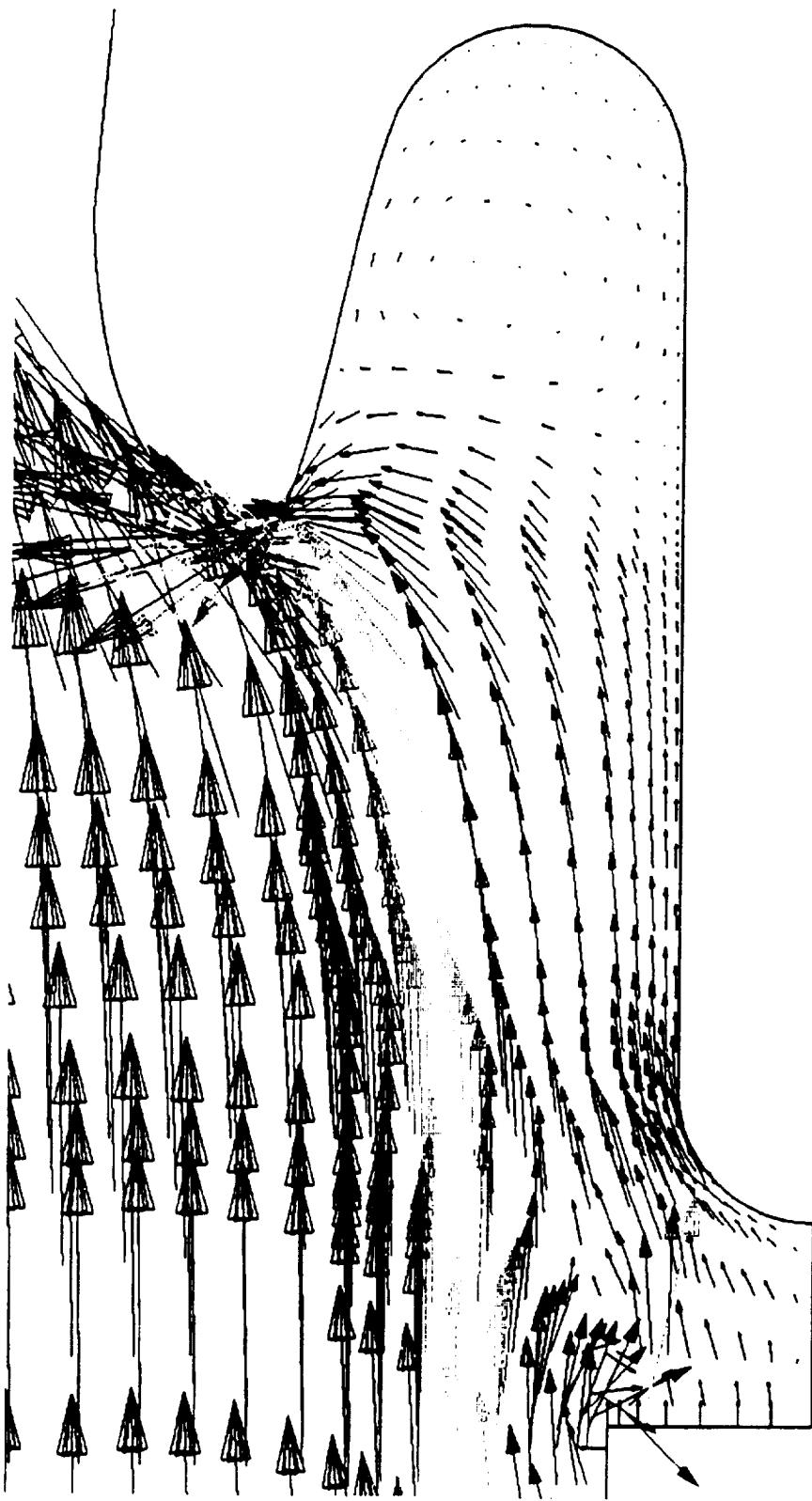
Velocity Field In The Submerged Nozzle Region

**Spin Motor At 50 % Web Time**

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**Velocity Field In The Submerged Nozzle Region
Spin Motor At 85 % Web Time**
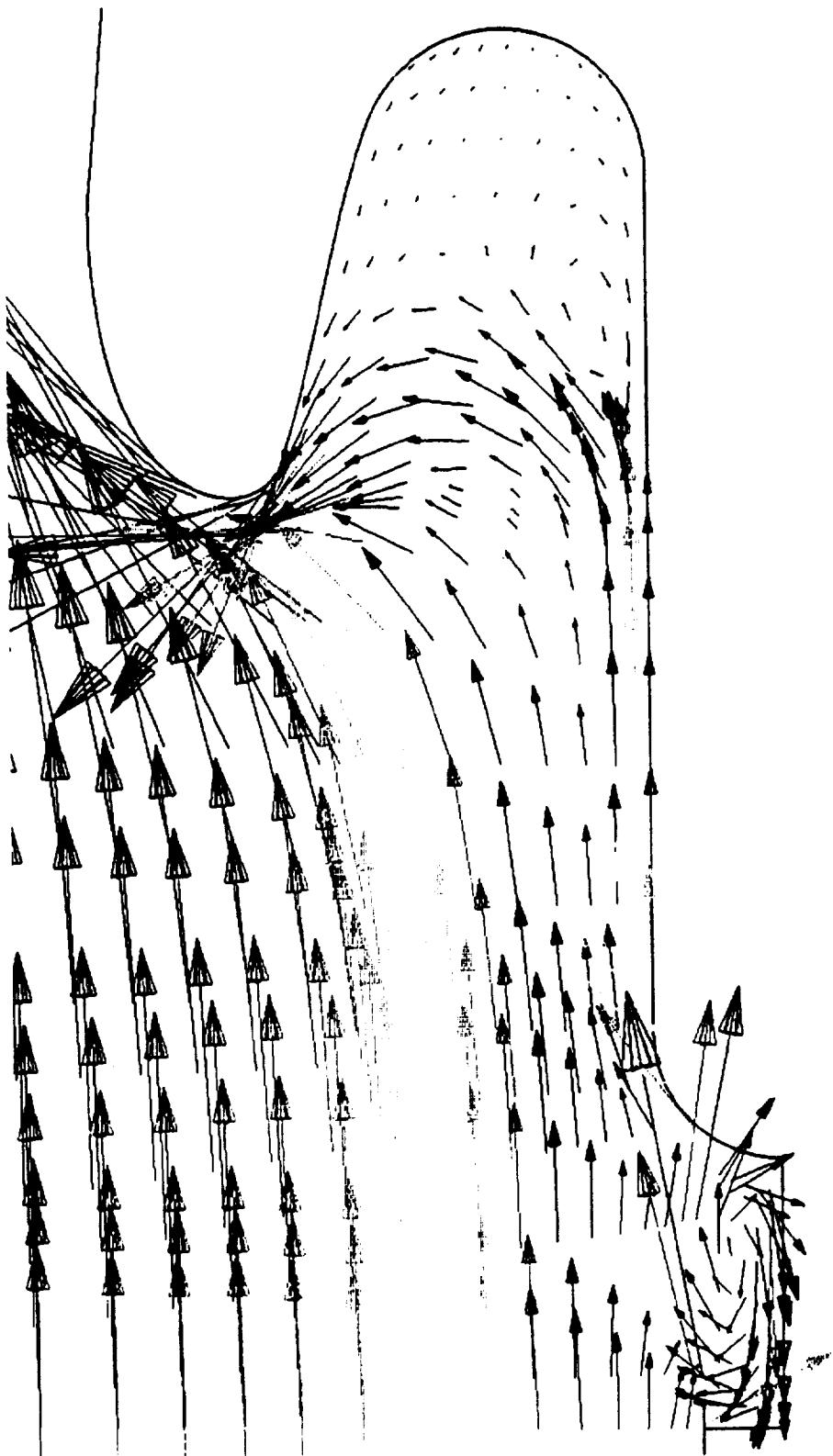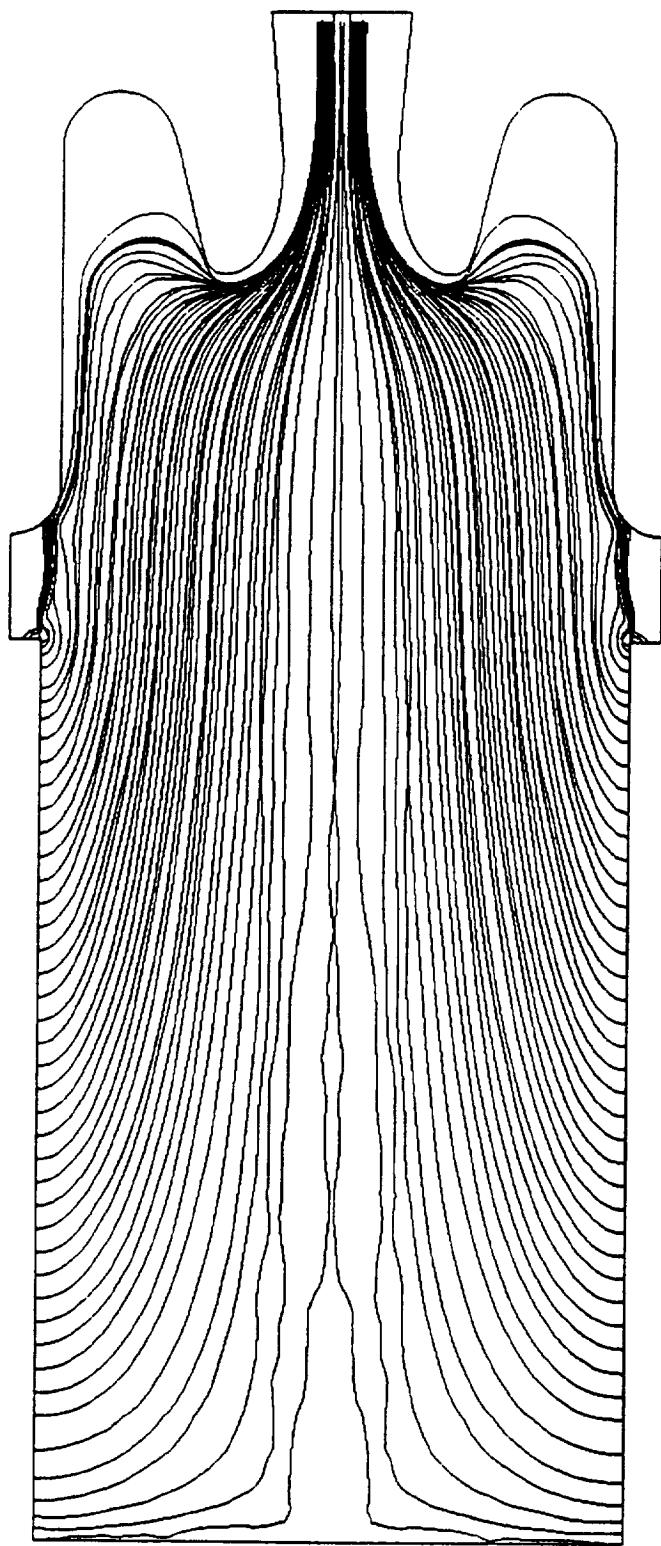
**20 Micron Diameter Particle Trajectories Spin Motor At 85 % Web Time**
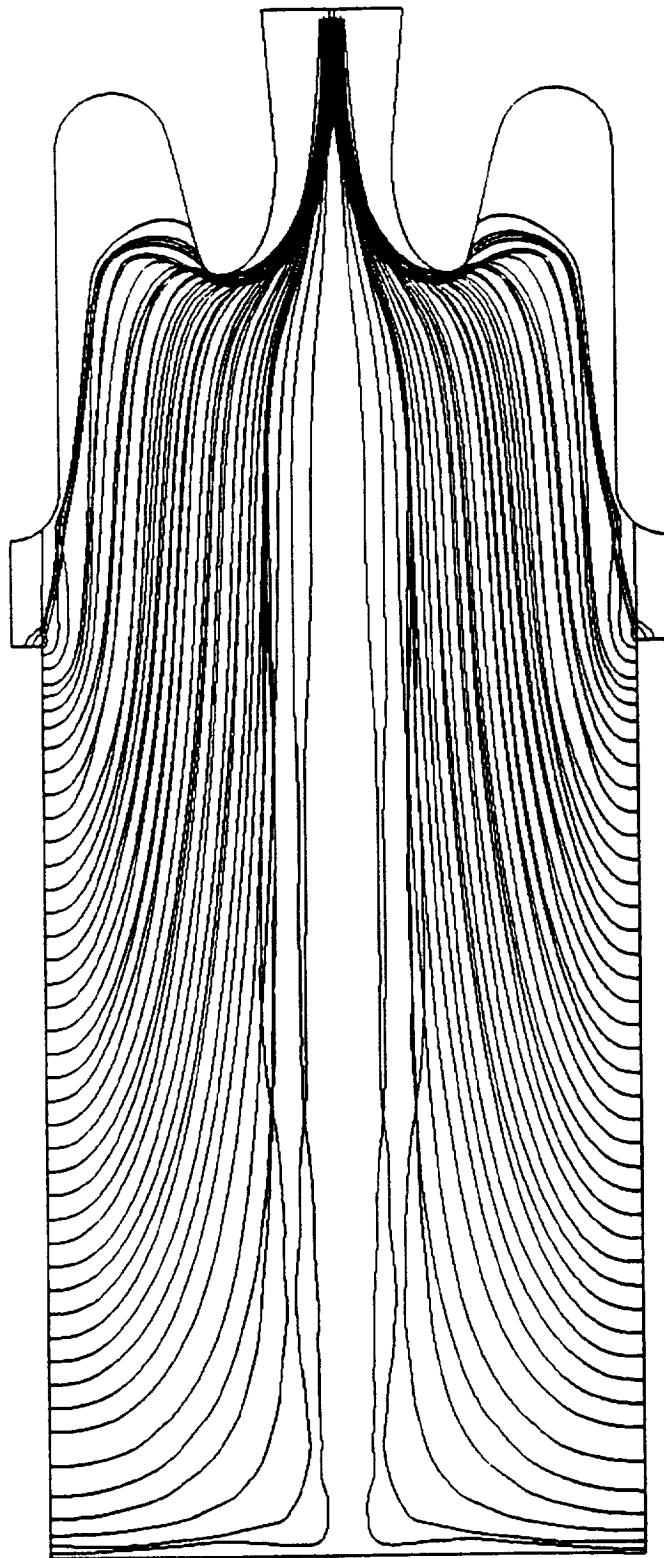
50 Micron Diameter Particle Trajectories Spin Motor At 85 % Web Time
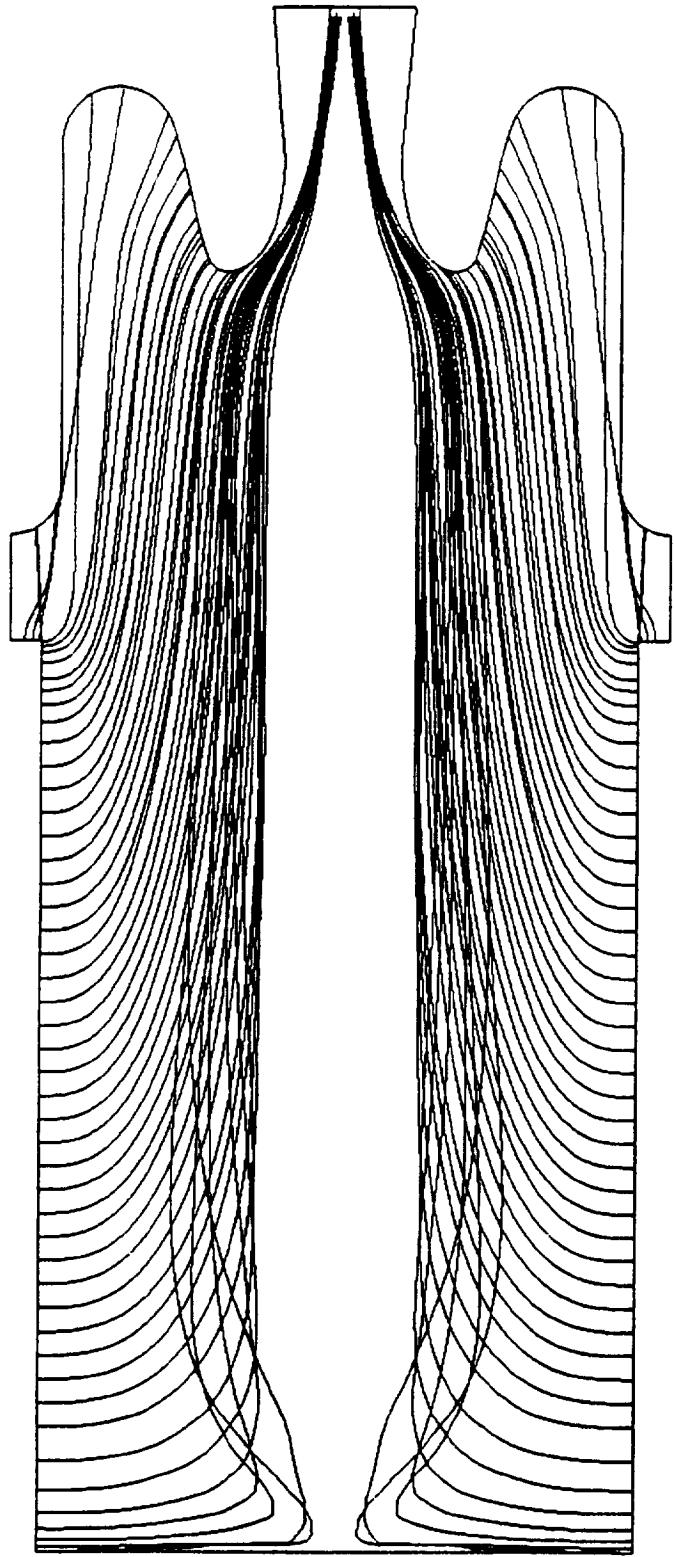
150 Micron Diameter Particle Trajectories Spin Motor At 85 % Web Time

Spin Motor Circumferential Velocity
WECCO, Surface Combustion, 400 RPM
15% Web Time

Legend:
- —— Axial Station Near Head End
- —□— Axial Station Near Aft End Grain
- —▽— Axial Station In Nozzle Entrance

Circumferential Velocity (feet/second)

Radius (Inches)

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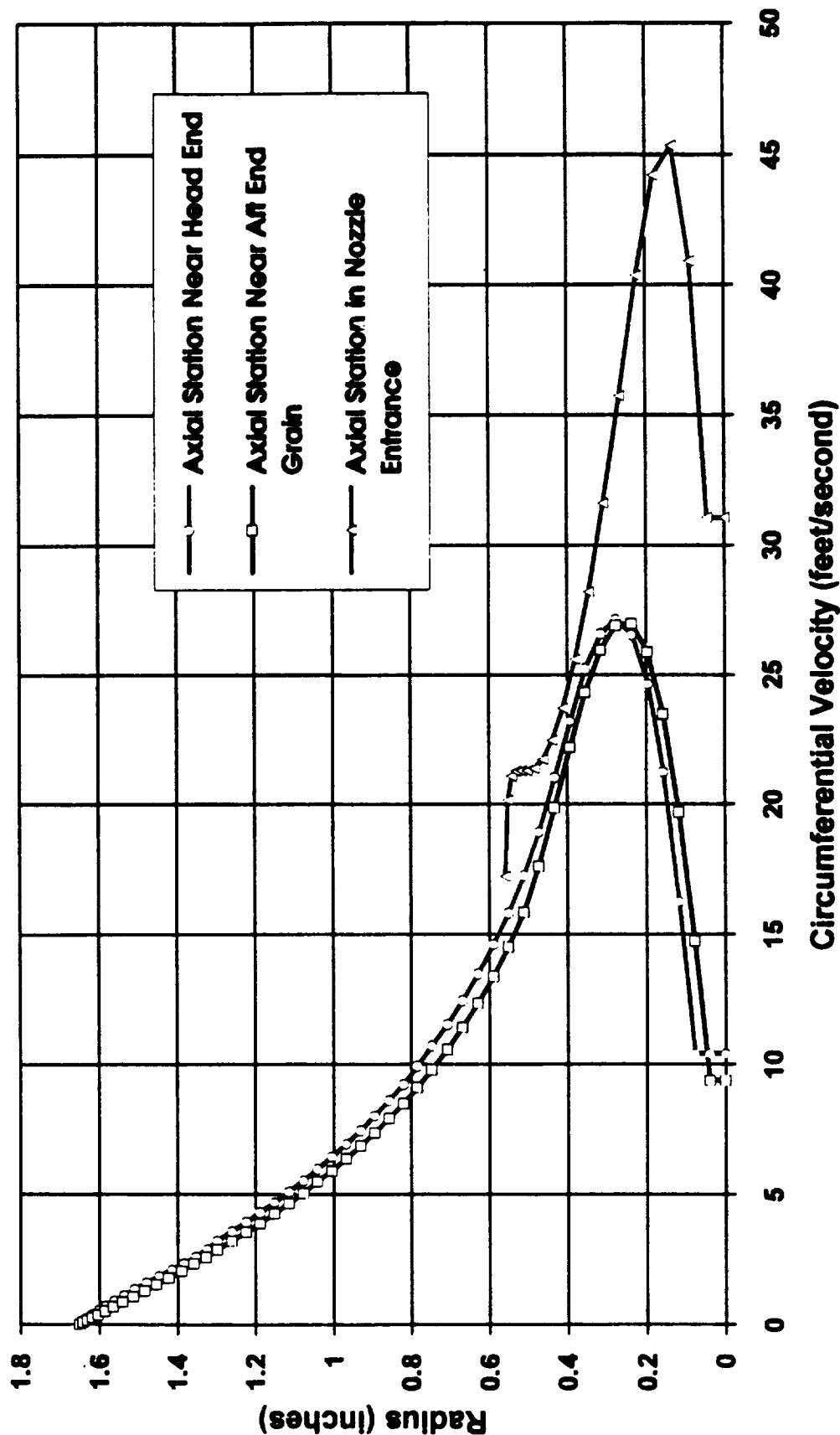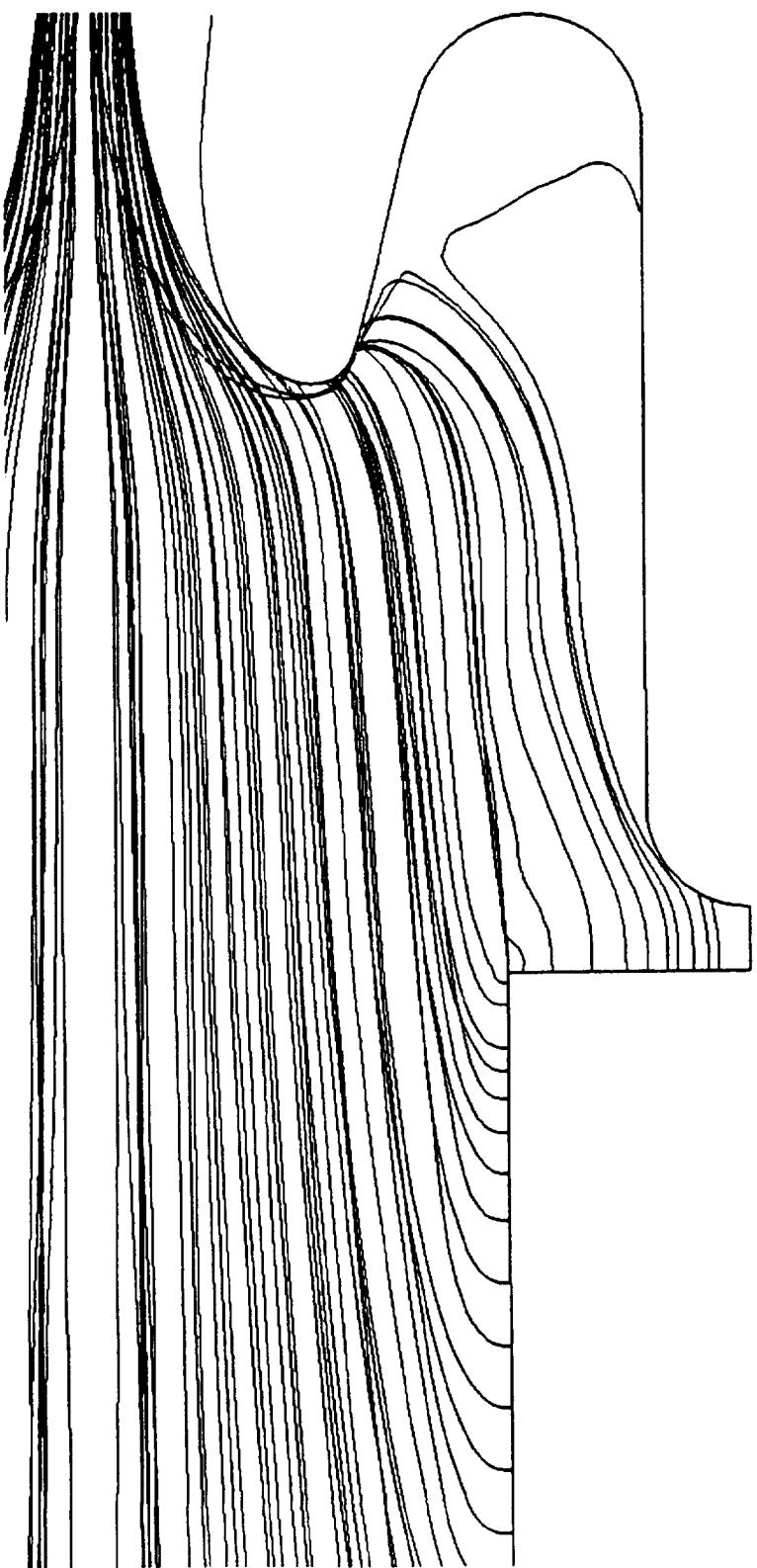
**50 Micron Diameter Particle Trajectories
Spin Motor At 15 % Web Time**

**50 Micron Diameter Particle Trajectories
Spin Motor At 50 % Web Time**

50 Micron Diameter Particle Trajectories

Spin Motor At 85 % Web Time

Nozzle Slag Accumulation Rate
## WECCO AP, Surface Combustion, 400 rpm

Legend:
- B, Analysis
- C, Analysis
- D, Analysis
- B+C+D, Analysis

X-axis: Percent Motor Web Time

Y-axis: Slag Accumulation Rate (grams/second)

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Nozzle Slag Accumulation
WECCO AP, Surface Combustion, 400 rpm

Legend:
- B, Analysis
- C, Analysis
- D, Analysis
- B+C+D, Analysis
- B, Experimental
- C, Experimental
- D, Experimental
- B+C+D, Experimental

Y-axis: Slag Accumulation (Grams)

X-axis: Percent Motor Web Time
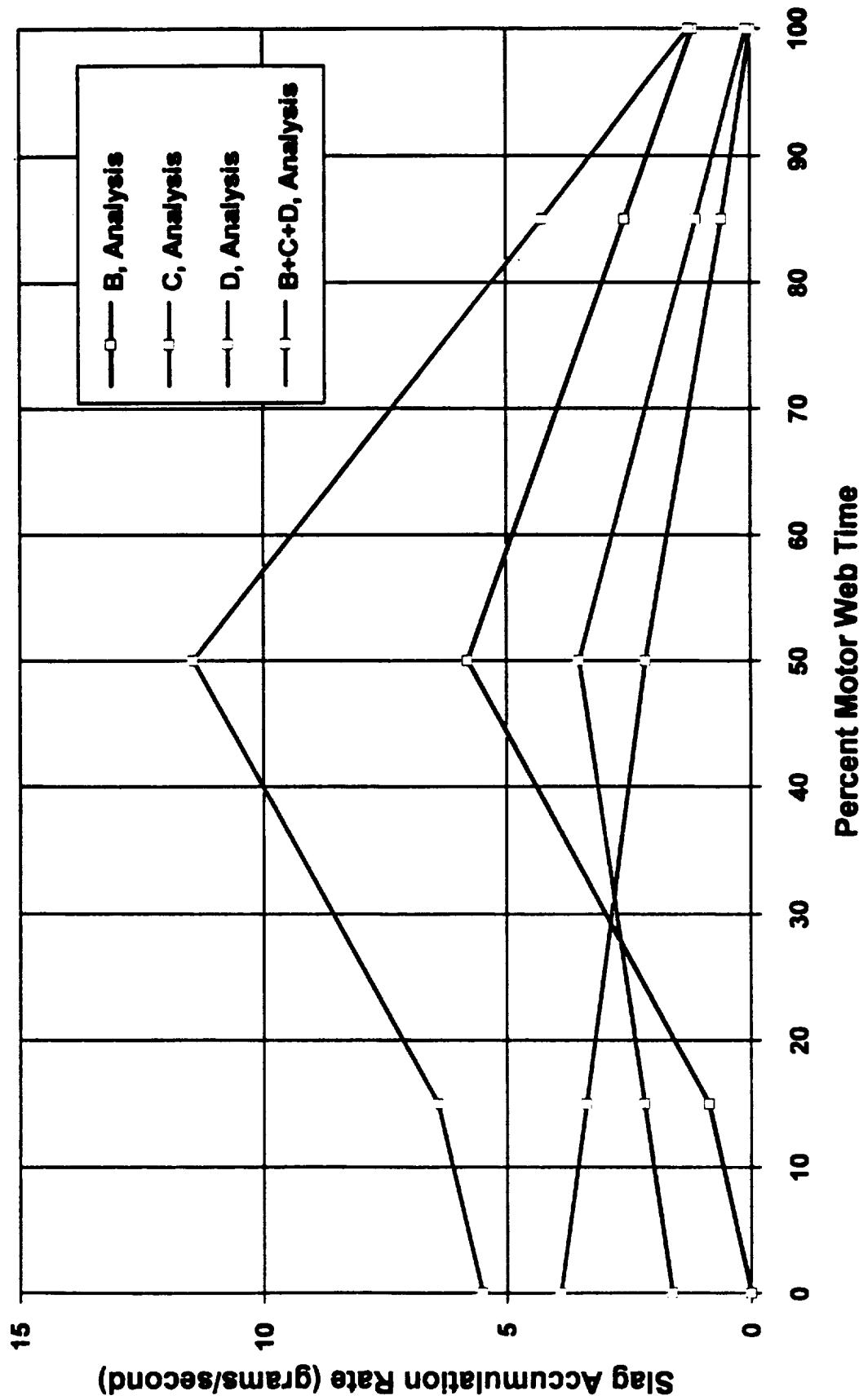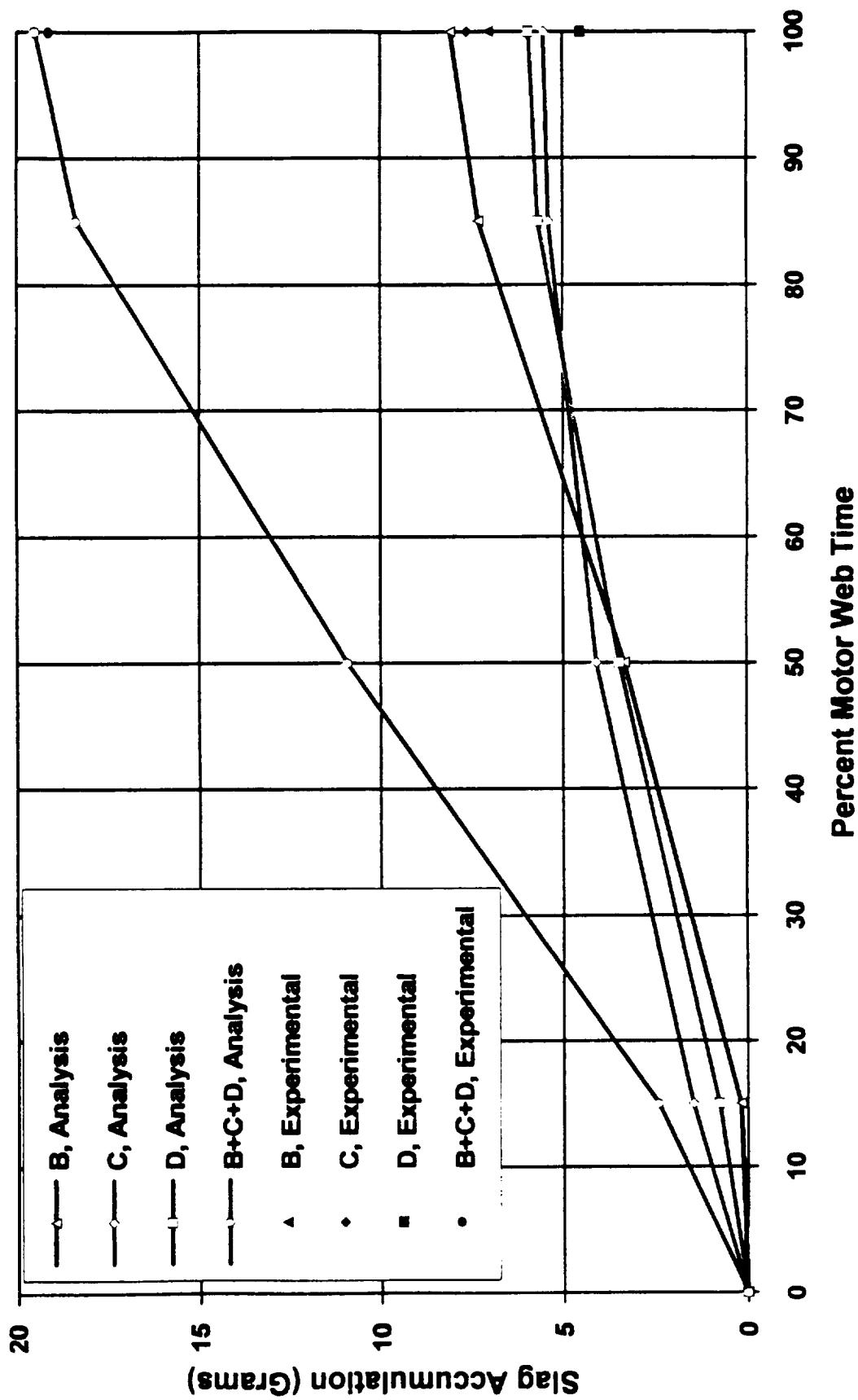
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FIVE INCH SPIN MOTOR SLAG DEPOSITS
CFD and Experimental

Slag Thickness — 4x
CFD
Experimental
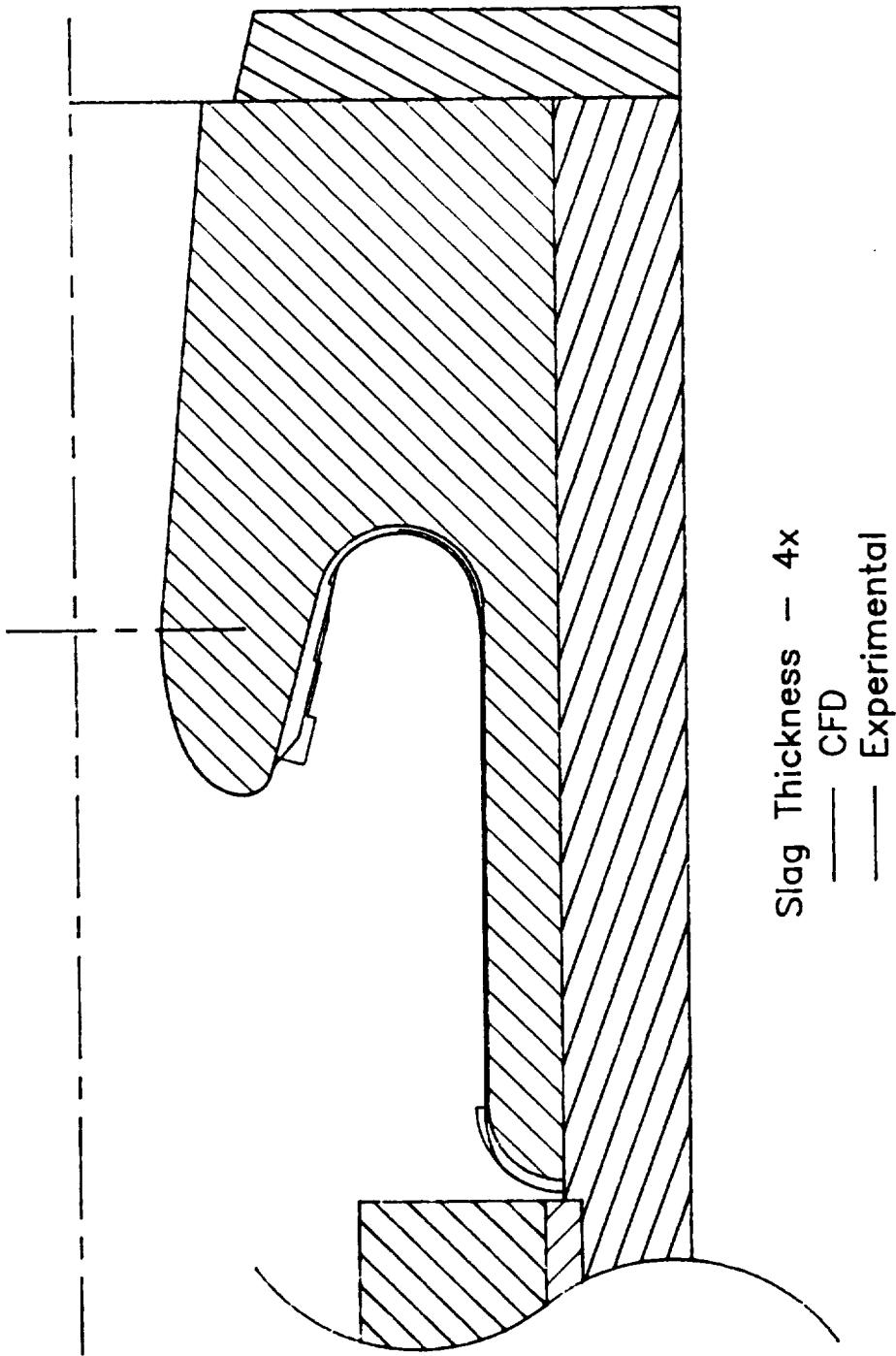
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Slag Accumulation Per Unit Area Along The Nozzle
WECCO AP, Surface Combustion, 400 rpm

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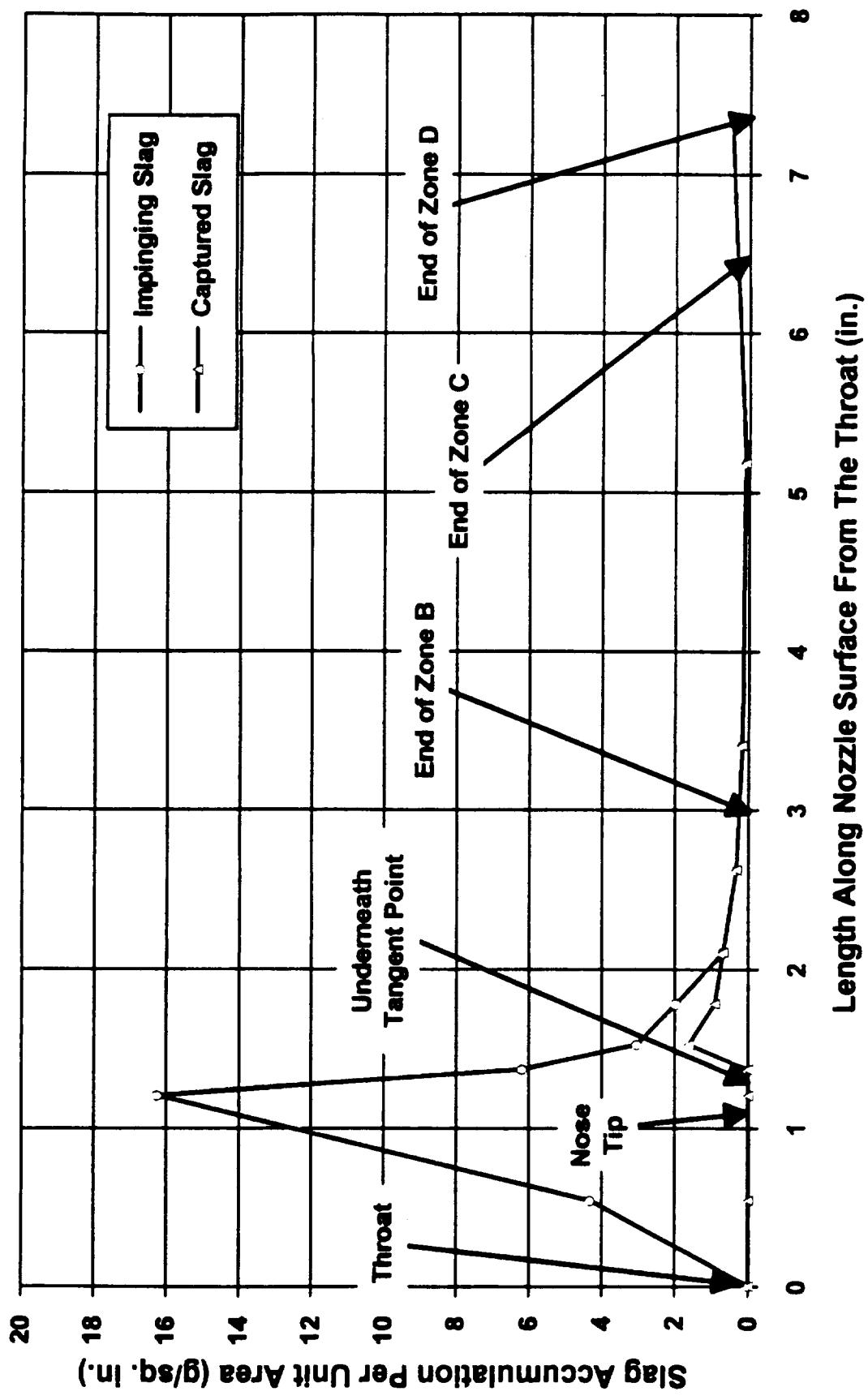
NOZZLE NOSE SLAG DEPOSITS

CFD

Experimental
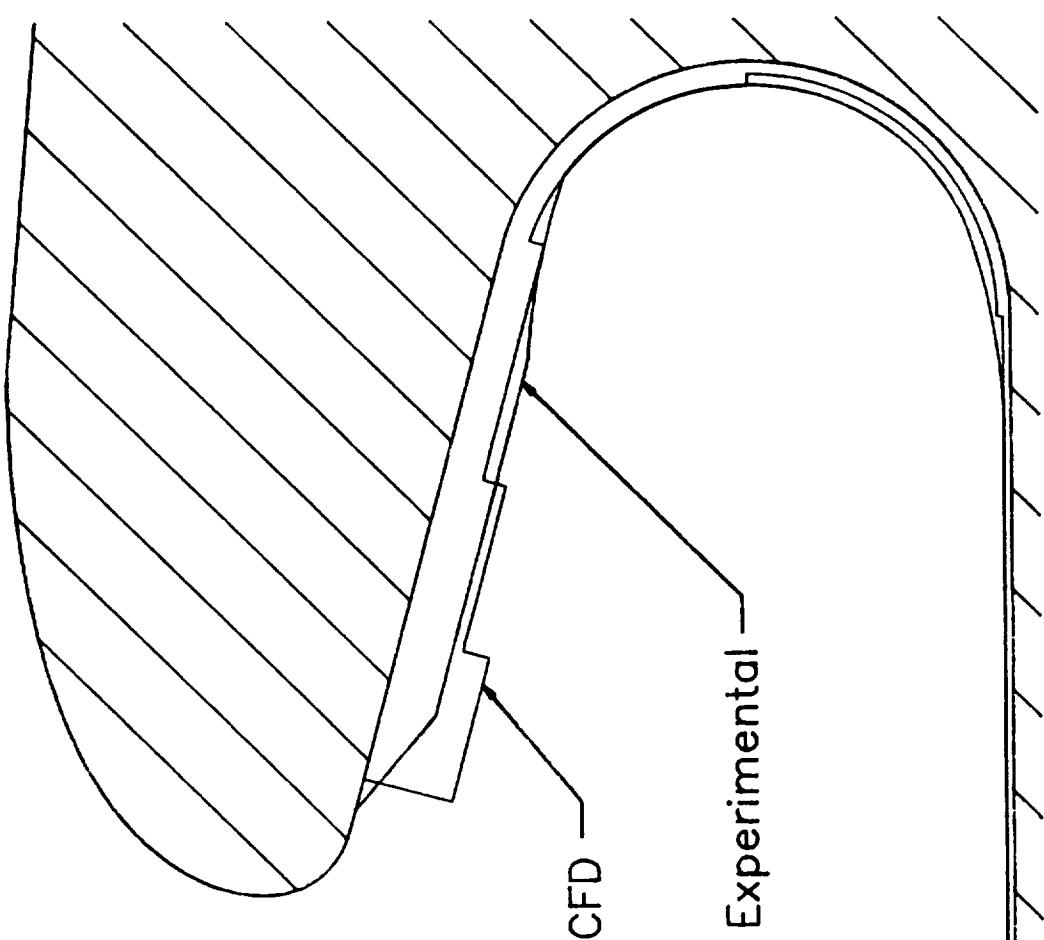
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NOZZLE FORWARD LIP SLAG DEPOSITS

Experimental

CFD
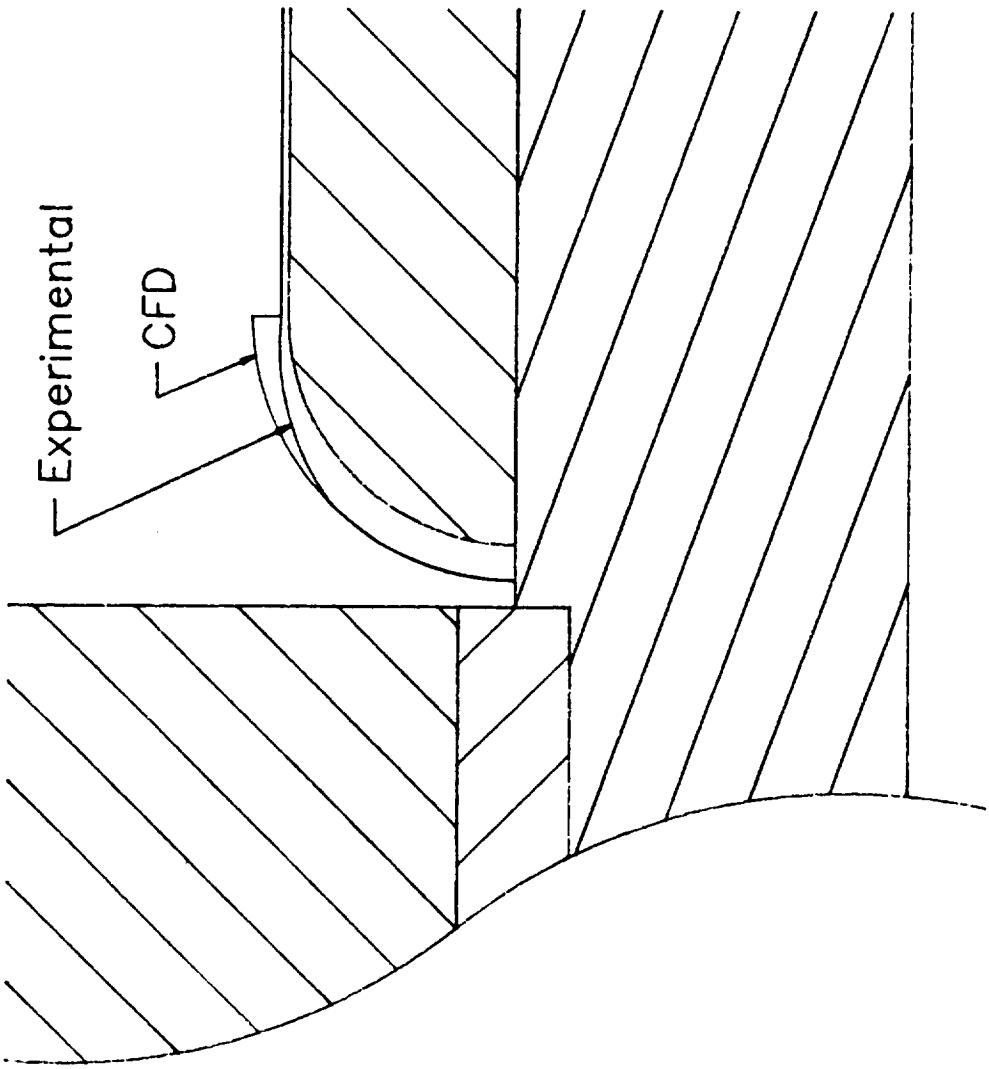
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Effect of Initial Particle Velocity on Slag Accumulation
WECCO AP, Surface Combustion, 400 rpm

Initial Particle/Gas Velocity Ratio

- 0.75
- 0.85
- 1.00
- Experimental Data

X-axis: **Percent Motor Web Time**

Y-axis: **Slag Accumulation (Grams)**

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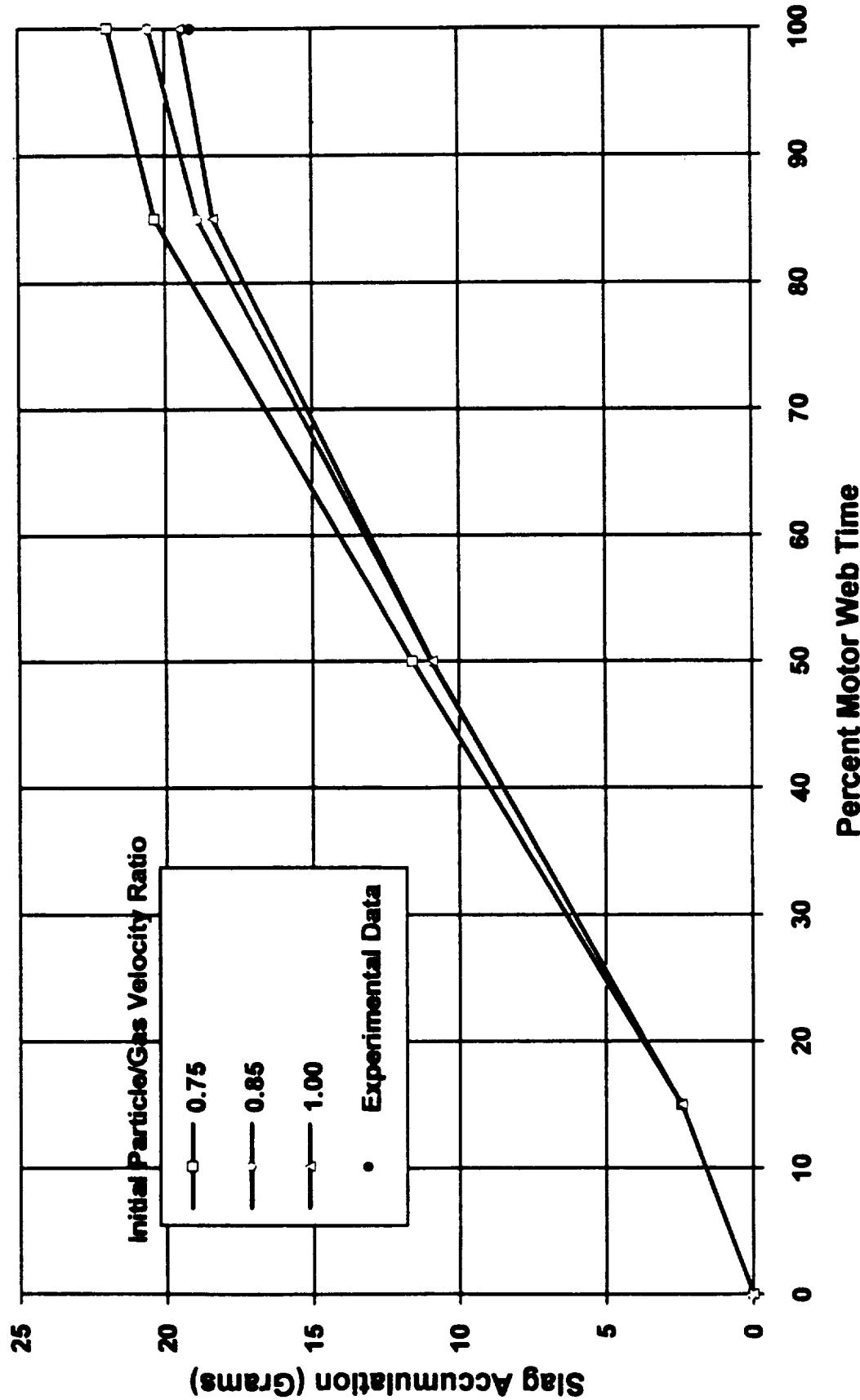
Effect of Particle Density on Slag Impingement Rates
WECCO AP, Surface Combustion, 400 RPM
85% Web Time

Legend:
- Density=100 lbm/cu.ft
- Density=60 lbm/cu.ft

Zone B: 24.03, 19.163
Zone C: 1.023, 3.59
Zone D: 3.207, 3.164
Zones B+C+D: 28.08, 25.92

X-axis: Nozzle Slag Zones

Y-axis: Slag Impingement Rate (grams/second), scale 0 to 50

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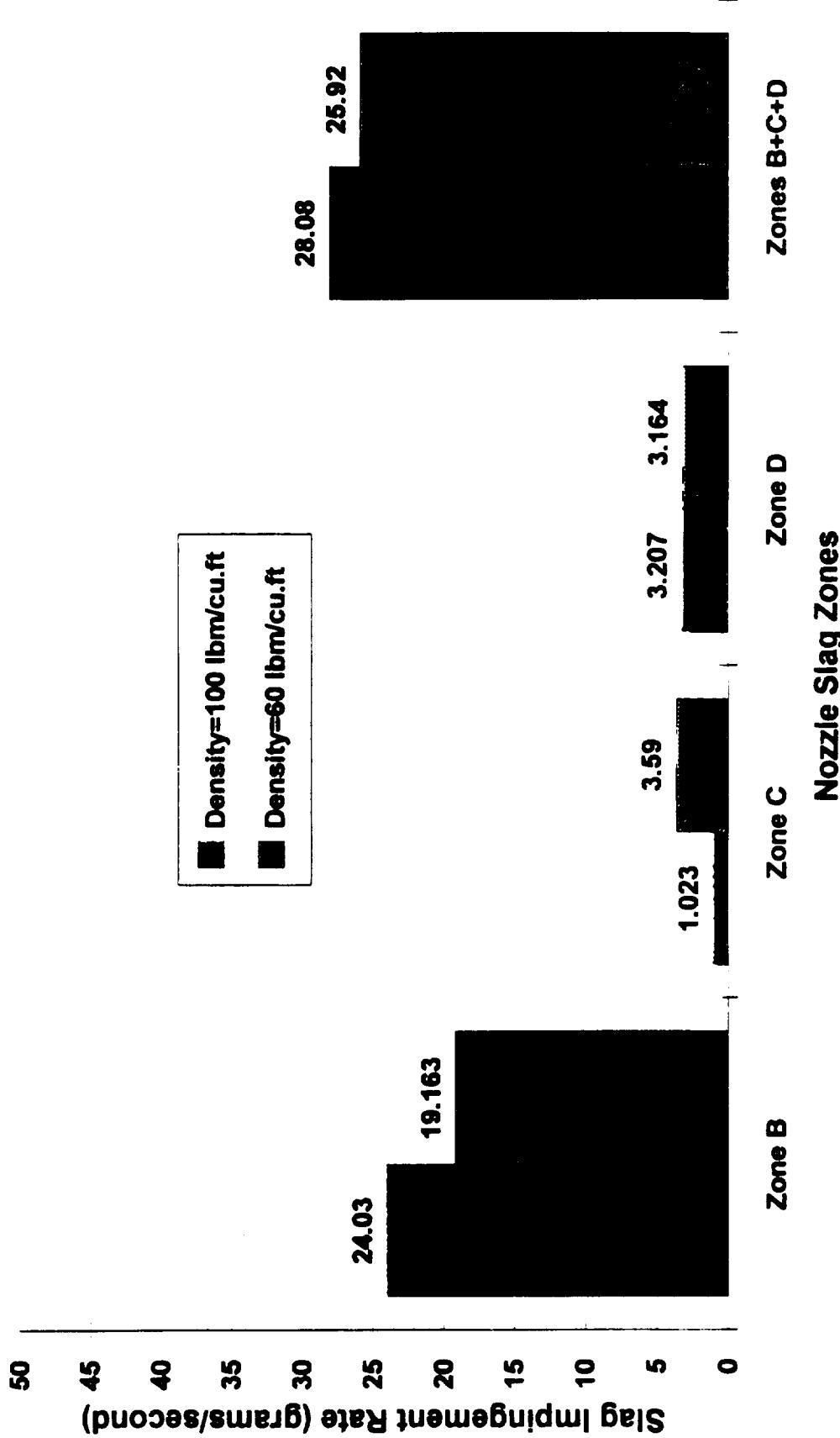
Nozzle Slag Accumulation
WECCO AP, Distributed Combustion, 400 rpm

Legend:
- B, Analysis
- C, Analysis
- D, Analysis
- B+C+D, Analysis
- B, Experimental
- C, Experimental
- D, Experimental
- B+C+D, Experimental

X-axis: Percent Motor Web Time

Y-axis: Slag Accumulation (Grams)

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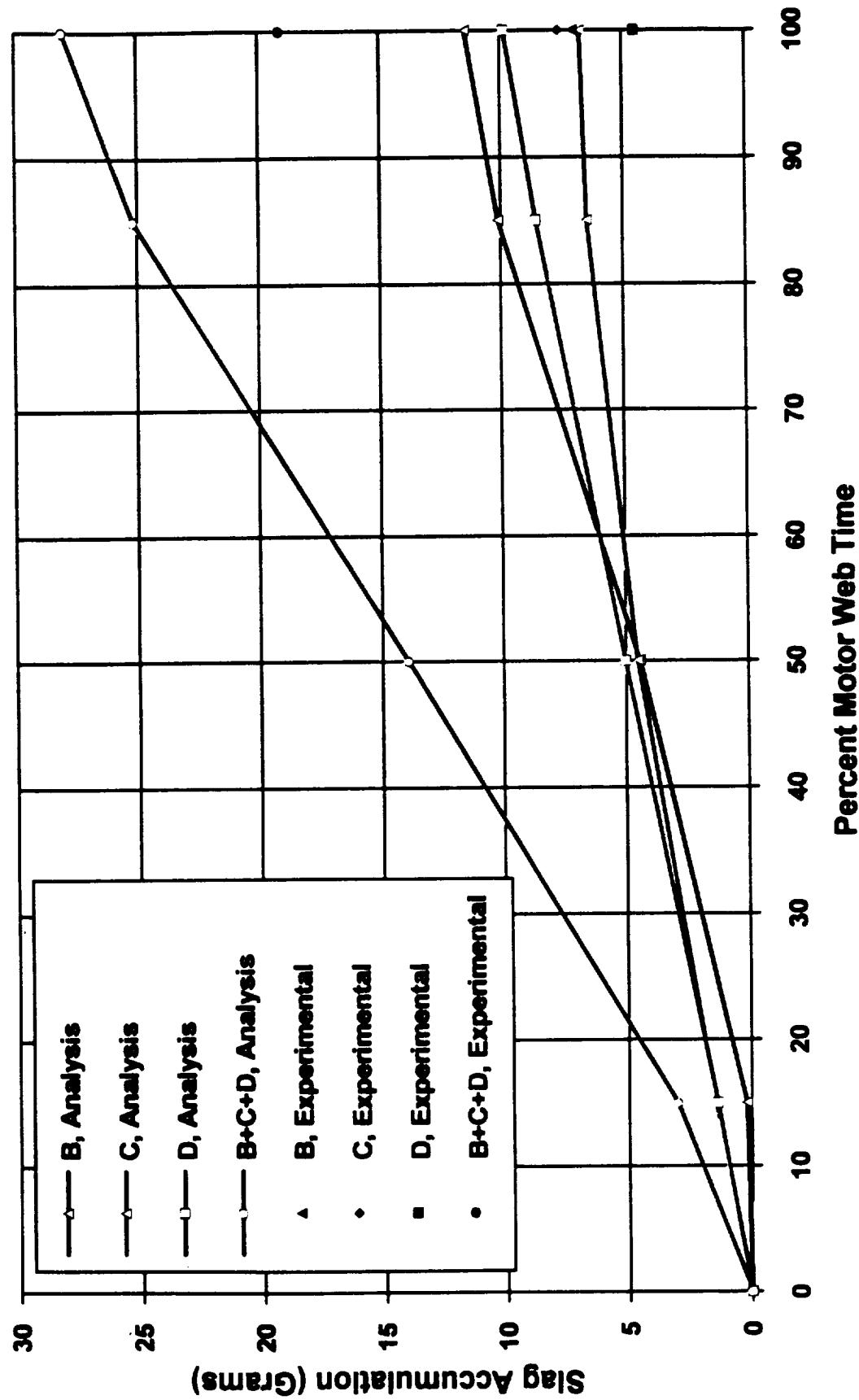
Unburned Aluminum in Zone B
WECCO AP, Distributed Combustion, 400 rpm
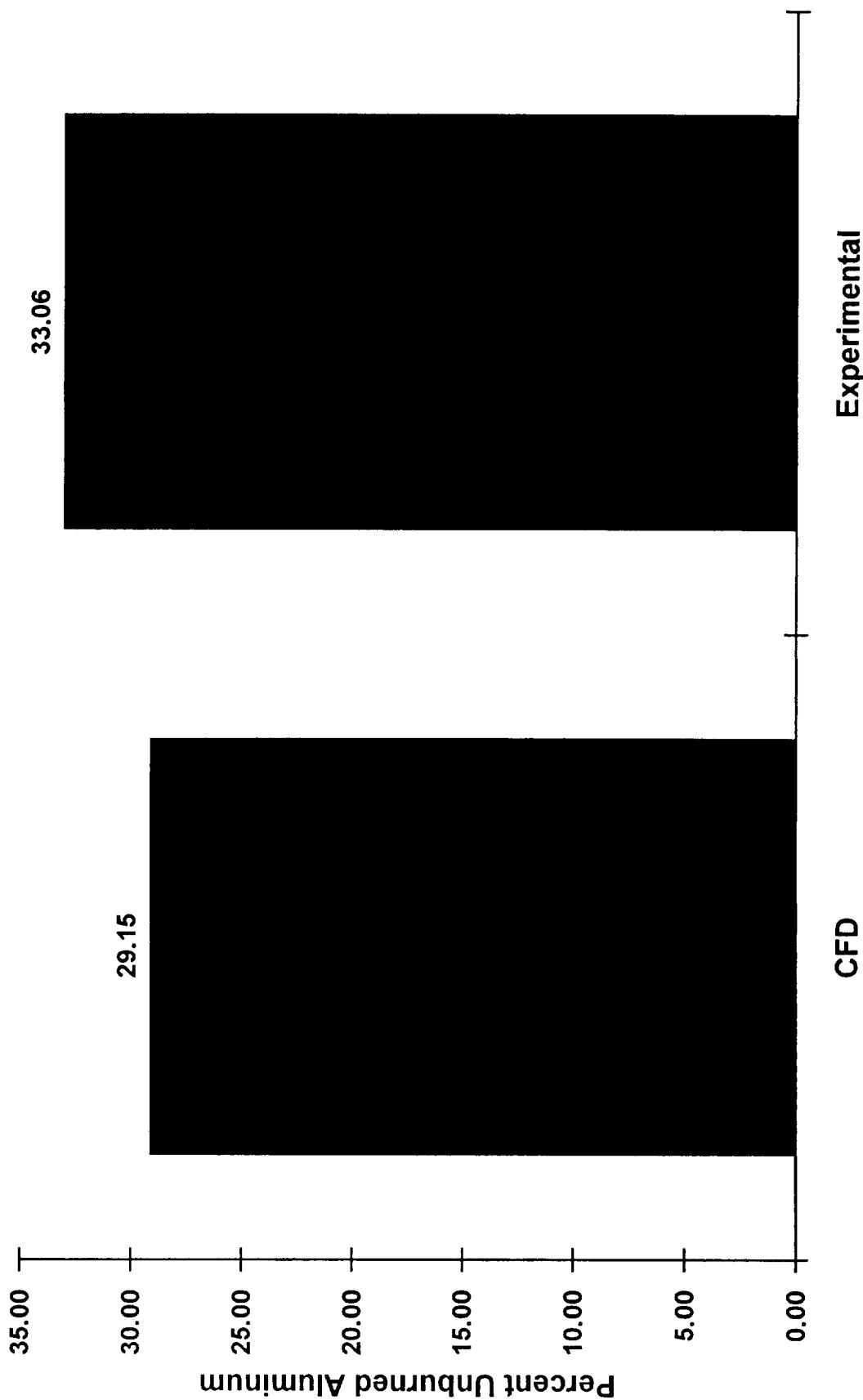
Conclusions

- The use of two-phase CFD analysis was highly successful indetermining in advance the viability of an experimental motor test program being designed to measure the propensity for slag production of propellants with various ingredient variations.

- A submerged nose nozzle design was successfully developed and motor test spin rate selected to maximize slag capture and retention weights using two-phase CFD.

- The two-phase CFD model for the 5-inch spin test motor proved to be a credible analysis tool in evaluation of the slag weight distributions in motor.

- The slag capture criteria is the most important factor in the prediction model for slag capture. Uncertainties in particle properties appear to be less important.

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