Axisymmetric Computational Fluid Dynamics Analysis of Saturn V/S1-C/F1 Nozzle and Plume

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Abstract

An axisymmetric single engine Computational Fluid Dynamics calculation of the Saturn V/S1-C vehicle base region and F1 engine plume is described. There were two objectives of this work, the first was to calculated an axisymmetric approximation of the nozzle, plume and base region flow fields of S1-C/F1, relate/scale this to flight data and apply this scaling factor to a NLS/STME axisymmetric calculations from a parallel effort. The second was to assess the differences in F1 and STME plume shear layer development and concentration of combustible gases. This second piece of information was to be input/supporting data for assumptions made in NLS2 base temperature scaling methodology from which the vehicle base thermal environments were being generated. The F1 calculations started at the main combustion chamber faceplate and incorporated the turbine exhaust dump/nozzle film coolant. The plume and base region calculations were made for ten thousand feet and 57 thousand feet altitude at vehicle flight velocity and in stagnant freestream. FDNS was implemented with a 14 species, 28 reaction finite rate chemistry model plus a soot burning model for the RP-1/LOX chemistry. Nozzle and plume flow fields are shown, the plume shear layer constituents are compared to a STME plume. Conclusions are made about the validity and status of the analysis and NLS2 vehicle base thermal environment definition methodology.

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- BACKGROUND
- OBJECTIVE
- APPROACH
- RESULTS
- CONCLUSIONS

BACKGROUND

- STME design had hydrogen rich turbine exhaust ejected near the nozzle lip - potential recirculation to vehicle base.

- Initial NLS base heating thermal design environment severely impacted vehicle base thermal design.

- An in house CFD effort to qualitatively assess NLS/STME base heating rates was begun.
  - this included similar axisymmetric analysis of Saturn V/S1-C/F1 and NLS/STME configurations

OBJECTIVES

- Calculate an axisymmetric approximation of the nozzle, plume and base region flow fields of S1-C/F1, relate/scale this to flight data and apply this scaling factor to NLS/STME axisymmetric results.

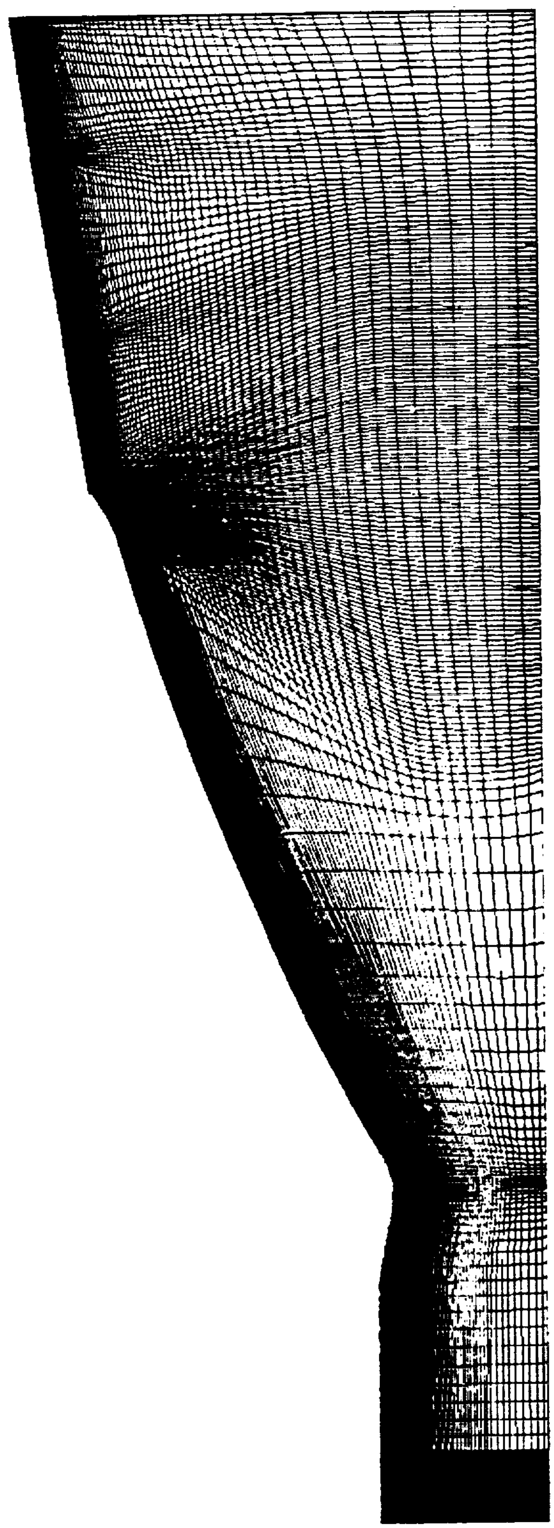
- Assess the differences in F1 and STME plume shear layer development and concentration of combustible gases. An input/supporting data for assumptions made in NLS2 Base Temperature Scaling Methodology from which the vehicle base thermal environments were being generated.

APPROACH

- Axisymmetric model of S1-C outboard engine
  - nozzle and plumes solved separately, frozen and reacting solution obtained for all cases.

- Nozzle calculations
  - bulk flow and turbine exhaust constituents from Thermal Analysis Branch and F1 engine balance
  - nozzle extension geometry approximated, 3 equal area slots vs. 1 large and 21 smaller slots

F1 MCC and Nozzle Grid



F1 MCC and Nozzle Grid
Nozzle Extension Detail

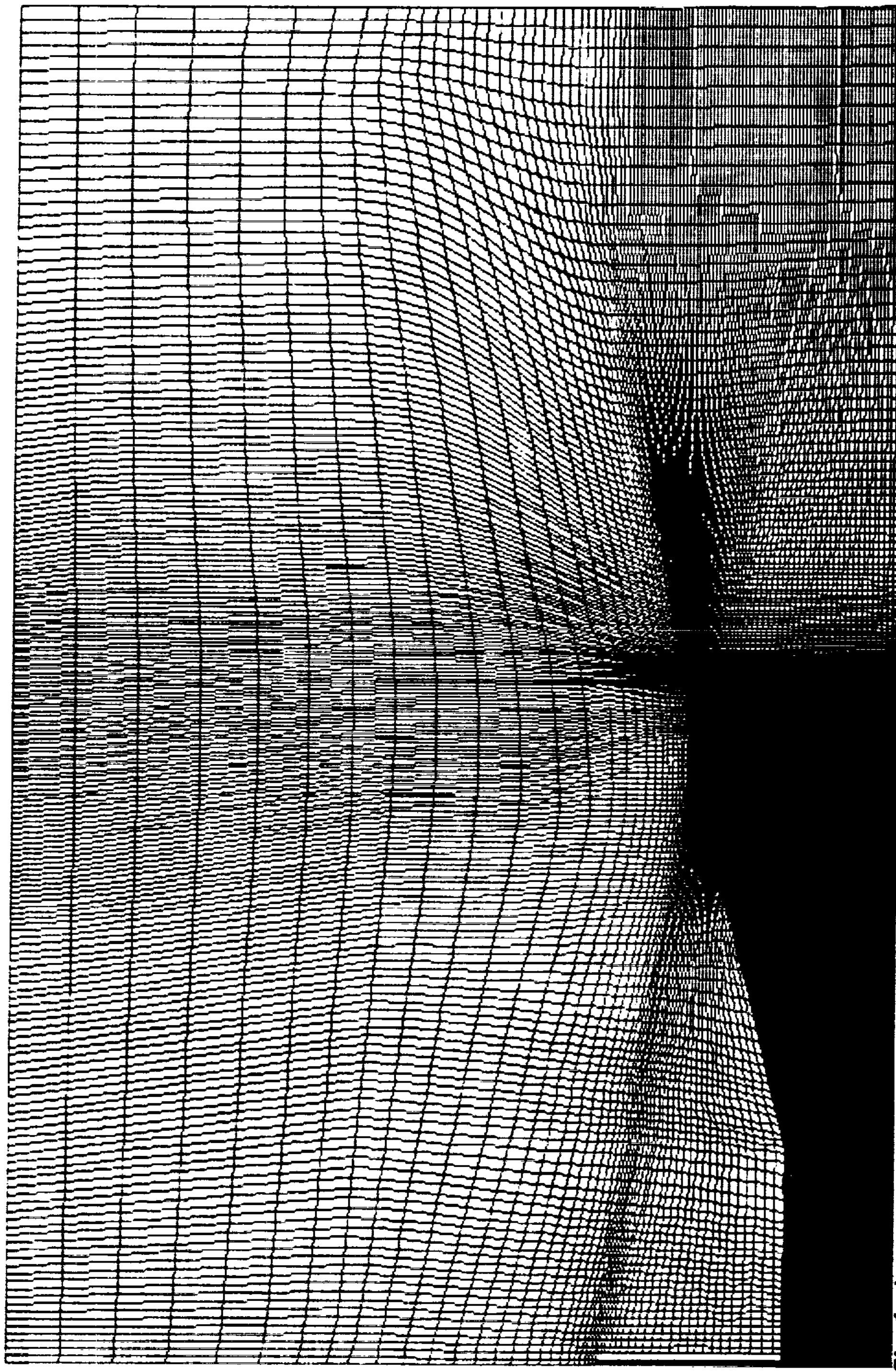
nozgrd.2.img

APPROACH, cont.

- Plume calculations
  - flow field at nozzle exit plane imposed as boundary condition
  - for base region flow, north and west boundaries initialized at flight velocities, fixed to ambient p and t
  - for plume studies, north and west boundaries specified as exits initially with zero velocity, fixed to ambient p and t
  - two altitudes solved, low - 10kft, high - 57kft

- Chemistry
  - finite rate, with 14 species and 28 reactions
  - soot modeled as solid carbon

10kft Plume Grid



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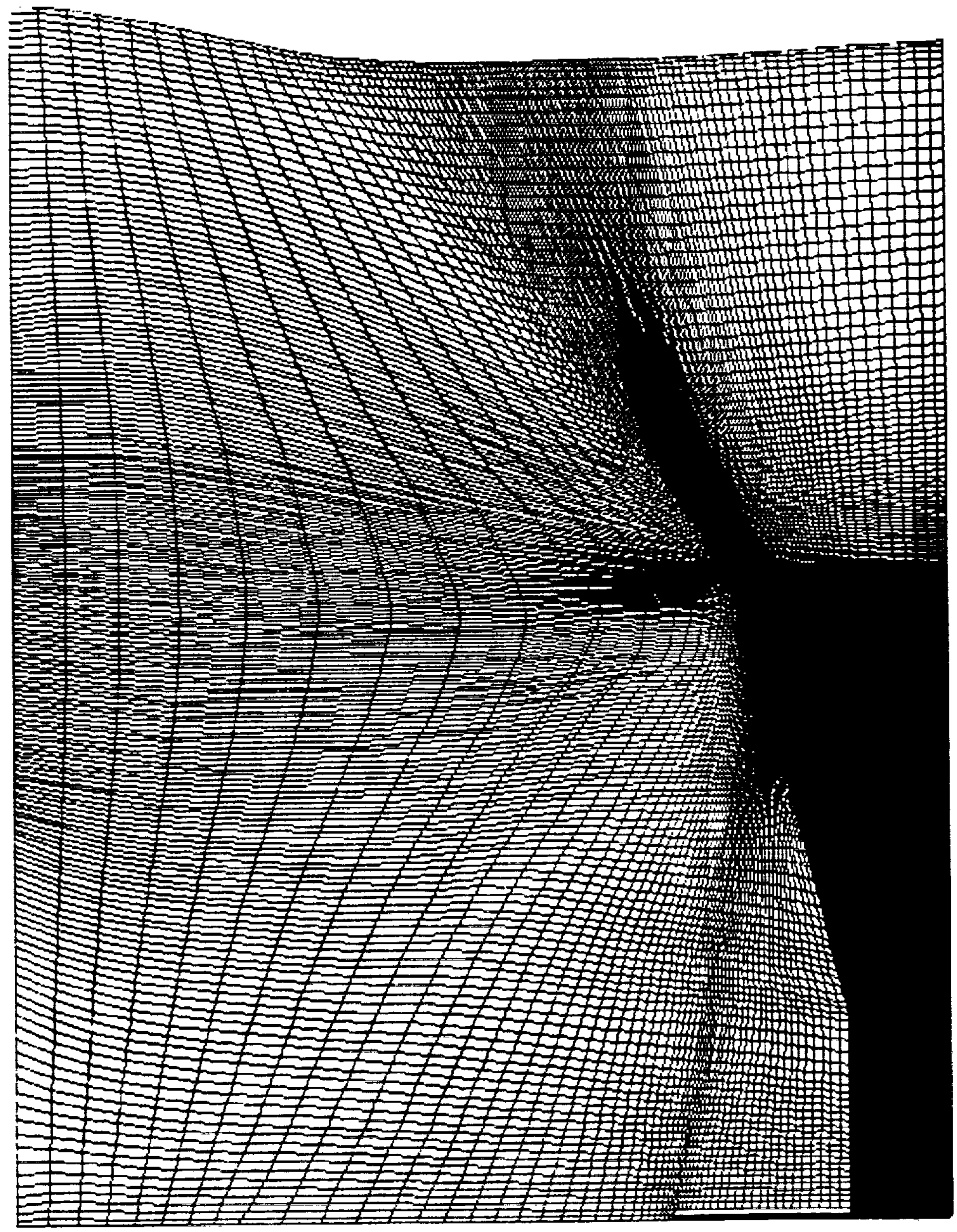
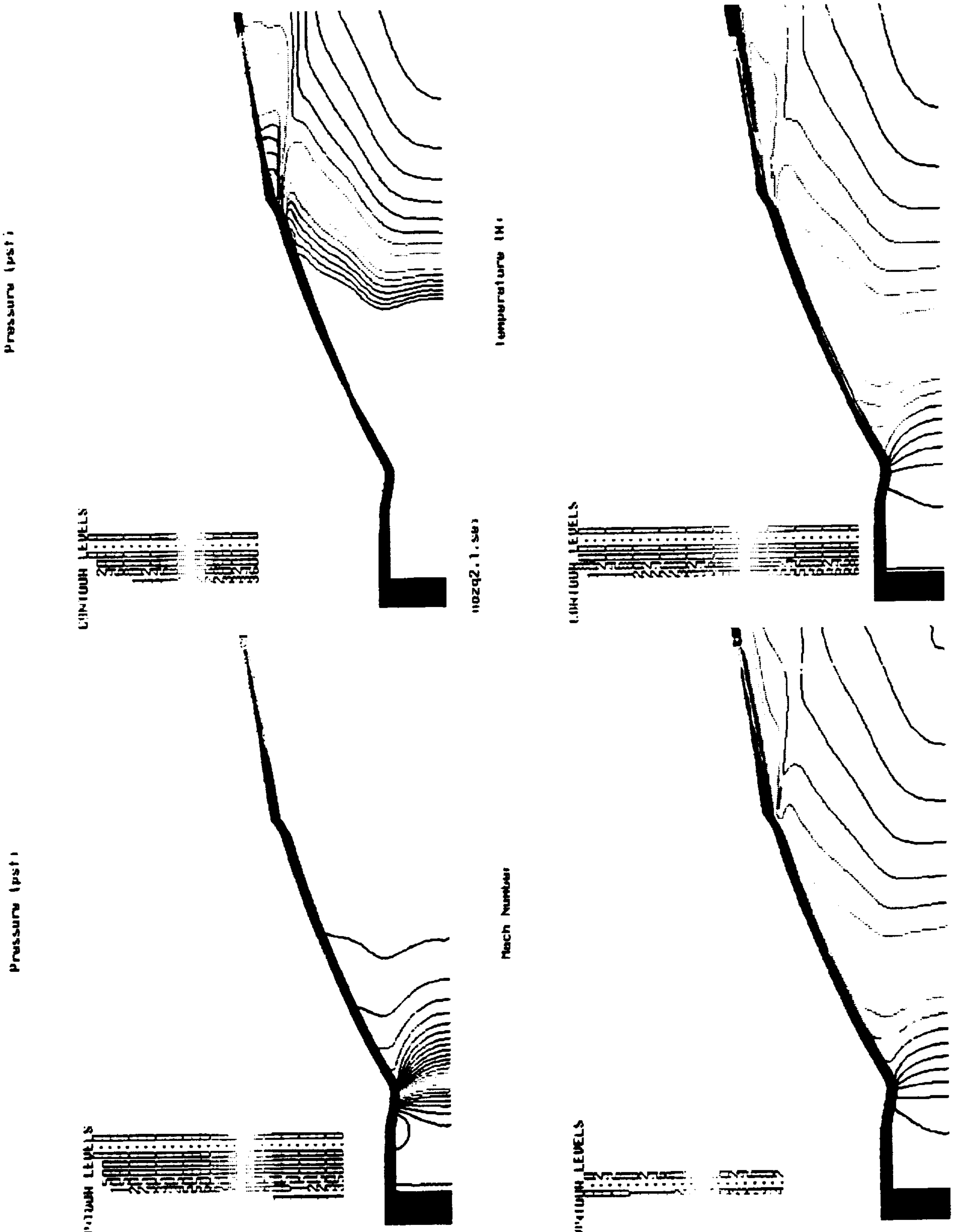
57kft Plume Grid

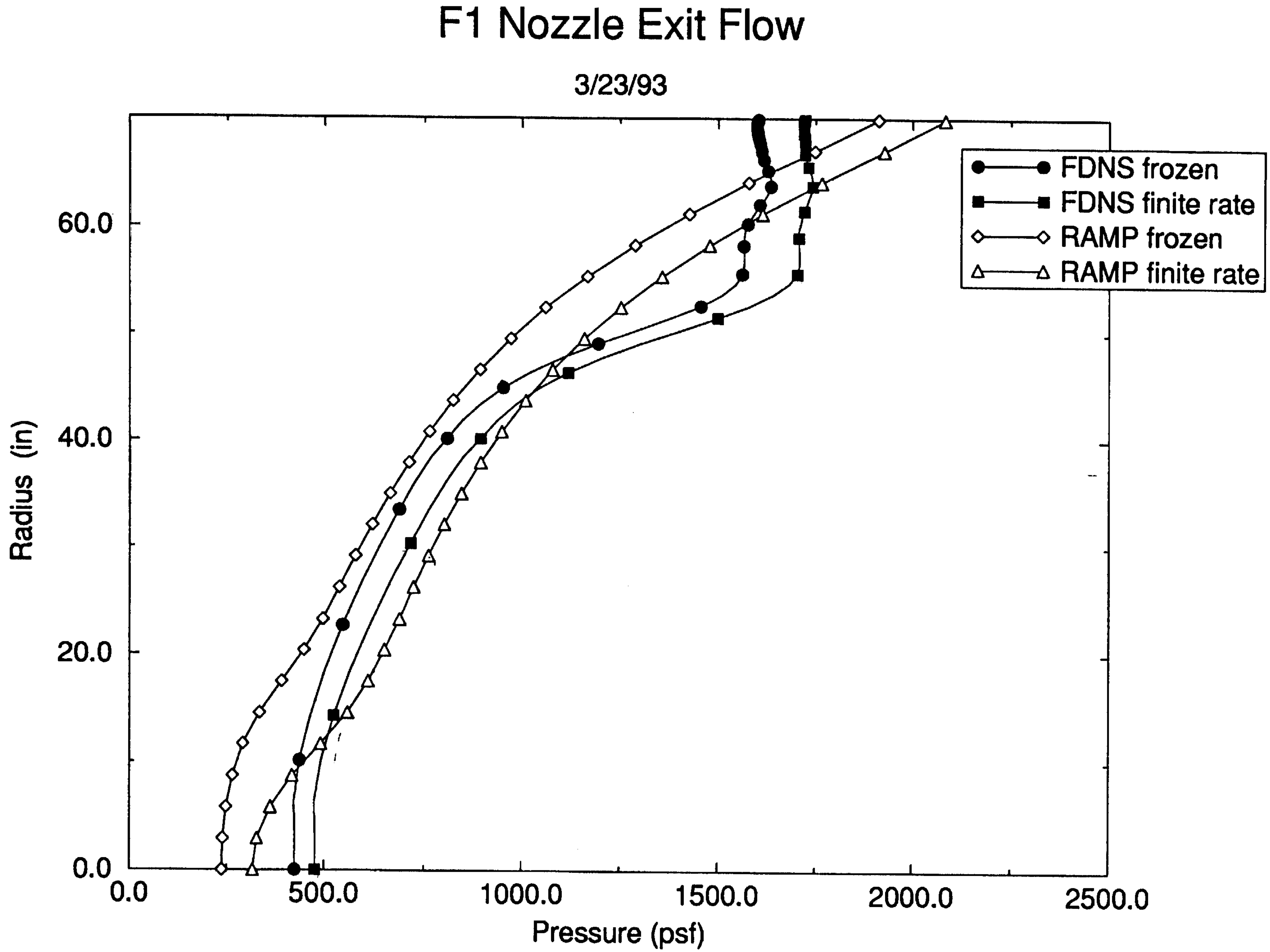


plums2.1.img

RESULTS

- Nozzle
  - effect of turbine exhaust seen well into the main flow field
  - compared to RAMP(MOC) calculation for smooth wall nozzle w/o turbine exhaust. Significant differences exist.
  - calculated thrust and Isp
    - frozen flow +.5%
    - finite rate +12%


Pressure (psi)
CONTOUR LEVELS
Pressure (psi)
CONTOUR LEVELS
Mach Number
CONTOUR LEVELS
Temperature (K)
CONTOUR LEVELS

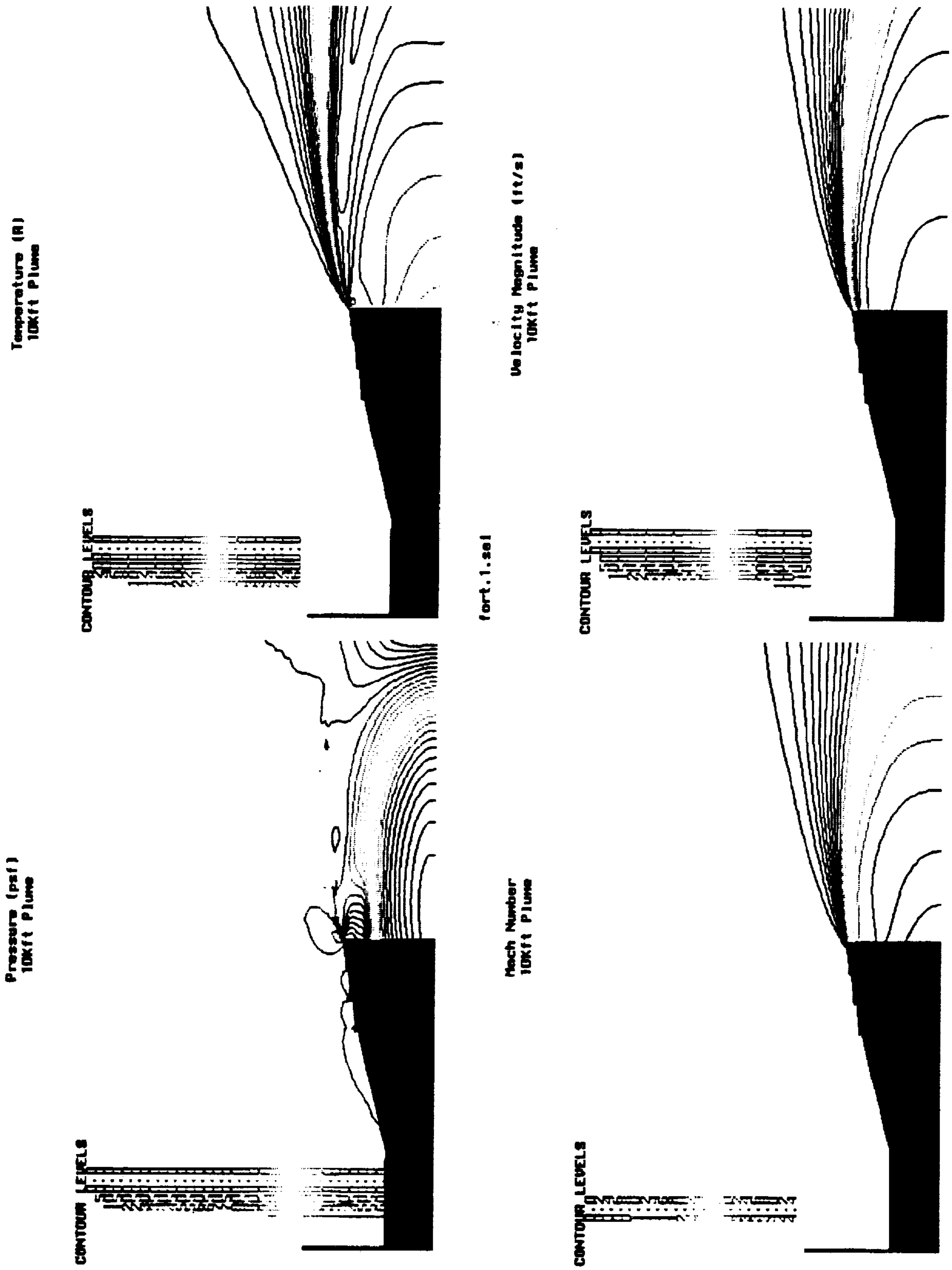


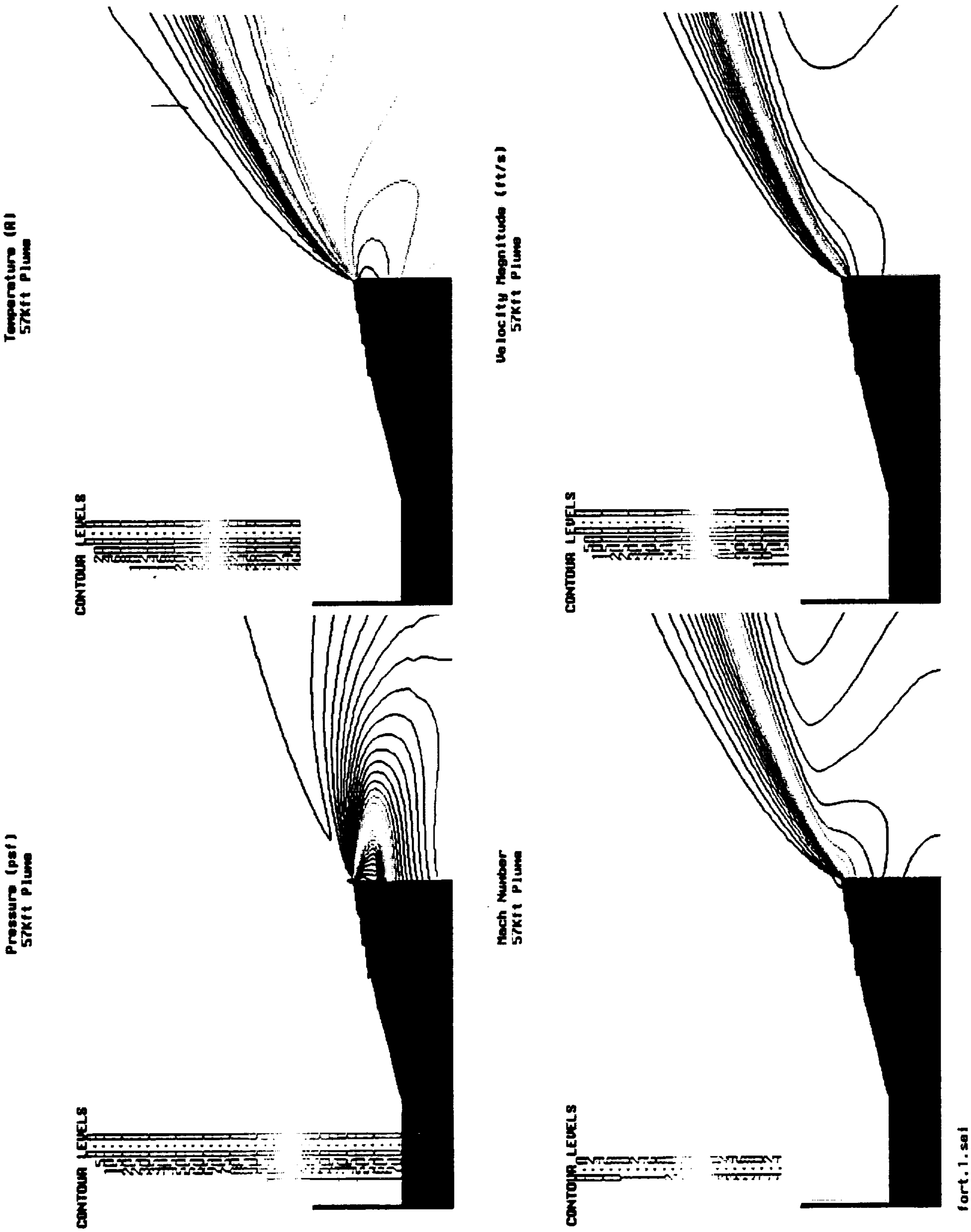
F1 Nozzle Exit Flow
3/23/93
FDNS frozen
FDNS finite rate
RAMP frozen
RAMP finite rate
Radius (in)
Pressure (psf)
0.0
20.0
40.0
60.0
500.0
1000.0
1500.0
2000.0
2500.0

RESULTS, cont.

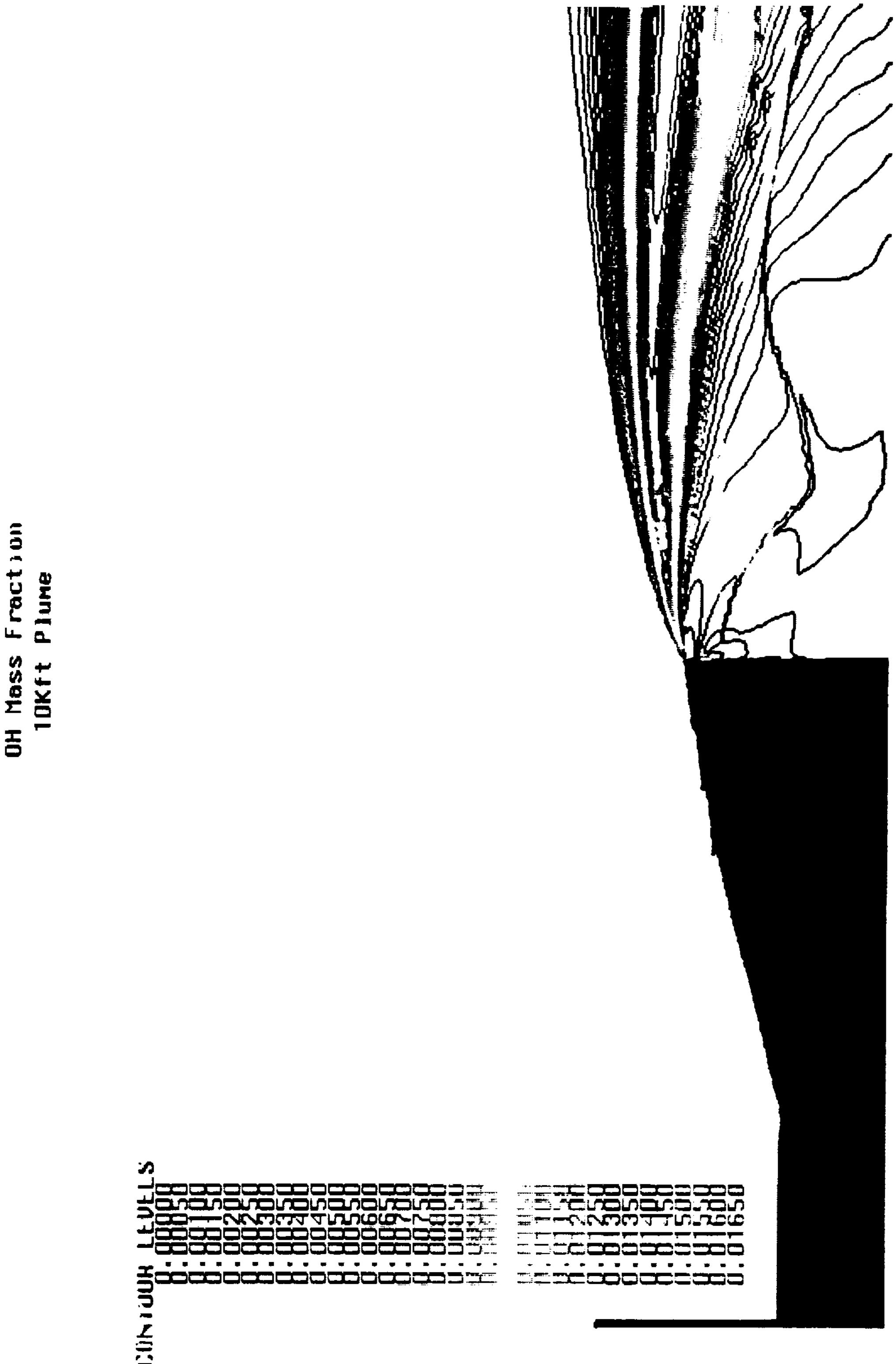
- Plume
  - finite rate chemistry shows reduced rate of reaction at the high altitude as expected
  - significant difference in after burning of soot between the low and high altitude, soot burning at 10kft may be too vigorous
  - Combustible plume products in shear layer at high altitude in lbm/s

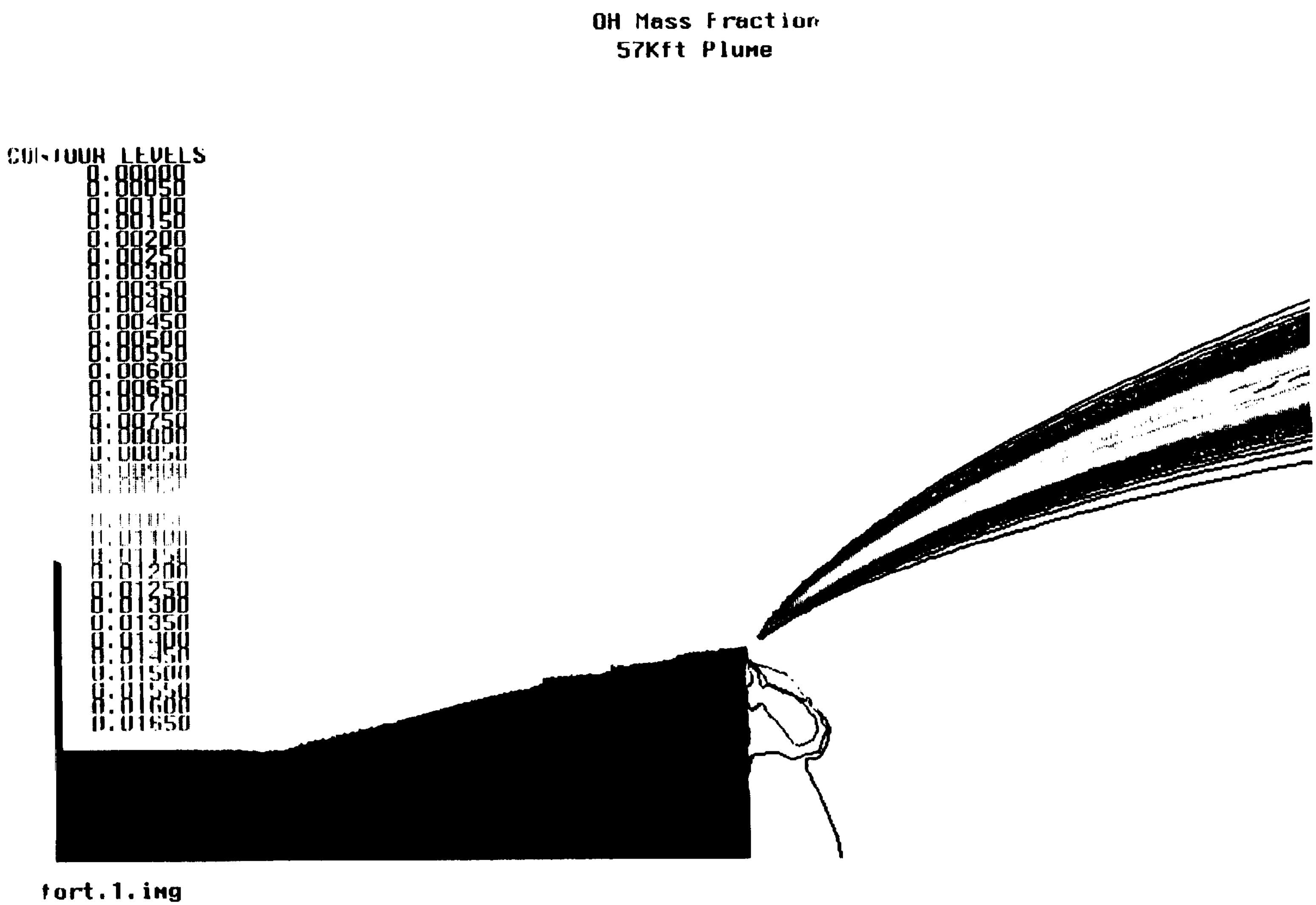
	nozzle radii downstream	
	1/2	1
F1	16.2	57.7
STME	29.6	53.3
ratio	1.8 to 1	.9 to 1


Temperature (R)
10Kft Plume
CONTOUR LEVELS
Velocity Magnitude (ft/s)
10Kft Plume
fort.1.sel
CONTOUR LEVELS
Pressure (psf)
10Kft Plume
CONTOUR LEVELS
Mach Number
10Kft Plume
CONTOUR LEVELS

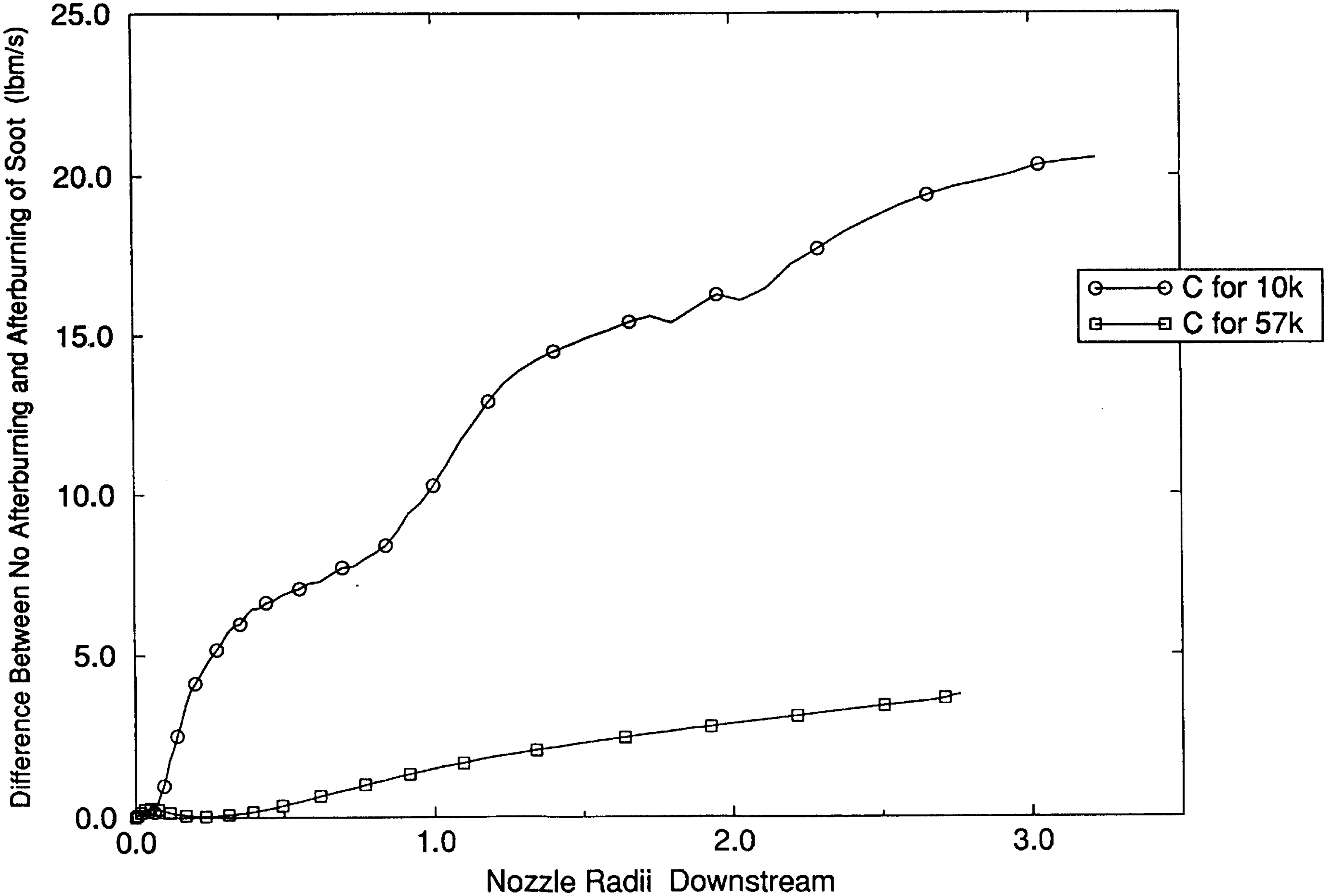


Temperature (R)
57Kft Plume
CONTOUR LEVELS
Velocity Magnitude (ft/s)
57Kft Plume
CONTOUR LEVELS
Pressure (psf)
57Kft Plume
CONTOUR LEVELS
Mach Number
57Kft Plume
CONTOUR LEVELS
fort.1.sel


OH Mass Fraction
10Kft Plume
CONTOUR LEVELS
0.00000
0.00050
0.00100
0.00150
0.00200
0.00250
0.00300
0.00350
0.00400
0.00450
0.00500
0.00550
0.00600
0.00650
0.00700
0.00750
0.00800
0.01250
0.01300
0.01350
0.01400
0.01450
0.01500
0.01550
0.01600
0.01650
fort.1.img


OH Mass Fraction
57Kft Plume
CONTOUR LEVELS
0.00000
0.00050
0.00100
0.00150
0.00200
0.00250
0.00300
0.00350
0.00400
0.00450
0.00500
0.00550
0.00600
0.00650
0.00700
0.00750
0.01200
0.01250
0.01300
0.01350
0.01500
0.01650
fort.1.img

Consumption of Soot Modeled as Carbon in F1 Plume
i.e., Afterburning



CONCLUSIONS

- Thrust matched well for F1 with frozen flow, more work needed to get the finite rate calculation to match thrust levels.
- Need to reconcile differences between FDNS and the RAMP calculations.
- Soot burning model is too vigorous at low altitude, appears qualitative correct at high altitude.
- Recirculation to the base region was not representative of the S1-C/F1base region flow field (1st objective).
- Appears to be a significant difference in the plume shear layer development between F1 and STME (2nd objective).
  - Indicates that plume shear layer development and combustible gas concentrations are not similar, therefore, the NLS2 Base Gas Temperature Scaling Methodology may be non conservative.