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A COMBINED EULERIAN-LAGRANGIAN TWO-PHASE ANALYSIS OF THE SSME HPOTP NOZZLE PLUG TRAJECTORIES

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Abstract

As a result of high cycle fatigue, hydrogen embrittlement, and extended engine use, it was observed in testing that the trailing edge on the first stage nozzle plug in the High Pressure Oxygen Turbopump (HPOTP) could detach. The objective of this study was to predict the trajectories followed by particles exiting the turbine. Experiments had shown that the heat exchanger coils, which lie downstream of the turbine, would be ruptured by particles traveling in the order of 360 ft/sec. An axisymmetric solution of the flow was obtained from the work of Lin et al [1] who used INS3D to obtain his solution. The particle trajectories were obtained using the method of de Jong et al [2] which employs Lagrangian tracking of the particle through the Eulerian flow field. The collision parameters were obtained from experiments conducted by Rocketdyne using problem specific alloys, speeds, and projectile geometries. A complete 3-D analysis using the most likely collision parameters shows maximum particle velocities of 200 ft/sec. in the heat exchanger region. Subsequent to this analysis, an engine level test was conducted in which seven particles passed through the turbine but no damage was observed on the heat exchanger coils.

References

1) Lin, S.-J. and Chang, J.L.C.: "Numerical Study of Laminar and Turbulent Flow Inside a Turnaround Duct With and Without Guide Vanes," AIAA Paper 87-0365, 1987.

2) de Jong, F.J., Sabnis, J.S., and McConnaughey, P.K.: "A Combined Eulerian-Lagrangian Two-Phase Flow Analysis of SSME HPOTP Nozzle Plug Trajectories; Part I- Methodology," To be presented at the AIAA Joint Propulsion Conference, 1989.

HIERARCHY OF ANALYSIS

- 2–D: PARTICLE EXITS TURBINE WITH NO SWIRL
- 3–D: PARTICLE WITH SWIRL, NO RADIAL STRUTS
- 3–D: PARTICLE WITH SWIRL, RADIAL STRUTS INCLUDED

PARAMETERS OF ANALYSIS

- 15 DIFFERENT PARTICLE RADIAL POSITIONS AT THE INLET TO THE DOMAIN FOR EACH RUN. (INNER TO OUTER WALL)
- DRAG COEFFICIENT OF PARTICLES – 0.4, 0.6, 0.8
    - TURBINE EXIT AXIAL VELOCITY OF PARTICLE FROM 180 TO 255 FT/SEC.
- SWIRL VELOCITY OF PARTICLE VARIED FROM ZERO TO BLADE SPEED
- LOSS OF NORMAL MOMENTUM AT THE WALLS:
    - COEFFICIENT OF RESTITUTION – 0.2, 0.4, 0.6, 0.8
- LOSS OF TANGENTIAL MOMENTUM AT THE WALLS:
    - COEFFICIENT OF SLIDING FRICTION – 0.0, 0.1, 0.2, 0.3

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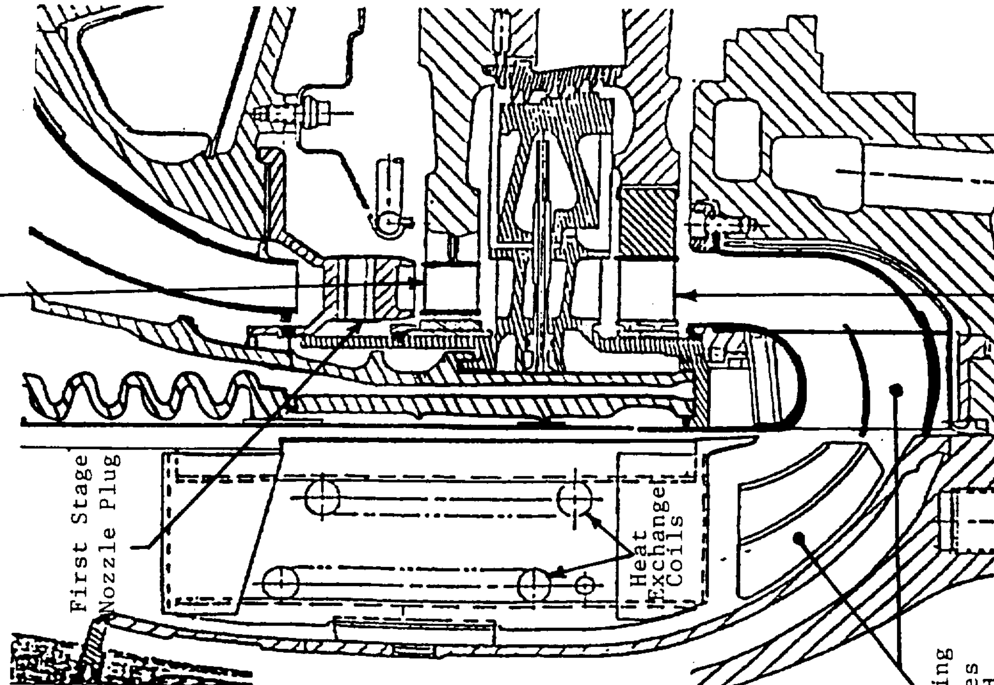
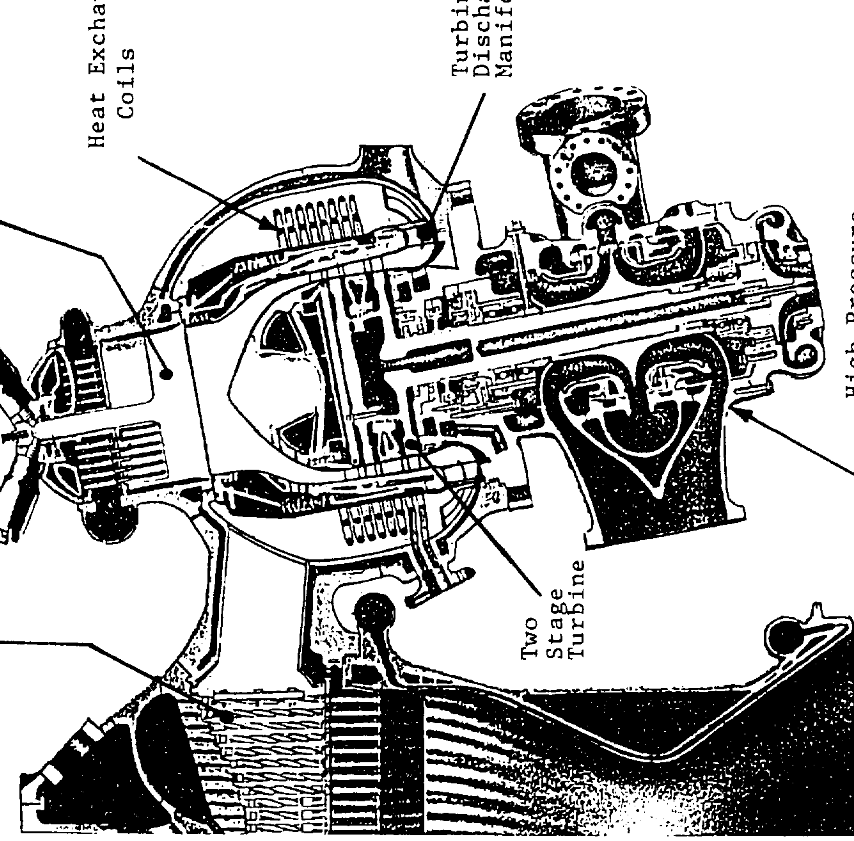
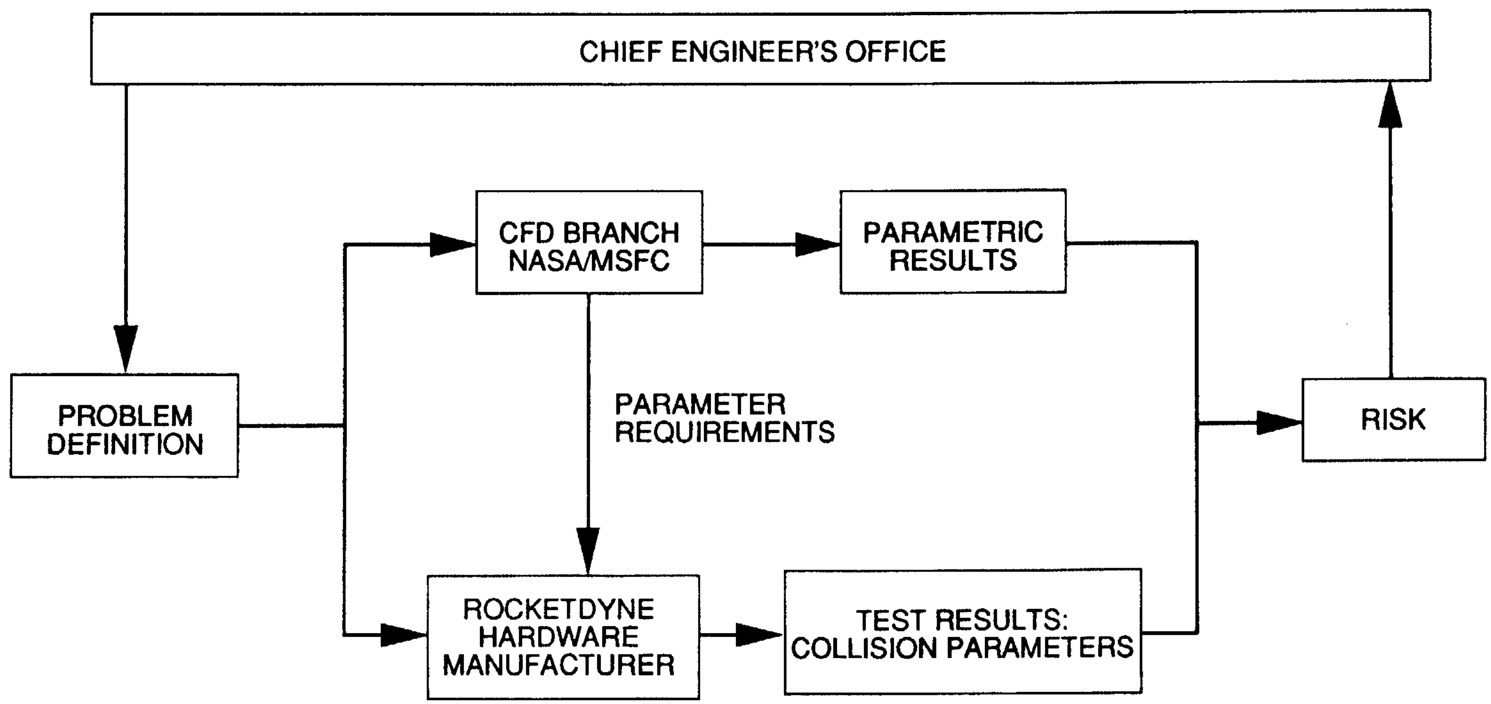

First Stage Turbine Blade
First Stage Nozzle Plug
Heat Exchange Coils
Second Stage Turbine Blade
Turning Vanes and Struts


Main Combustion Chamber
High Pressure Oxygen Turbopump Preburner
Heat Exchanger Coils
Turbine Discharge Manifold
Two Stage Turbine
High Pressure Oxygen Pump

SSME HPOTP NOZZLE PLUG TRAJECTORIES



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OBJECTIVE

- TO DETERMINE THE LOCATIONS AND VELOCITIES OF NOZZLE PLUG IMPACTS ON THE HPOTP LOX HEAT EXCHANGER. TEST DATA INDICATED IMPACT VELOCITIES OF 360 FT/SEC WOULD CAUSE HEAT EXCHANGER COIL RUPTURE.

JUSTIFICATION

- RESULTS REQUESTED BY SSME CHIEF ENGINEER TO ASSESS:
  - RISK OF FULL SCALE ENGINE TEST.
  - RISK OF RETURN TO FLIGHT OF THE SPACE SHUTTLE WITH CURRENT DESIGN.

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TECHNICAL APPROACH

- USED LIN's AND CHANG's (ROCKETDYNE) AXISYMMETRIC SOLUTION OF THE FLOW IN THE HPOTP HOT GAS MANIFOLD
  - SOLUTION OBTAINED USING INS3D:
  - INCOMPRESSIBLE $M = 0.1$
  - $Re \equiv 3 \times 10^6$, 588 FT/SEC AXIAL VELOCITY

- TRAJECTORIES CALCULATED USING LAGRANGIAN TRACKING OF THE PARTICLES THROUGH THE EULERIAN FLOW FIELD
  - METHOD OF F. J. de JONG AND J. S. SABNIS OF SRA
  - $\vec{F} = m\vec{a}$ ON THE PARTICLE THROUGH THE FLOW FIELD
  - COLLISION MODEL AT THE WALLS.

- VALIDATION
  - INS3D: COMPARED TO EXPERIMENTAL MEASUREMENTS FOR VARIOUS INCOMPRESSIBLE INTERNAL FLOWS.
  - LAGRANGIAN TRACKER: COMPARED AGAINST EXPERIMENTAL MEASUREMENTS IN A TWO-PHASE MIXING LAYER FLOW.

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SSME HPOTP NOZZLE PLUG TRAJECTORIES

OVERVIEW

- INTRODUCTION TO THE PROBLEM
- OBJECTIVES
- TECHNICAL APPROACH
- RESULTS
- CONCLUSION/IMPACT

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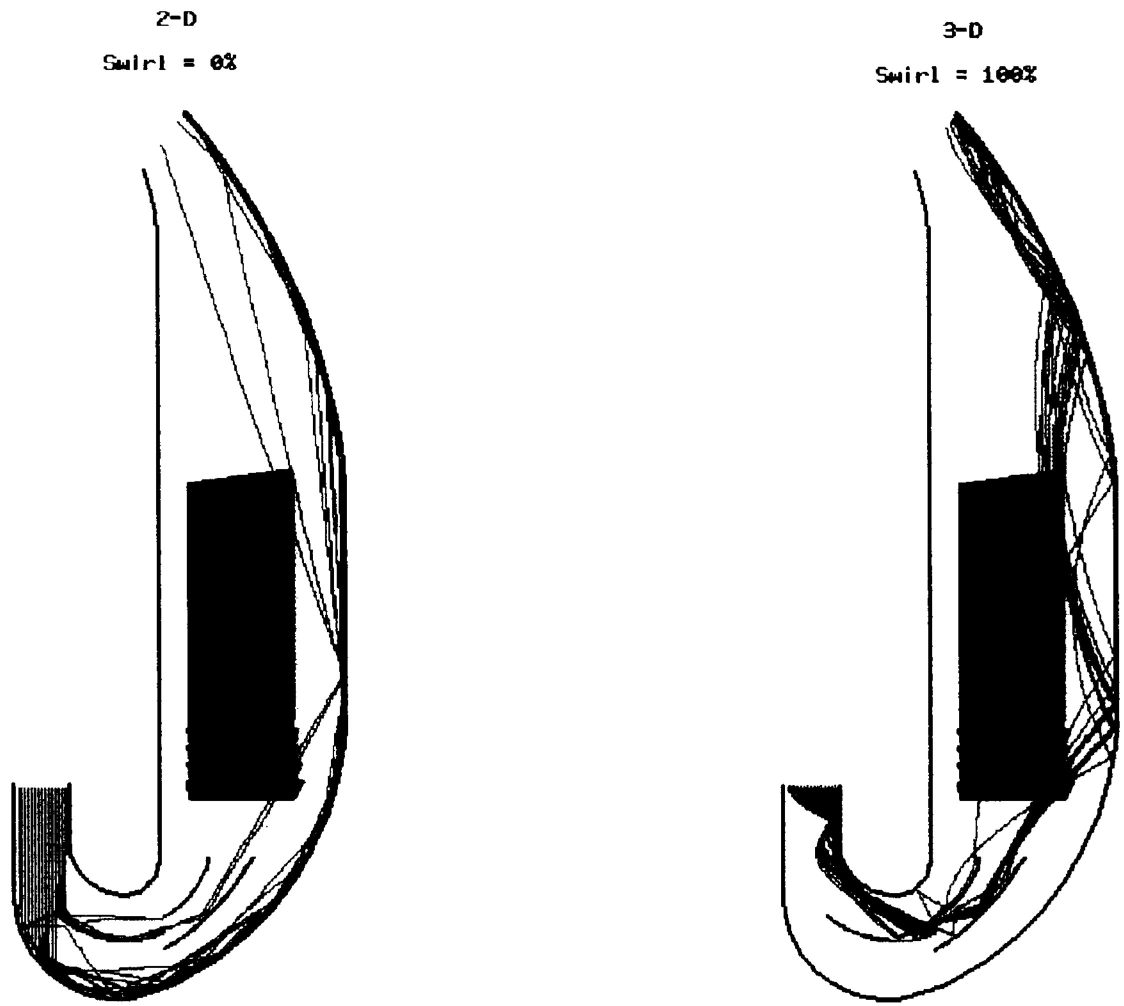
HPOTP Nozzle Plug Trajectories

Drag Coefficient = 0.6
Coeff. of Restitution = 0.6
Coeff. of Sliding Friction = 0.0



PARTICLE VELOCITIES* AT THE HEAT EXCHANGER (FT/SEC)

FOR ALL CASES SHOWN: $C_D = 0.6$; $\mu = 0.0$

C_{RES}		2–D $V_{SWIRL} = 0.0$	3–D, NO RADIAL STRUTS $V_{SWIRL} = 1310$ ft/sec
0.4	V_{MAX}	192	635
	V_{MEAN}	–	610
	V_{MIN}	152	572
0.6	V_{MAX}	204	672
	V_{MEAN}	–	611
	V_{MIN}	200	435
0.8	V_{MAX}	224	765
	V_{MEAN}	–	683
	V_{MIN}	167	465

*SWIRL COMPONENT NOT INCLUDED (NOT NORMAL TO COILS)

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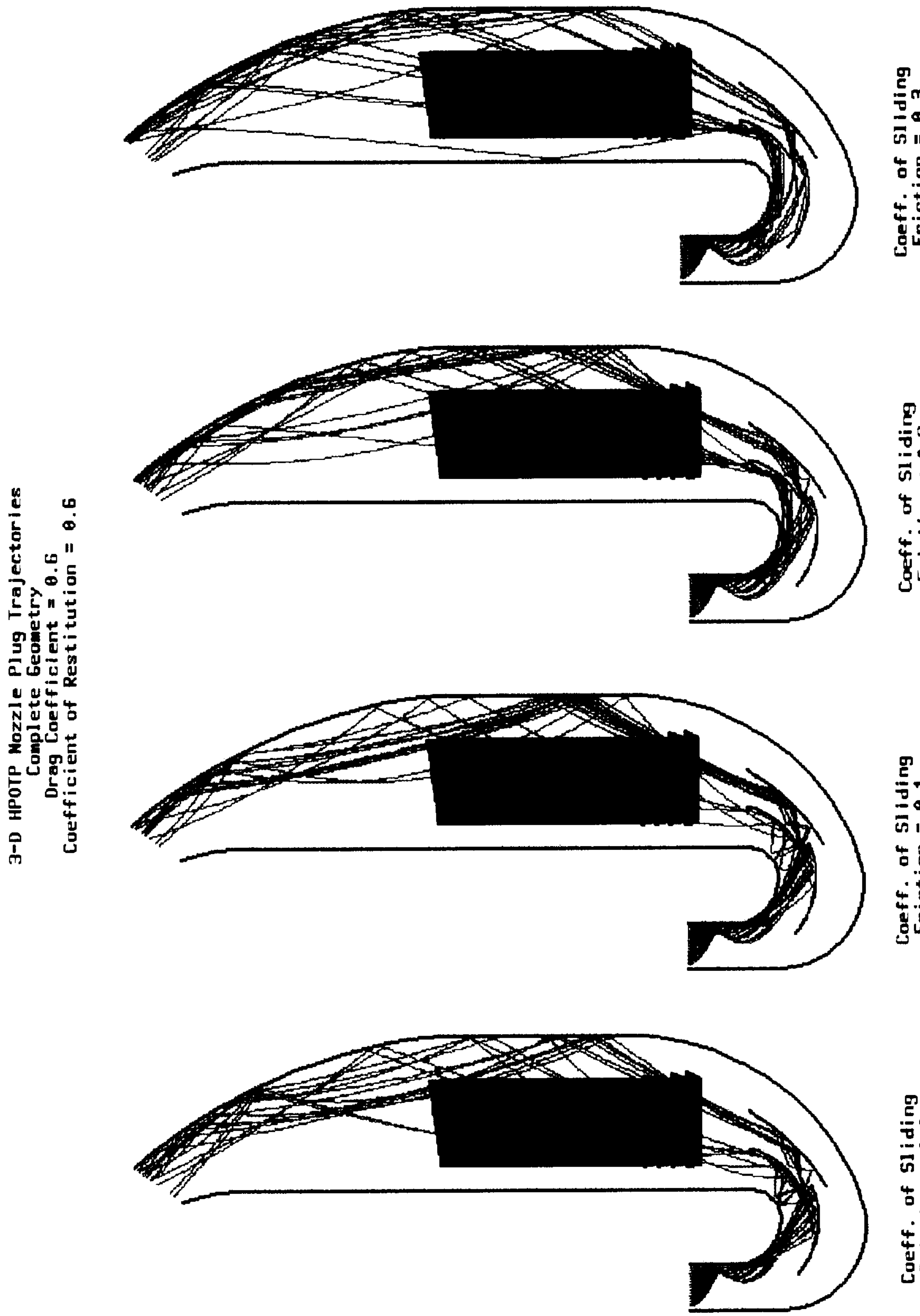

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3-D ANALYSIS WITH RADIAL STRUTS (COMPLETE GEOMETRY)

PARTICLE VELOCITIES* AT HEAT EXCHANGER (FT/SEC)

$C_D = 0.6$ V_{SWIRL} = BLADE SPEED

μ (COEFF. OF SLIDING FRICTION)	$C_{RESTITUTION}$ 0.2	**0.4	0.6	0.8	
**0.1	150.9	130.0	156.3	210.1	$\bar{V}$
	141.1	61.5	82.3	61.7	V_{MIN}
	161.1	176.7	302.5	328.6	V_{MAX}
0.2	82.4	65.2	75.4	96.4	$\bar{V}$
	76.9	49.5	42.4	38.2	V_{MIN}
	86.3	110.2	161.8	150.7	V_{MAX}
0.3	49.5	60.5	54.6	55.2	$\bar{V}$
	43.3	51.9	26.8	21.4	V_{MIN}
	56.0	66.4	94.3	69.0	V_{MAX}

*SWIRL COMPONENT NOT INCLUDED (NOT NORMAL TO COIL)
**EXPECTED MEAN VALUE FOR COEFFICIENT BASED ON TEST DATA

5-717-9-83

IMPACT

- DECISION MADE TO CONDUCT FULL SCALE TEST WITH PURPOSELY CUT NOZZLE PLUGS:
  NO DAMAGE TO THE HEAT EXCHANGER
- DECISION MADE TO USE CURRENT DESIGN ON RETURN TO FLIGHT

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CONCLUSIONS

- PARTICLE MOTION DOMINATED BY COLLISION PARAMETERS
- MOST PARTICLES WILL HIT THE HEAT EXCHANGER DUE TO "FOCUSING" OF THE TURNING VANES.
- MEAN COLLISION PARAMETERS ($C_{RES} = 0.6$, $\mu = 0.1$) YIELD MAXIMUM PARTICLE IMPACT VELOCITIES OF 180 FT/S
- WORST CASE STACK OF COLLISION PARAMETERS YIELDS MAXIMUM IMPACT VELOCITIES OF 300 FT/S (RUPTURE VELOCITY IS 360 FT/S).

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