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Progress in Computing Nozzle/Plume Flow Fields

Stephen M. Ruffin

NASA Ames Research Center, Moffett Field, CA

Ethiraj Venkatapathy

Eloret Institute, Sunnyvale, CA

William J. Feiereisen

NASA Ames Research Center, Moffett Field, CA

Seung-Ho Lee

Eloret Institute, Sunnyvale, CA

Abstract

The long-term goal of this work is to develop the capability to predict chemically-reacting, multi-stream nozzle and plume flow fields. Two basic Navier-Stokes solvers, including the widely used F-3D code, are upgraded to include several upwind difference schemes and portable chemistry packages. Current computational capabilities for solving equilibrium single-stream and multi-stream, frozen gas and finite rate chemistry problems are described. A variety of complex nozzle and plume flows have been computed. Solutions presented herein include axisymmetric plume flow for ideal and equilibrium air, 3-D NASP nozzle/afterbody flow, and an internal nozzle calculation comparing various finite-rate chemistry packages.

Motivations, Objective, and Applications

Motivations

- Flow in nozzle and propulsive plume strongly influence performance of hypersonic vehicles.
- Ground-based facilities can not fully simulate these flow fields.
- Validated, accurate and efficient flow codes are needed to design integrated propulsion systems of hypersonic vehicles.

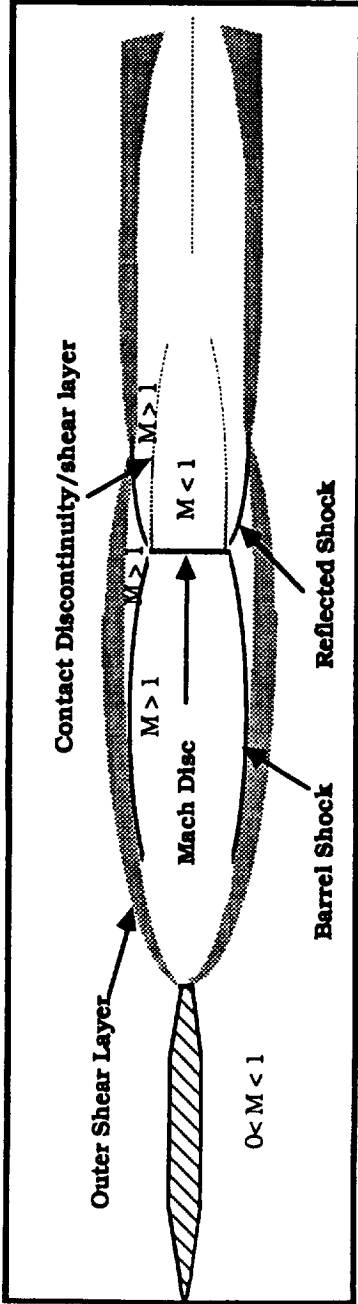
Objective

- Develop computational ability to predict chemically reacting, multi-stream, nozzle/plume flow fields.

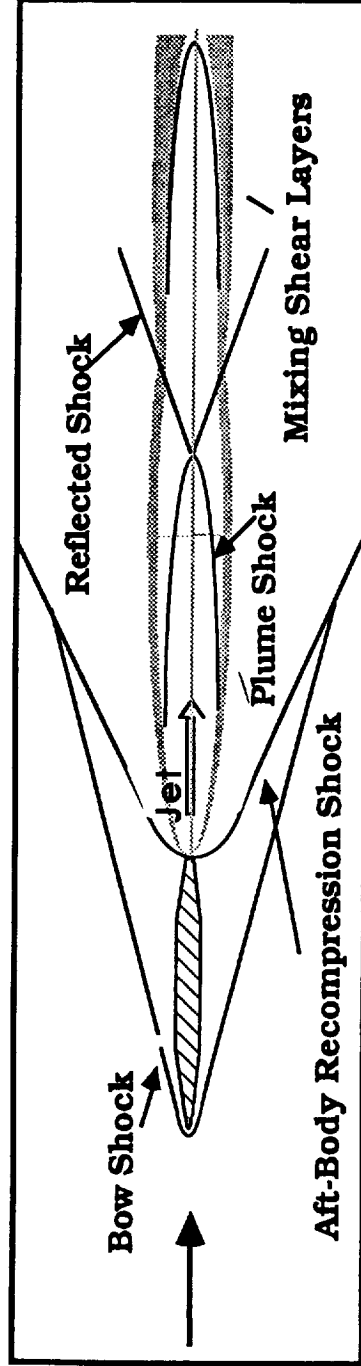
Applications

- NASP, Space Shuttle, general plume flows and signatures

SCHEMATIC OF AXISYMMETRIC PLUME FLOWS



Plume Flow in Subsonic External Stream



Plume Flow in Supersonic External Stream

Nozzle/Plume Flow Solvers

Difference Scheme	2-D Axisym. Eqns. Flux-Split in 2-D	3-D Eqns. Flux-Split in 1-D Central Diff. in 2-D	3-D Eqns. Roe's upwind averaging in 3-D
Implicit Soln. Algorithm	Beam & Warming in "delta form"	Two-Factor Flux-Split	LDU-ADI
Viscous Terms	in 1-D	in 1-D	in 3-D
Chemistry	Ideal Gas Equil. single-stream Equil. multi-stream Frozen	Ideal Gas Finite-Rate	Ideal Gas Equil. single-stream
Calibration	Ideal Gas: Mach disk location for jet plumes Equil. 1-stream: Shock standoff dist., and shape and species distribution for blunt body flow.	Ideal Gas: Numerous flows including Space Shuttle, Mach No., pressure and Mach disk location for plumes Finite-Rate: H ₂ -air species distribution for axysymm. nozzle.	Ideal Gas: Numerous flows including Space Shuttle, Mach No., pressure and Mach disk location for plumes plume structure in quiescent freestream

Nozzle/Plume Flow Solvers (cont.)

- All calculations performed for laminar flow
- Adaptive grid routine used for all 2-D cases
(3-D adaptive grid routine recently completed)
- 3-D code can handle multiple, patched-grid regions
and generalized specification of boundary conditions

Equilibrium and Frozen Gas Chemistry

Constant Elemental Composition (i.e., single-stream)

- Uniform gas throughout flow field

Equilibrium Gas

- table look-up, curve fits
- relatively fast
- must be pre-calculated

Variable Elemental Composition (i.e., multi-stream)

- Solution of species partial density equations allows for convection, diffusion and mixing of multiple streams

Equilibrium Gas

- Gordon-McBride free energy minimization
- arbitrary gas mixtures

Frozen Chemistry

- No reactions

Finite Rate Chemistry

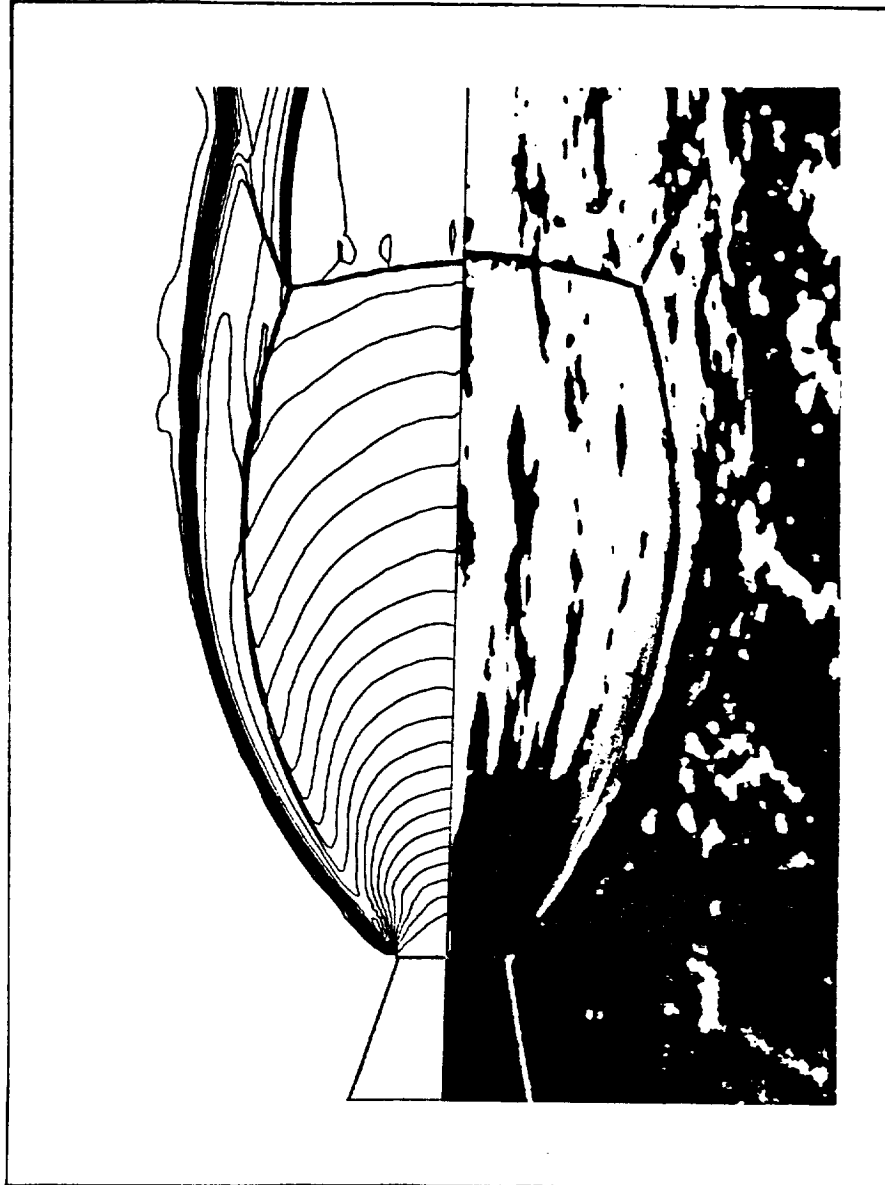
- H₂ - air chemistry currently being used
 - JANNAF plume model (Dash and Pergament, 1980)
 - 7 Species: H, H₂, H₂O, O, OH, O₂, N₂
 - 8 Reactions
- Specific heats from curve fits (Gordon and McBride data)
- Binary diffusion
 - Fick's Law with $D_{i,j}$ given by Reid, et.al., 1977)
- Non-catalytic wall
- Chemistry Coupling
 - Fully-Coupled
 - Invert large matrix of order $5 + (N_{\text{species}} - 1)$ per node
 - Loosely-Coupled
 - Locally constant $\bar{\gamma}$
 - P not affected by species concentration variations
 - Invert two smaller matrices of order 5 and $N_{\text{species}} - 1$ per node.

Types of Nozzle/Plume Flows Computed

Cases	Main complexity is due to:			References
	Fluid Dyn. Features	Body Geom.	Flow Chem.	
I. Axisymmetric Single-Nozzle Plume A. Not including afterbody Ideal gas, sub. freestream Ideal gas, sup. freestream B. Including afterbody Ideal Gas Equil. single-stream Equil. multi-stream Frozen	X			AIAA 89-0129
	X			AIAA 88-3158
↓ ↓	X	X	X	AIAA 88-2636
	X	X	X	AIAA 88-2636
	X	X	X	in preparation
	X	X	X	in preparation
II. 3-D Multiple-Nozzle Plume A. Not including afterbody B. Including afterbody	X			AIAA 88-3158
	X	X		AIAA 89-0129
III. Hypersonic Nozzle/Afterbody A. 2-D Geometry Subsonic freestream Supersonic freestream B. 3-D Geometry Plume region alone Complete geometry	X			AIAA 89-0446
	X			AIAA 89-0446
	X	X		AIAA 89-0446
	X	X		AIAA 89-0446
IV. Internal Nozzle, finite rate chem.	↓		X	in preparation

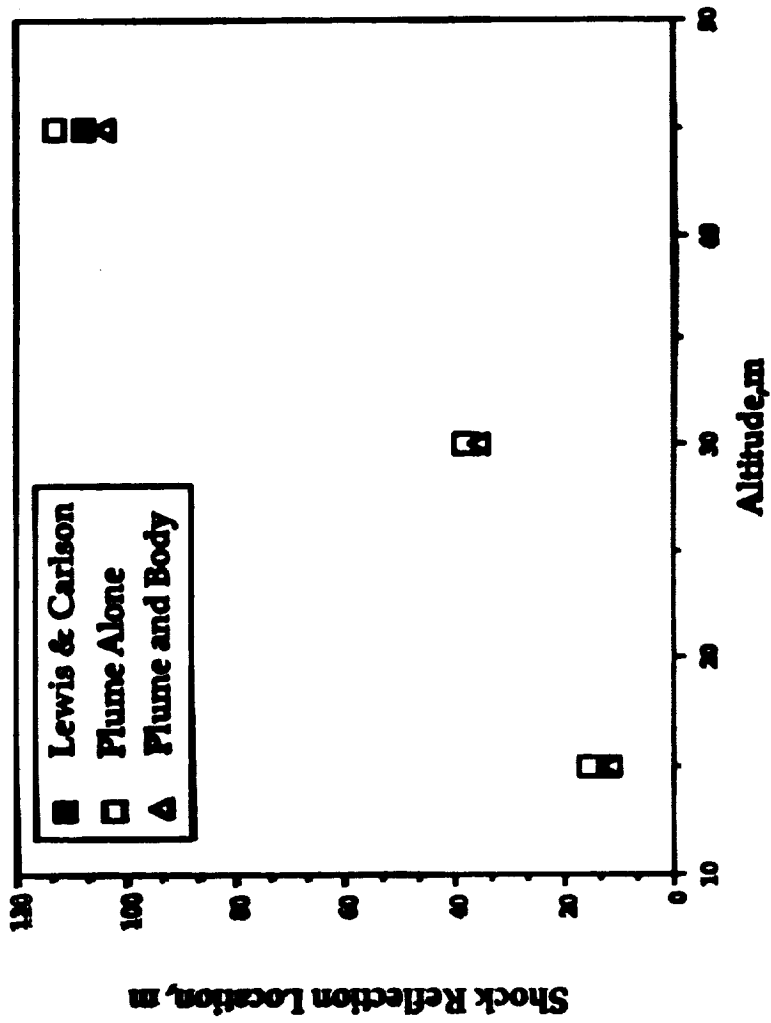
Axisymmetric Plume Flow in Quiescent Air
 $P_j/P_{inf} = 21.9$ - $M_j = 1.5$

Upper Half - Computed Mach Contours with Adapted Grid

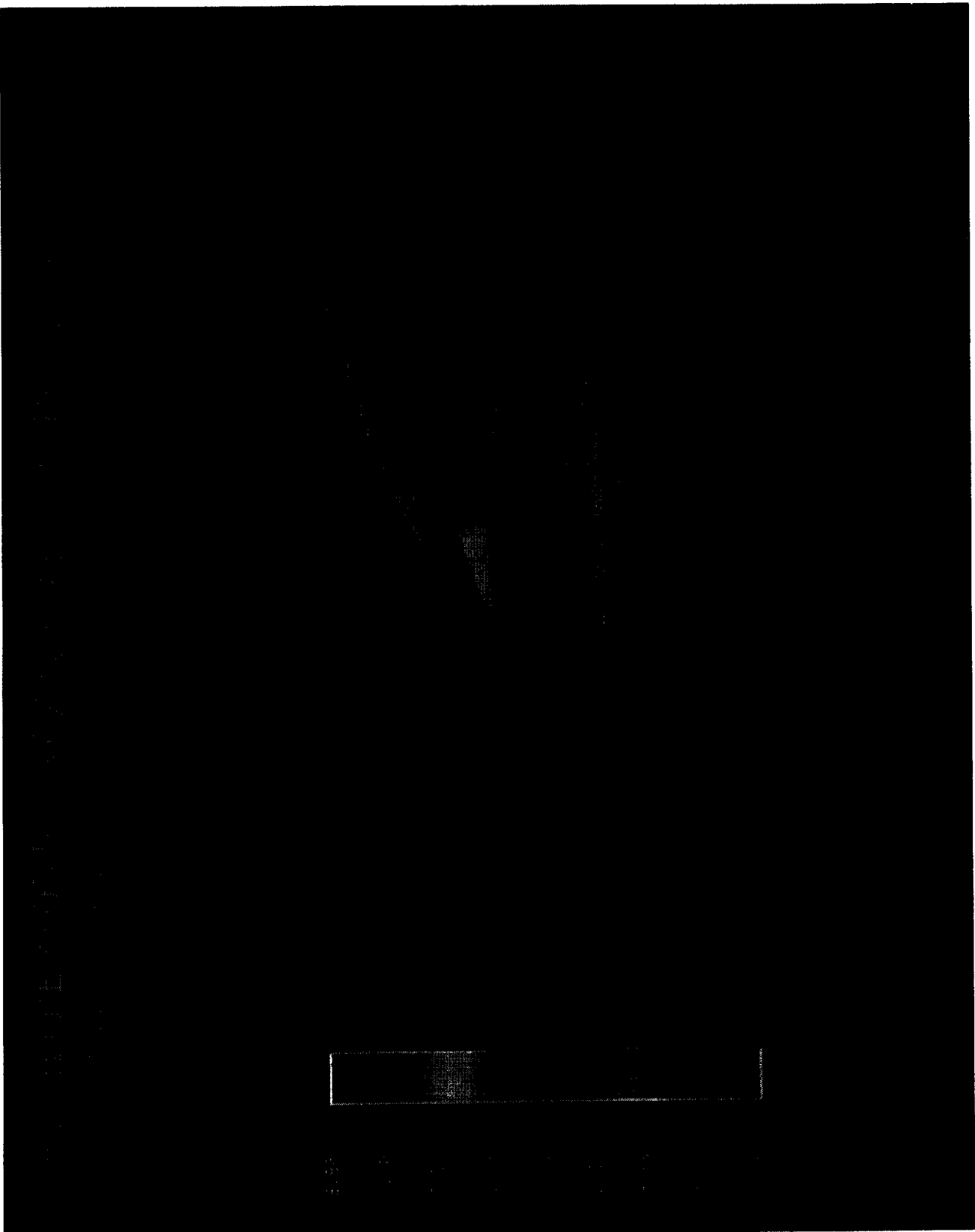


Lower Half - Experimental Shadowgraph - (NASA TR R 6)

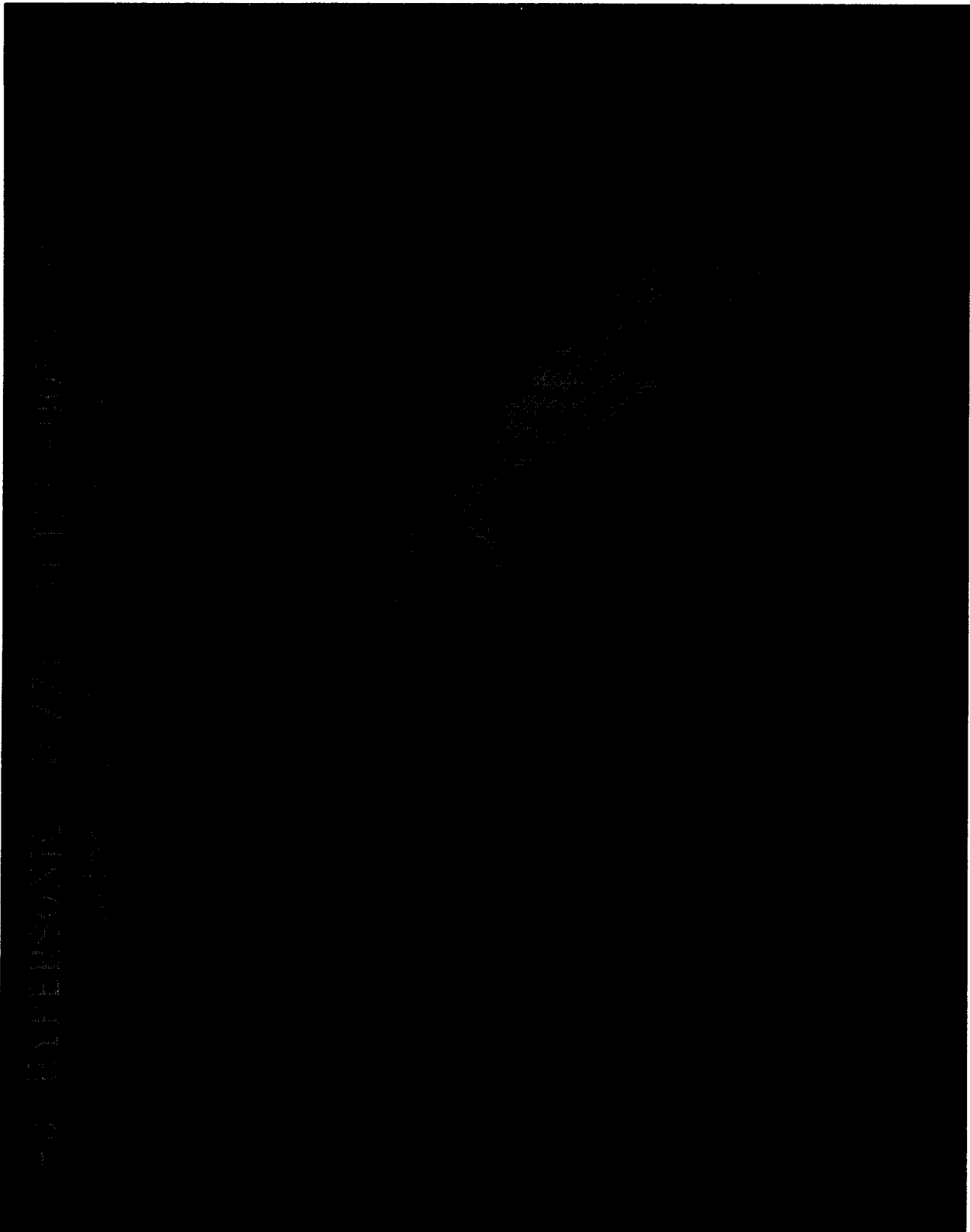
Axisymmetric Plume Solutions



Comparison of Shock Reflection Location vs Altitude



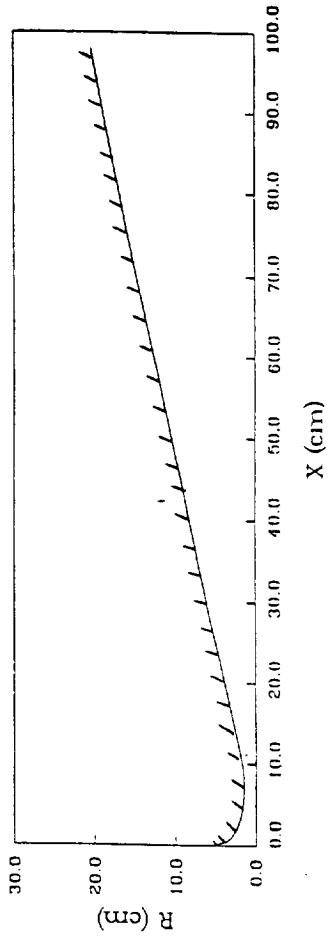
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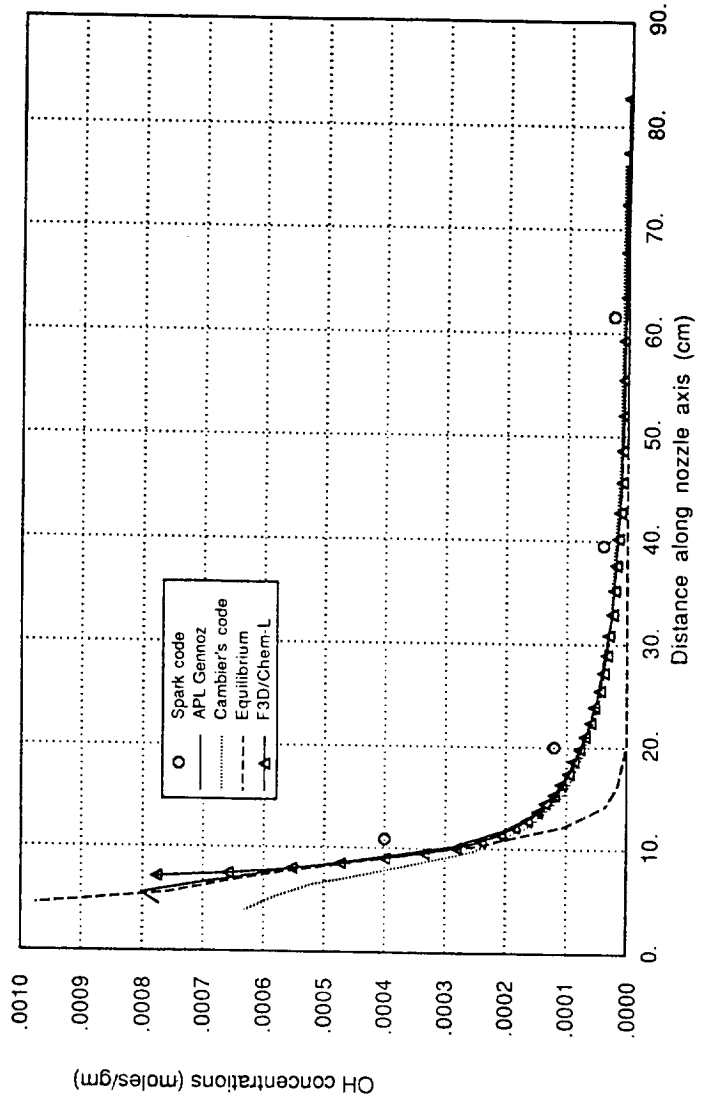
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NOZZLE GEOMETRY



OH CONCENTRATIONS VERSUS DISTANCE ALONG NOZZLE AXIS



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Concluding Remarks

- A variety of nozzle/plume flows have been successfully computed.
 - Complex flow structures and geometries have been studied
 - Good agreement with experimental and other computed results has been found for plume structure and Mach disk location.
- Equilibrium single-stream, equil. multi-stream, finite rate, and frozen chemistry packages have been incorporated.
- Turbulence modeling for complex plume flows is currently being studied
- 3-D code will be validated against hypersonic nozzle/afterbody experimental data
- Significant progress has been made toward goal of a single code capable of solving complex chemically reacting nozzle/plume flow fields.