Thermal & Fluids Analysis Workshop TFAWS 2004

Jet Propulsion Laboratory

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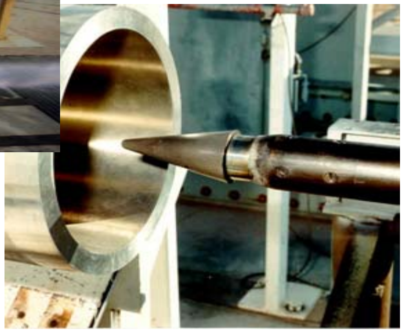
COMPARISON OF ENGINEERING LEVEL AND FULL NAVIER STOKES PREDICTIONS WITH TEST DATA AT THE NAVY'S AIR BREATHING ENGINE AND AEROTHERMAL TEST FACILITY T-RANGE



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Overview

- A comparison of engineering level and full Navier-Stokes predictions of flow-field heating conditions was made for a series of aerothermal tests performed at the Naval Air Warfare Center Air Breathing Engine and Aerothermal Test Facility, T-Range, in China Lake CA.
- Thin skin calorimeters were used to quantify the aerothermal boundary conditions imparted to a test fixture.
- The engineering level analysis code ATAC3D, developed under an Army SBIR, was used to derive the local boundary conditions.
- The full Navier-Stokes computational fluid dynamics code OVERFLOW was used to quantify the relative flow field and resulting heat fluxes for comparison to the engineering predictions and data
- This presentation will discuss the analytic and experimental methods utilized to determine boundary conditions and possible flowfield effects on a complex test fixture.

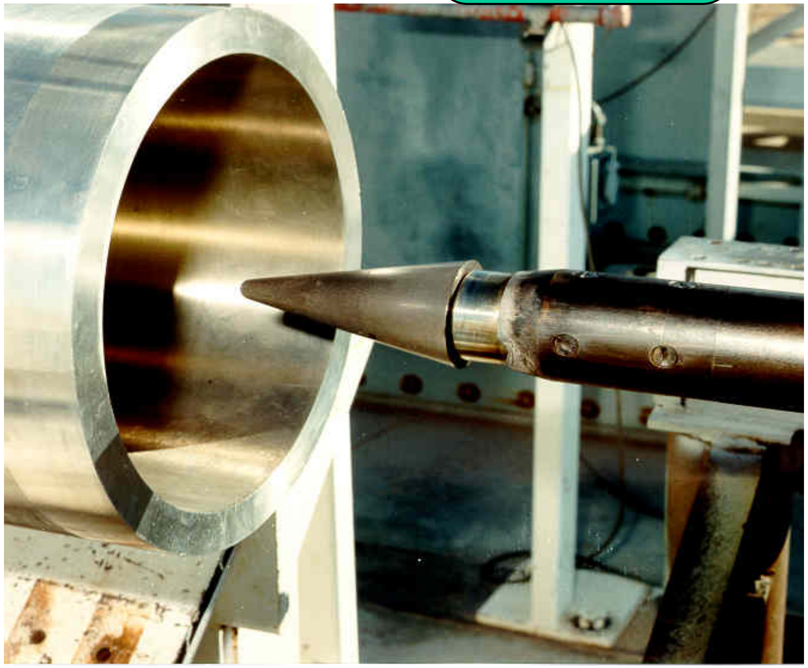
T-Range Capabilities

- High-Pressure Air Blow Down Facility
- 2900 cu ft of air stored at 3000psia
- Propane/Air combustion used to raise enthalpy of air increased
- Air exhausted to atmosphere at 2300 ft above sea level
- Makeup oxygen used for engine testing to replace that used in propane/air combustion

T-Range Capabilities

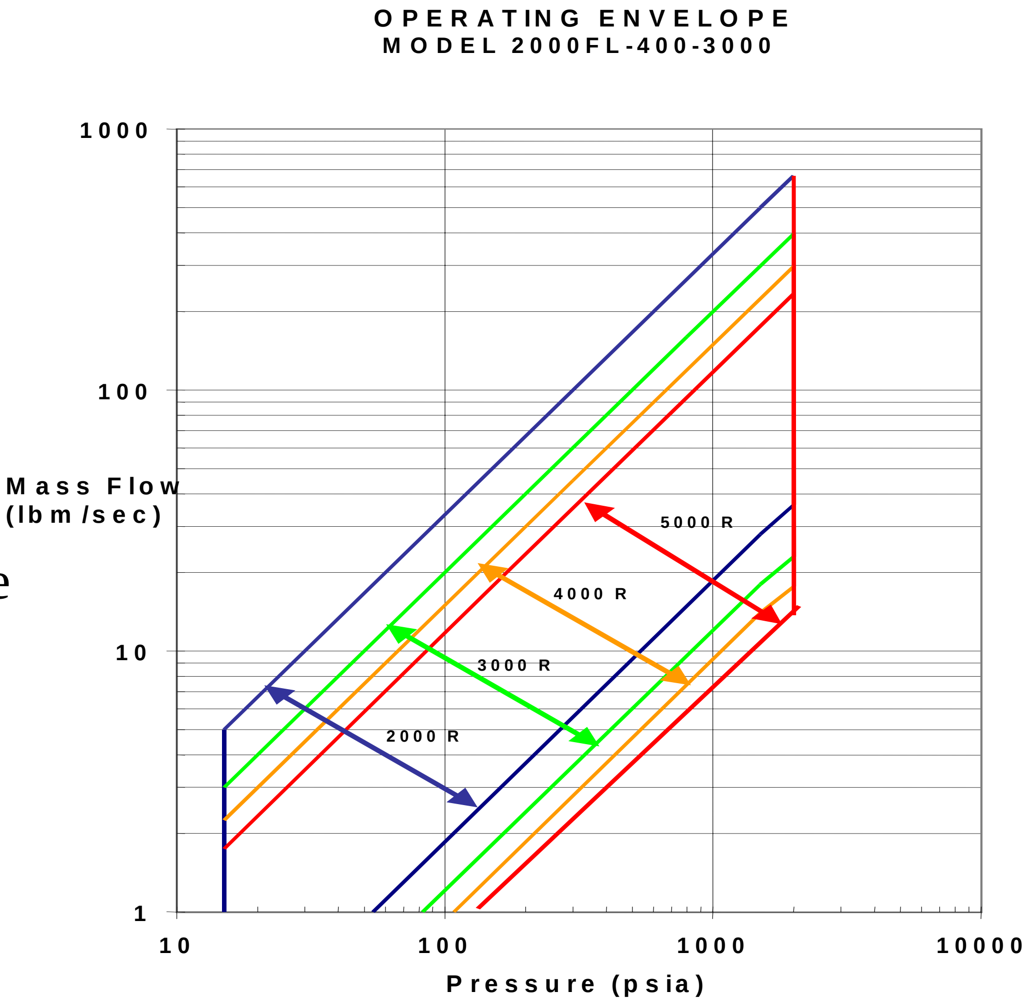
- Air, propane and O_2 digitally controlled by PC running LabView with full proportion-integral-differential gain control loops
- T_t of air adjusted w/mass flow to match hot wall heat fluxes and surface temperatures in flight
- Free-jet nozzles: P_t in air heater held constant so flow is perfectly expanded to avoid shocks and expansion waves
- Direct-connect engines: Computer control used to vary P_t and T to match variation due to missile altitude and velocity changes

Test article in nozzle free-jet



T-Range Enhancements

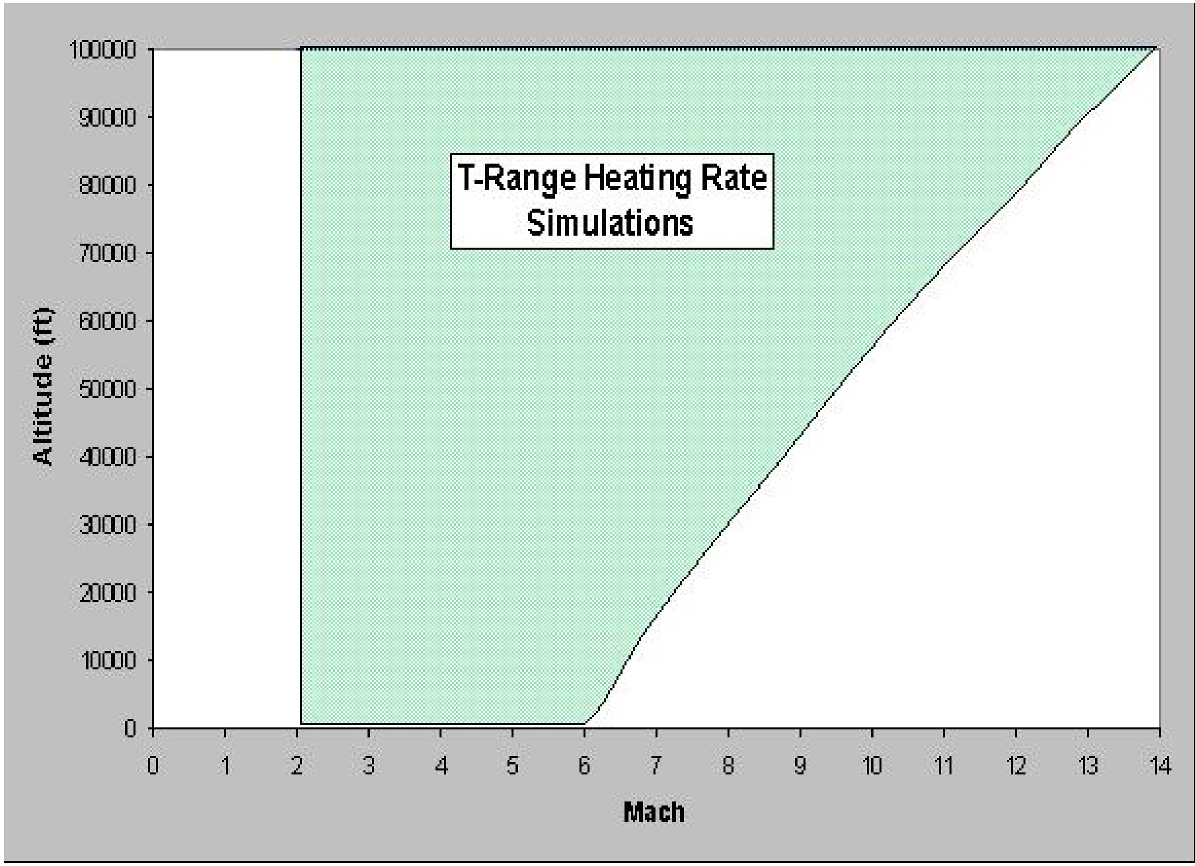
- New air heater and nozzle being installed
  - Capable of continuous operation at 4500 °F
  - Nozzle (13.4” exit) will operate at Mach 3.65
  - SUE burner uses a replaceable water-cooled liner to increase mass flow and T_t for both test cells
- Additional air storage, totaling 4650 cu. ft.



T-Range Enhancements

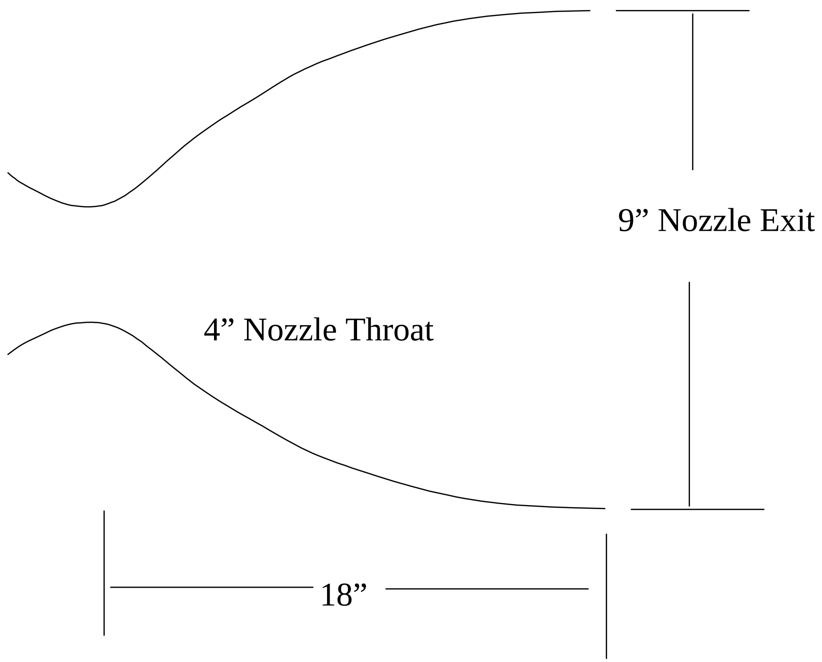
- Stagnation heating rates up to 1000 btu/ft^2-sec

(ref: 2-inch diameter hemisphere)



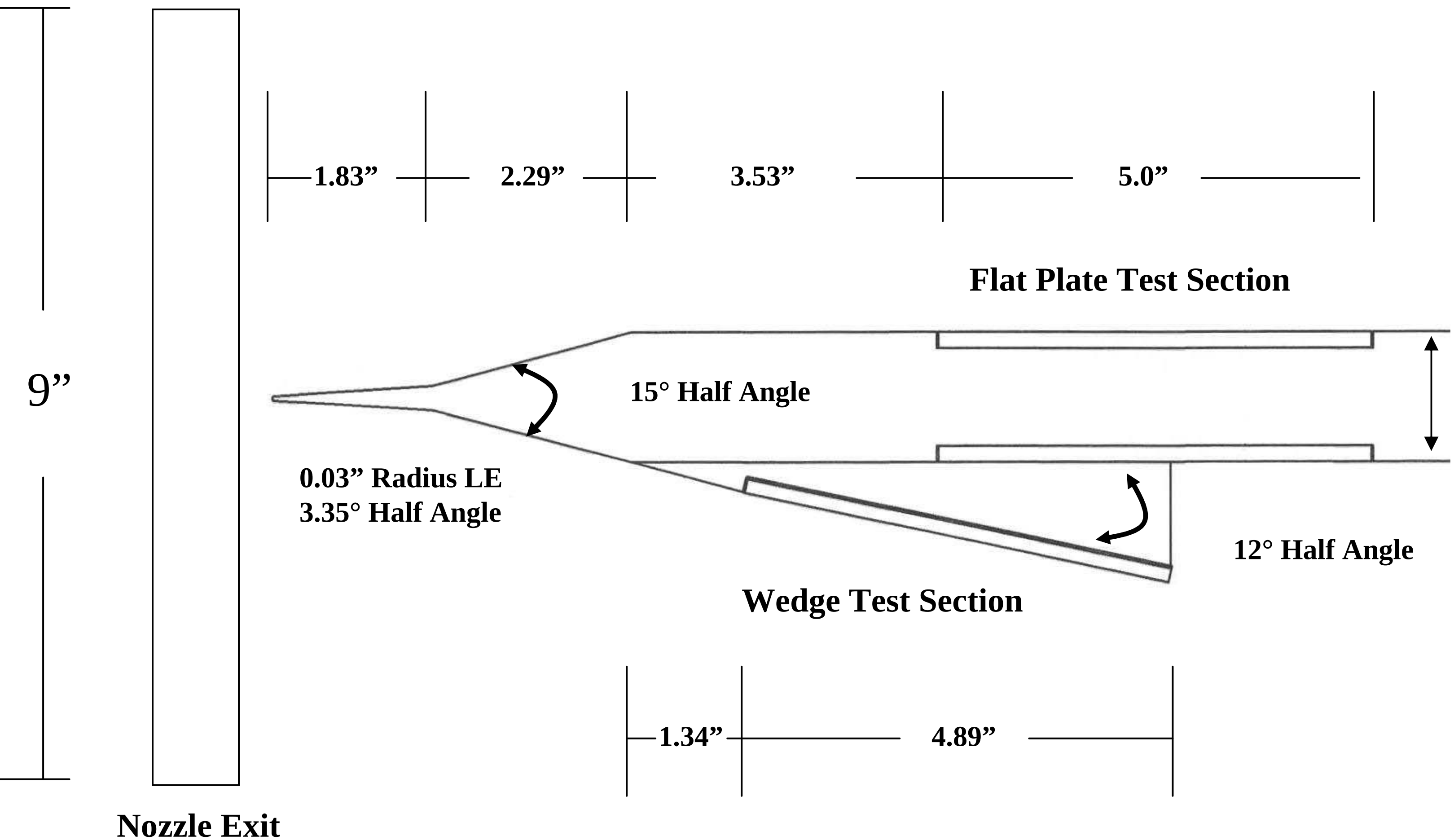
T-Range Flow Conditions

- Facility Conditions for Current Test
  - Mach 1.9 Semi-Contoured Nozzle, $P_{CHAMBER}$=90 psi (mass flow, m_{DOT}, and $T_{CHAMBER}$ were variable to match transient environment of interest)
  - Facility channel labeled TPL-1 was used as a measure of chamber temperature. The value of TPL-1 was used as the total temperature in both ATAC3D and OVERFLOW

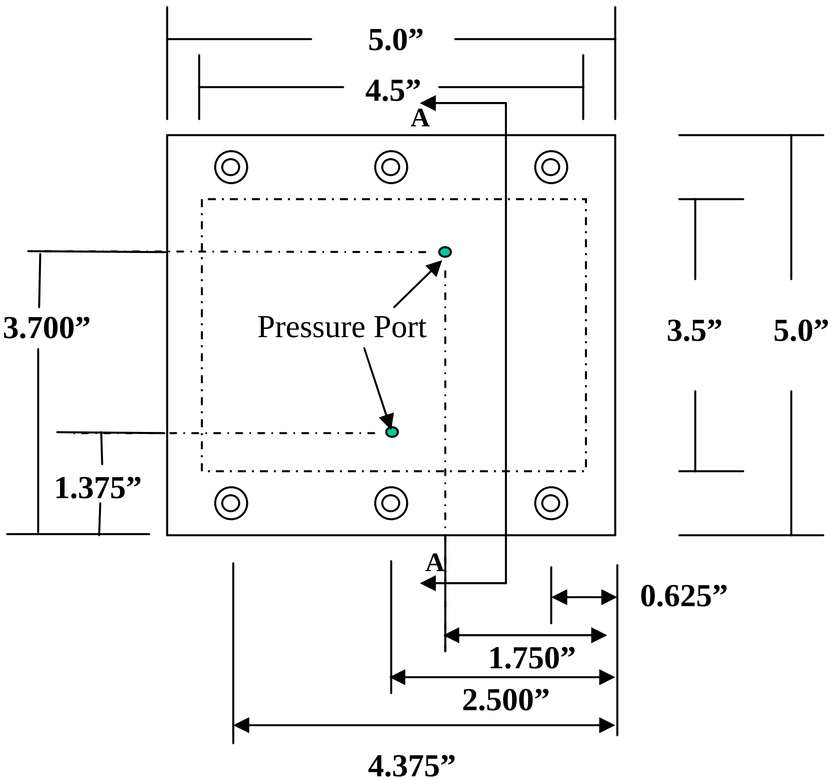


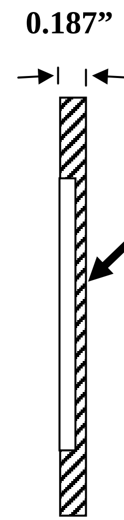
Mach 1.9 Nozzle Contour

Wedge Test Fixture



Thin Skin Calorimeter Design



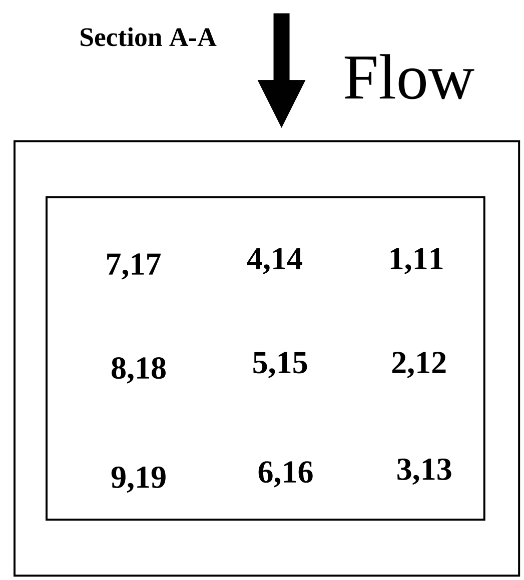


Section A-A

Thin Skin Wall Thickness

0.125” for Wedge Calorimeter
- Includes 2 Pressure Ports
- 9 Welded Backside Thermocouples

0.069” for Flat Calorimeter
- No Pressure Ports
- 9 Welded Backside Thermocouples

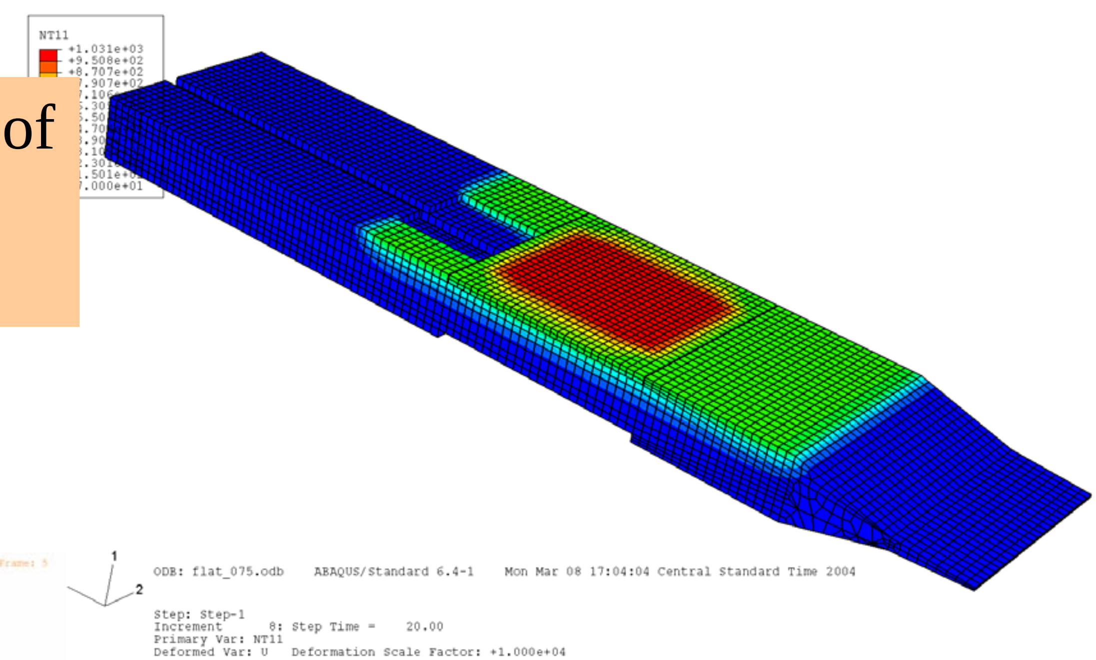


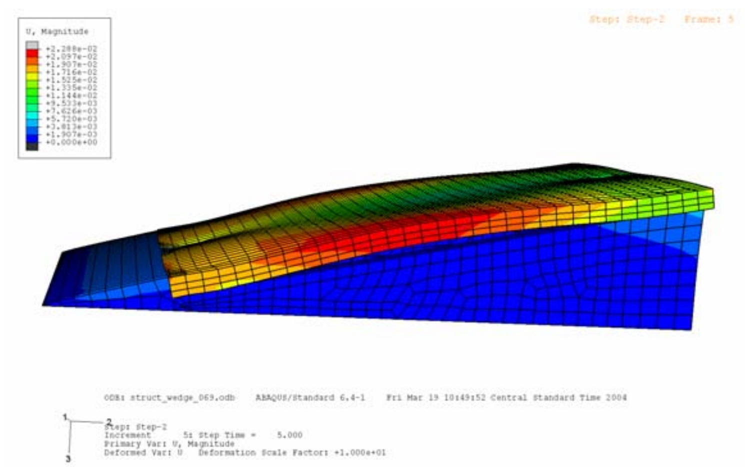
Thermocouples

#s correspond to Wedge,Flat

3-D Finite Element Analysis

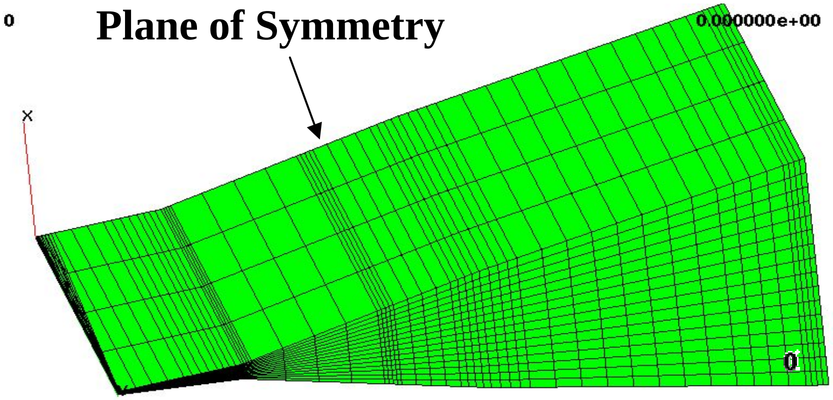
FEA provided comparison of 1-D versus 3-D thermal response of calorimeter



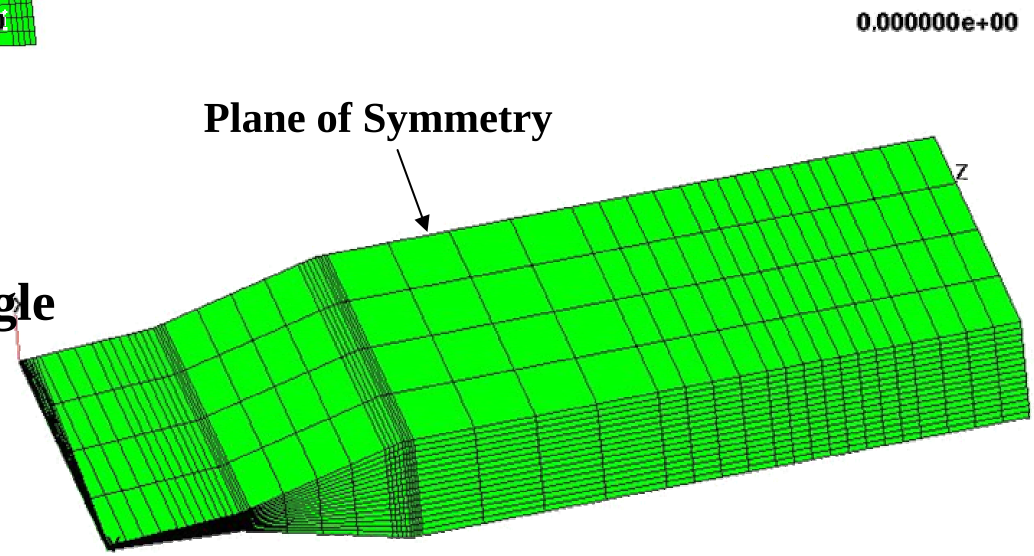


Detailed FEA provided confidence in calorimeter thermostructural response

ATAC3D Analysis Configurations

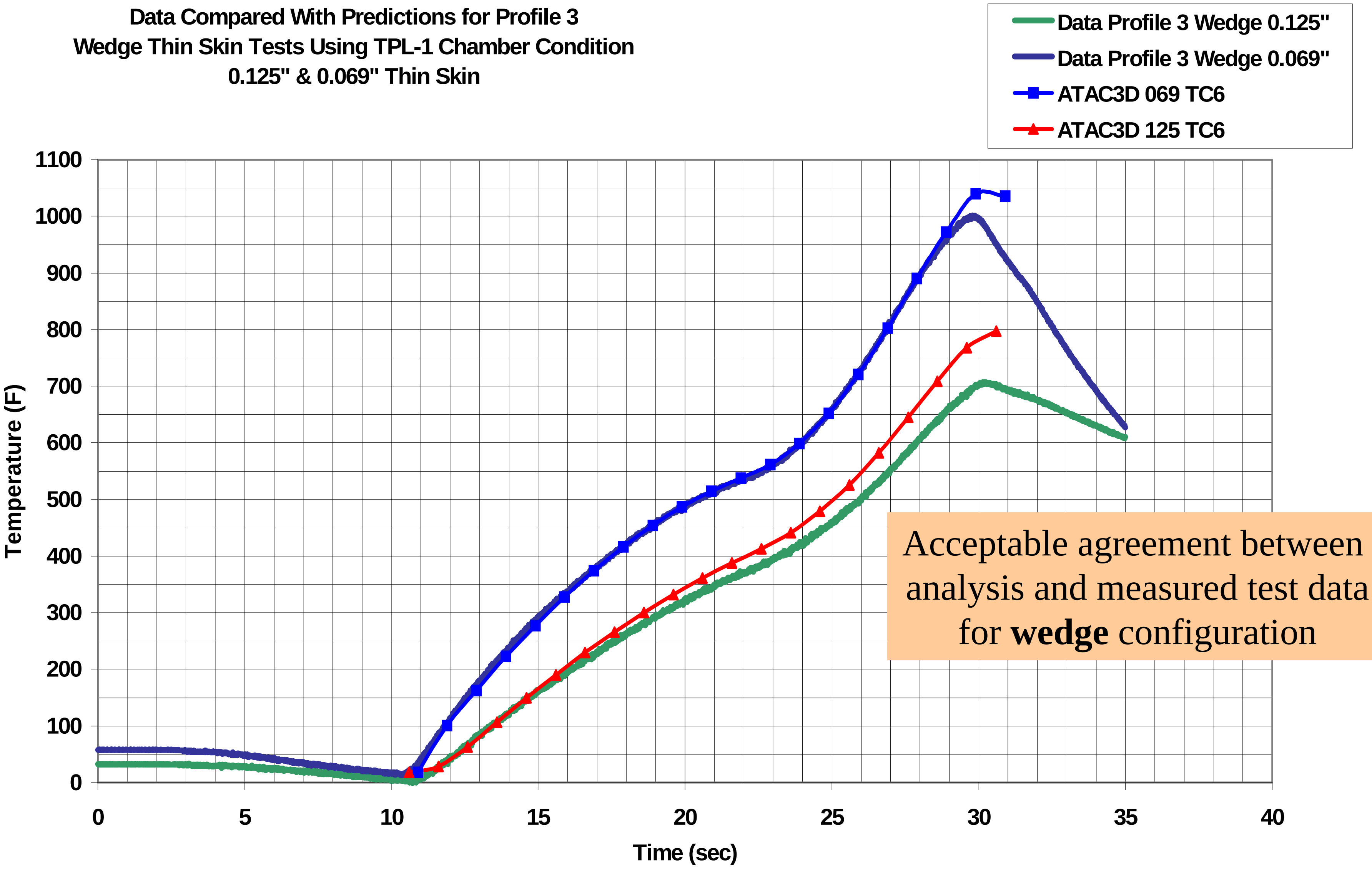


- **0.03” Radius LE**
- **3.35° Fin Leading Edge Half Angle**
- **15° 2nd Wedge**
- **12° Test Section Wedge**



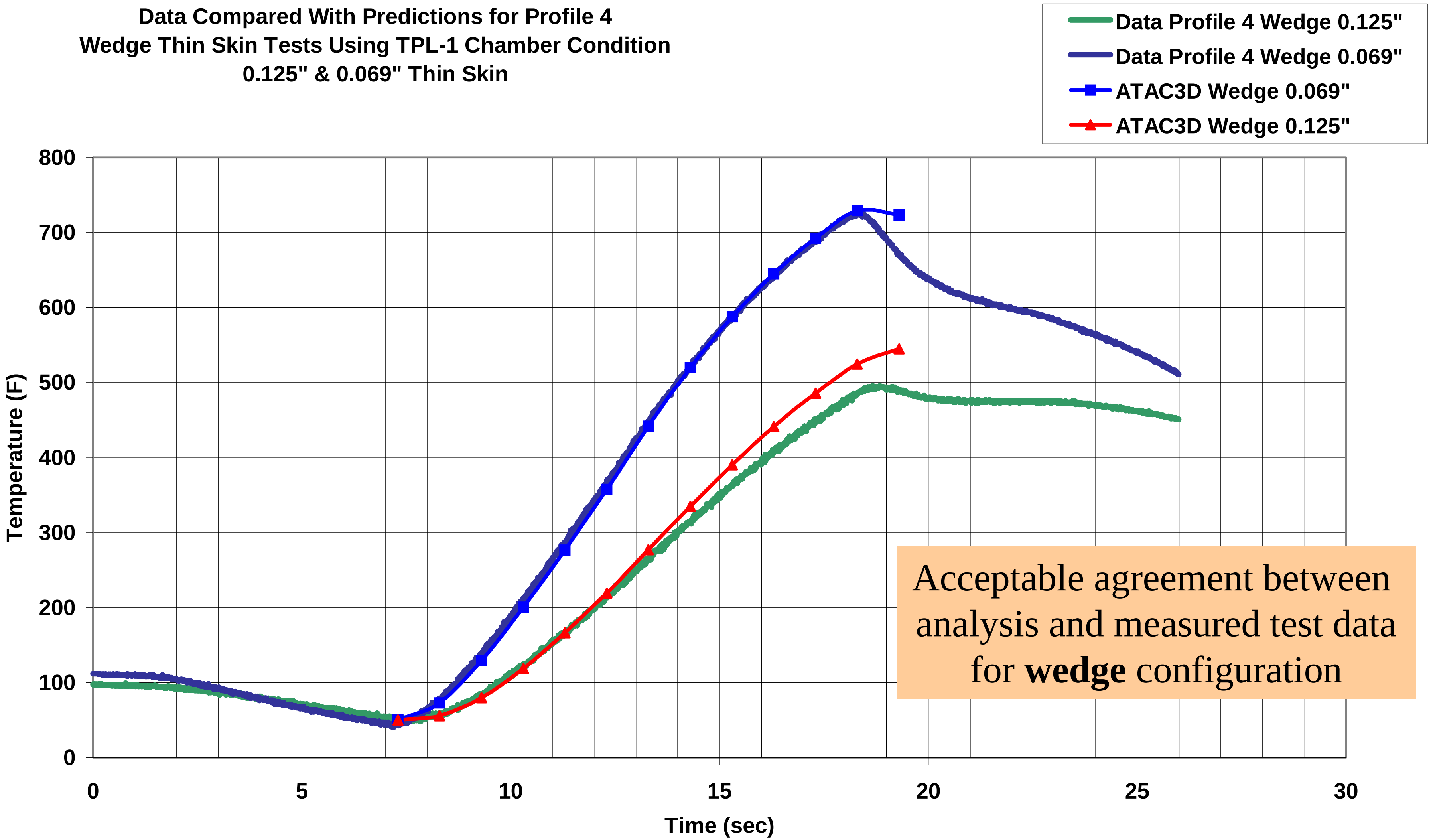
- **0.03” Radius LE**
- **3.35° Fin Leading Edge Half Angle**
- **15° 2nd Wedge**
- **Flat Test Section Wedge**

Comparison of Thin Skin Data and Predictions Profile 3 Wedge



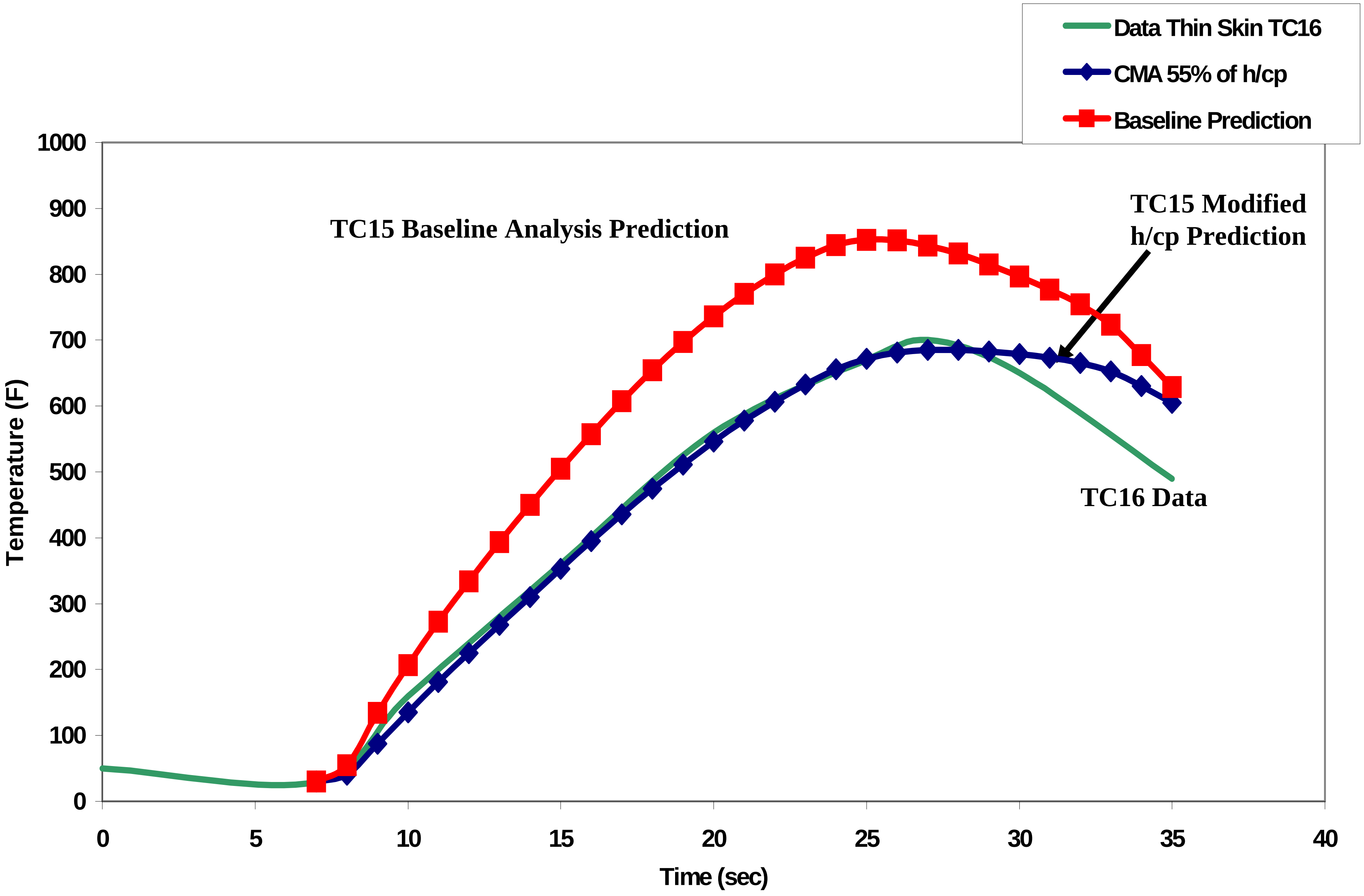
Acceptable agreement between analysis and measured test data for **wedge** configuration

Comparison of Thin Skin Data and Predictions Profile 4 Wedge

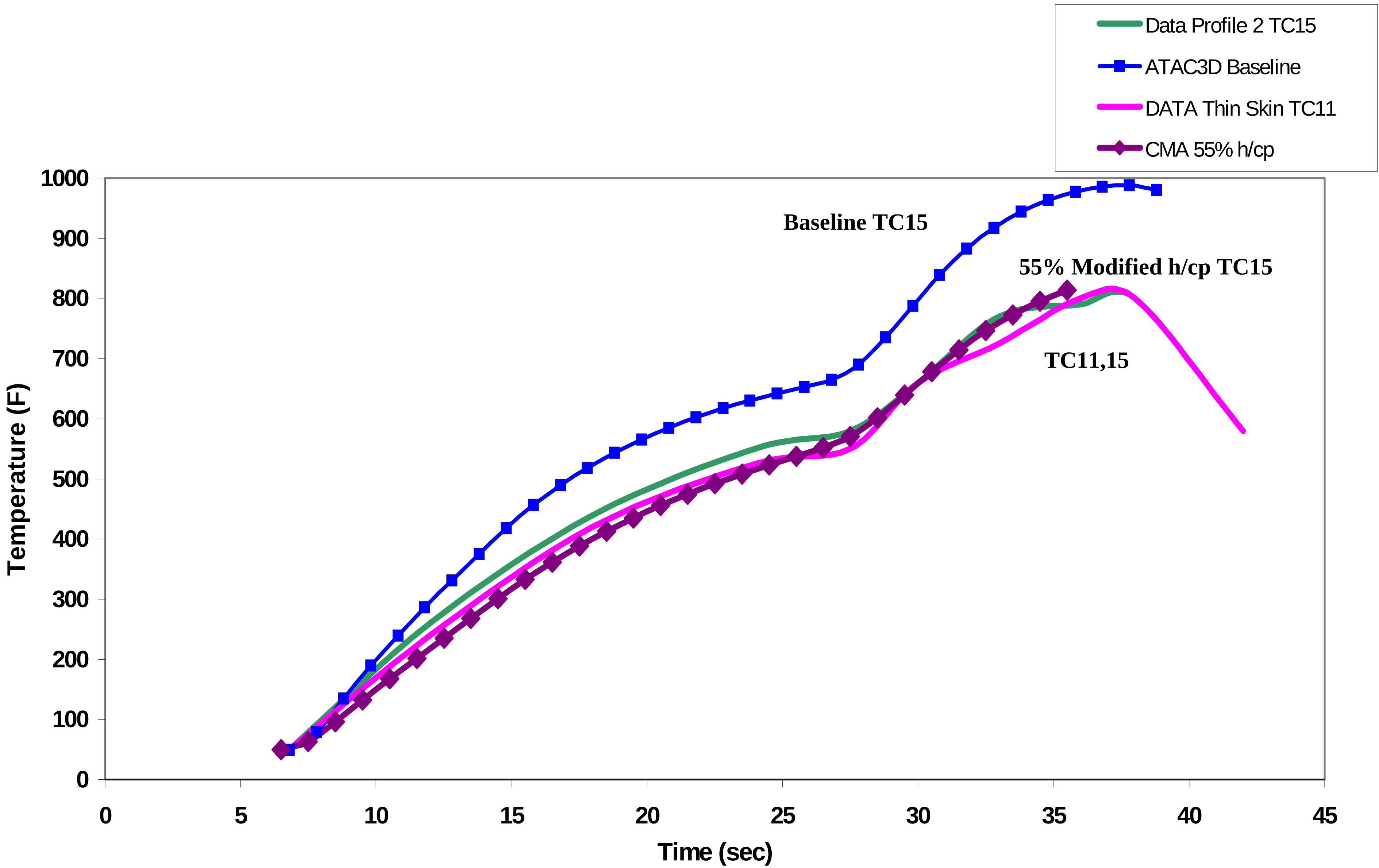


Acceptable agreement between analysis and measured test data for **wedge** configuration

Profile 1 Predictions and Data
Flat Test Section



Profile 2 Predictions and Data
Flat Test Section

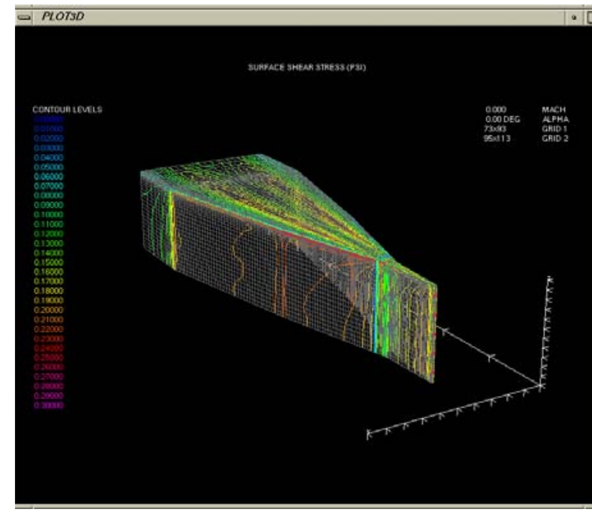


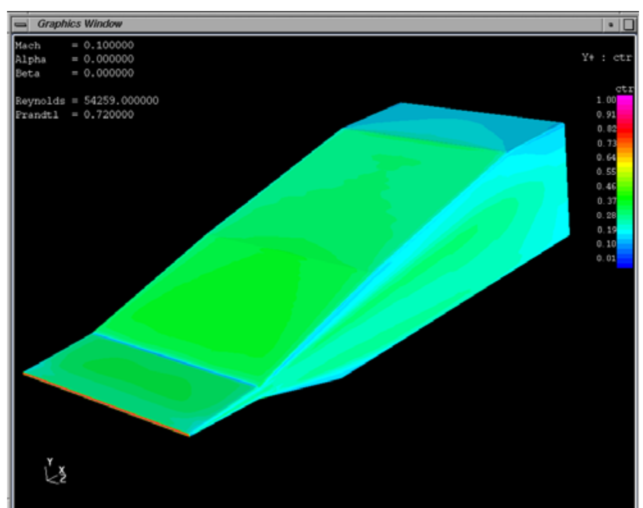
Predictions and Data Comparison

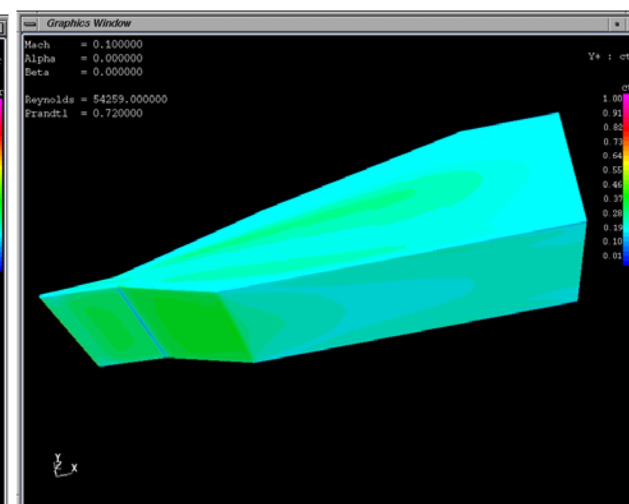
- Why does ATAC3D provide good agreement for the 12 degree wedge calorimeter data but over predicts the thermal response for the flat configuration?
  - Laminar versus Turbulent flow?
  - Flow separation?
  - Prandlt-Meyer expansion fan causing below ambient pressure distribution?
  - Need to assess engineering method for predicting heating
- CFD was utilized to visualize the flowfield over the 2 configurations and provide a more rigorous characterization of the aerothermal environment

CFD Modeling Assumptions

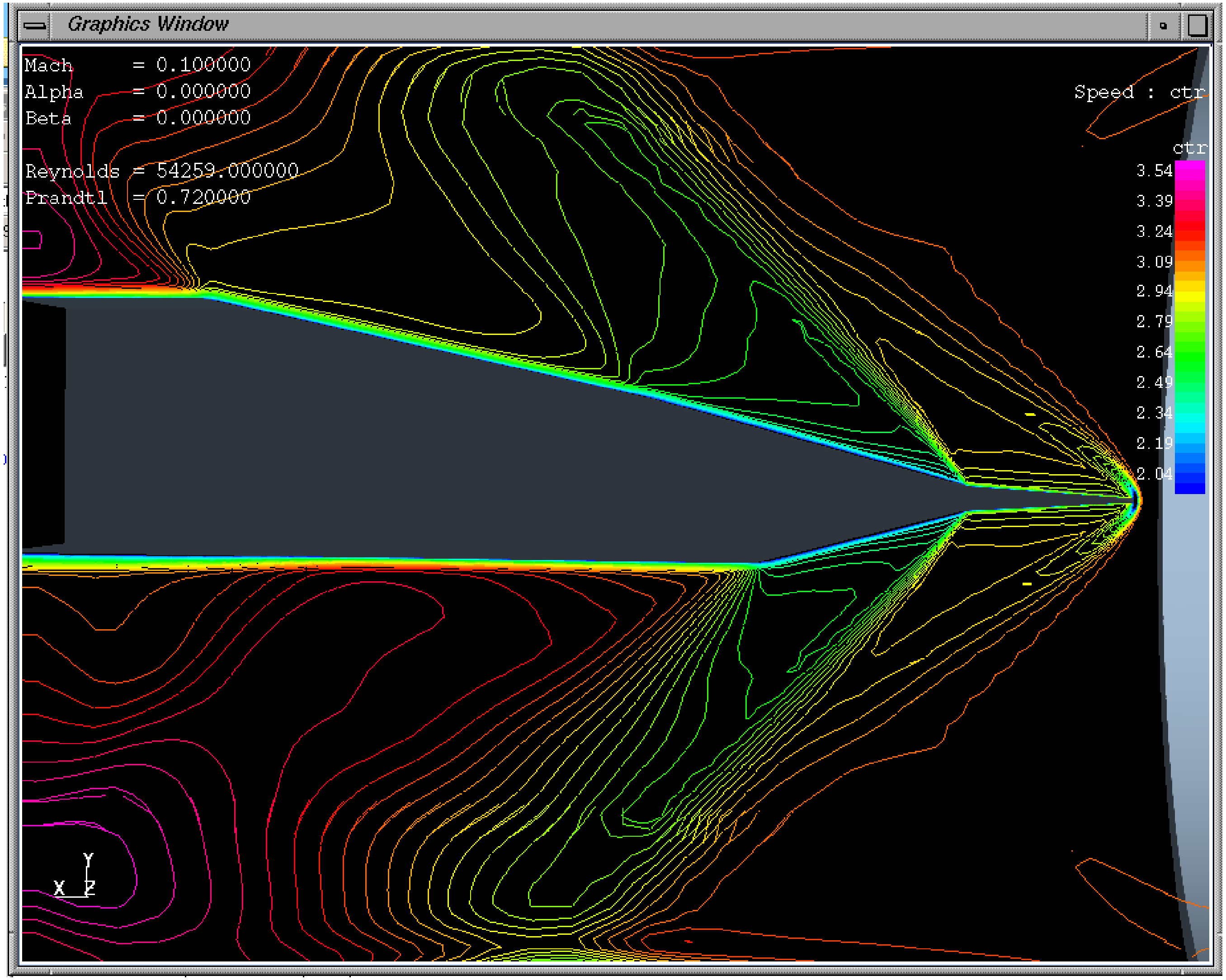
- OVERFLOW full Navier-Stokes code
- 3-dimensional flow
- Real gas effects
- Nozzle contour modeled
- Boundary layer resolved for various chamber and wall temperatures of interest: (1200°F-300°F,600°F:1800°F-300°F, 800°F)





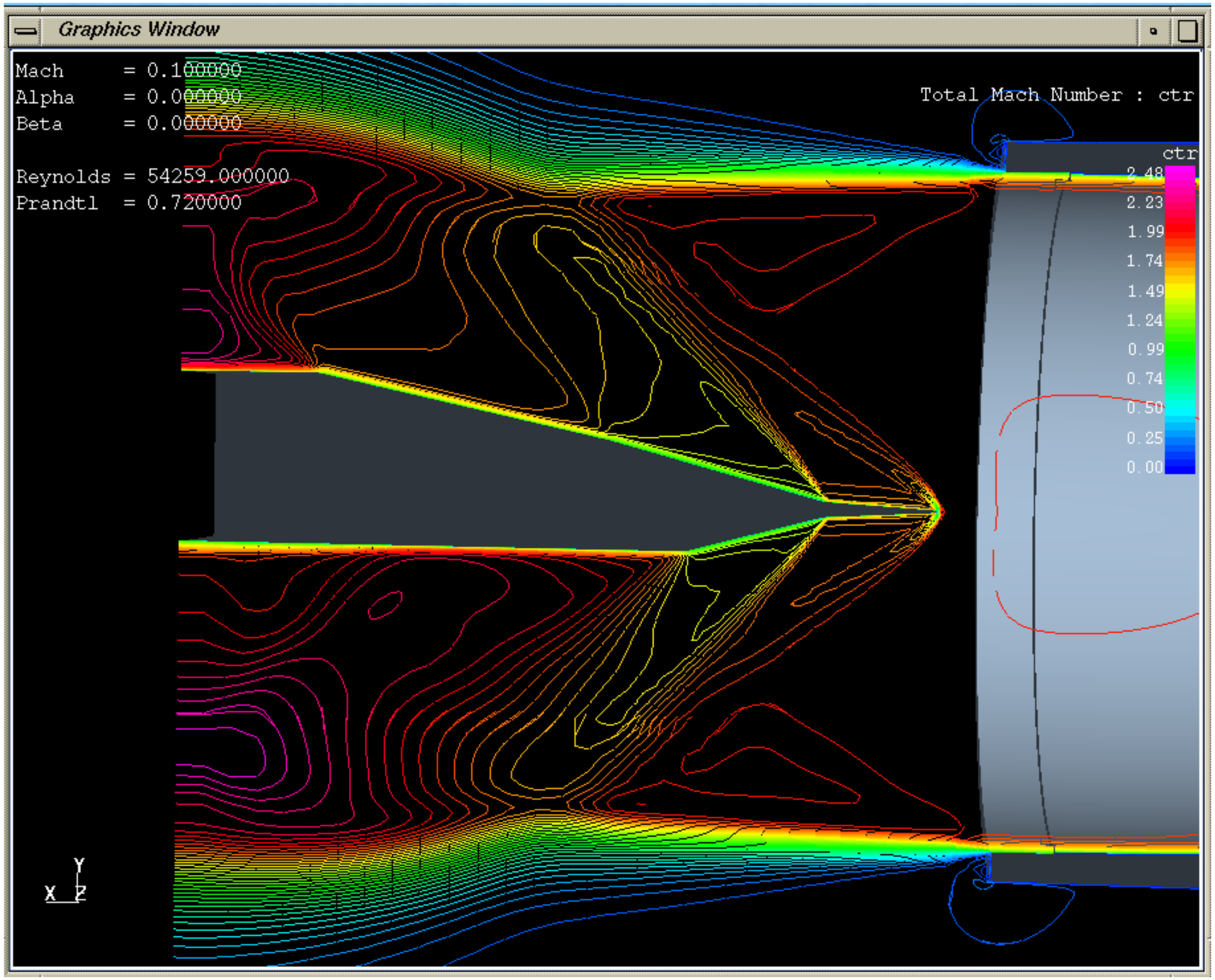


Velocity Contours



Non-dimensionalized by the free-stream speed of sound (337.9 m/s, 1108.6 ft/s)

Mach Number Profile

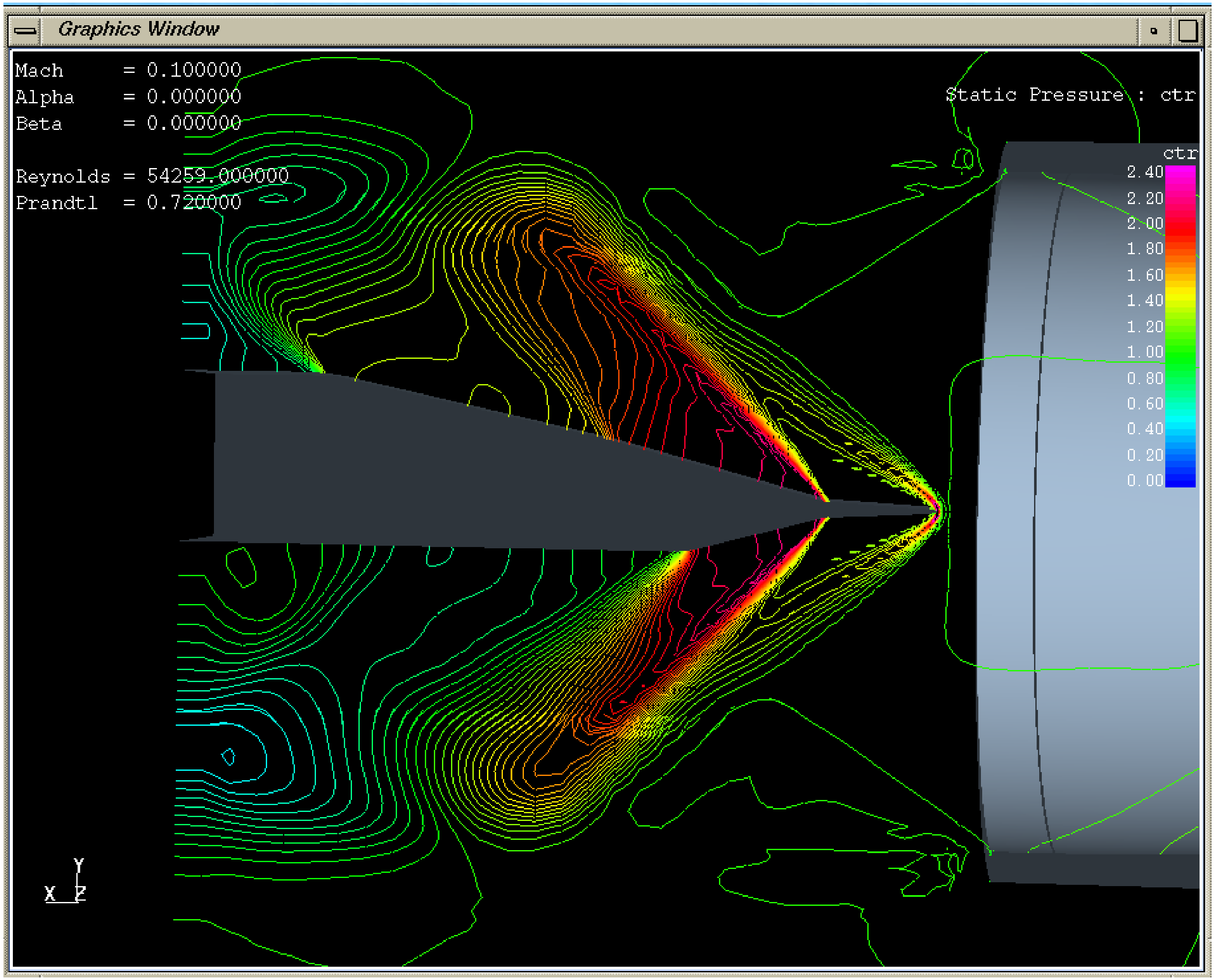


T0=1200F, Twall = 300F

Boundary Layer well resolved at the wall for both velocity and temperature.

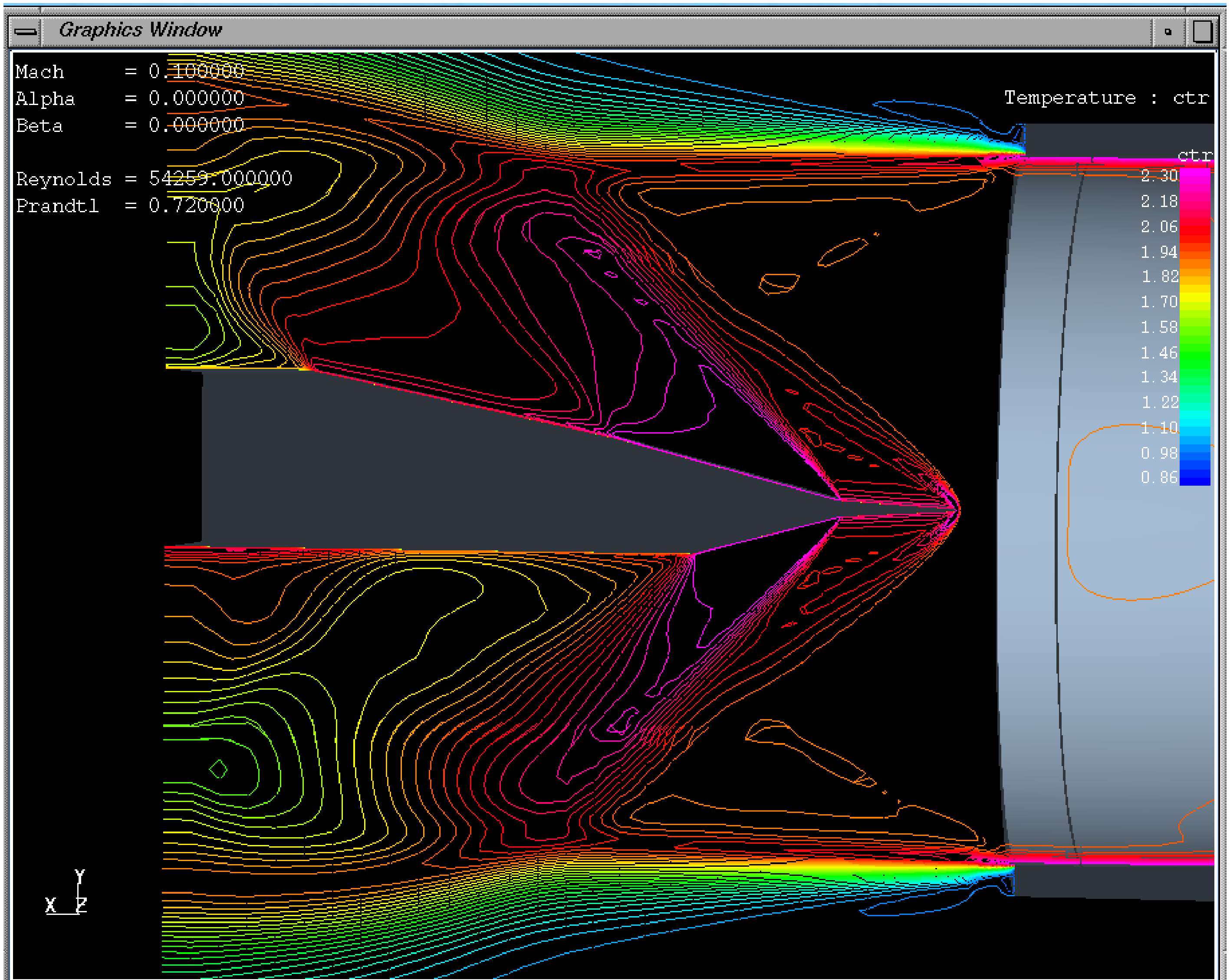
No Flow Separation & Verified Uniform Flow

Static Pressure (P amb. = 1.0)

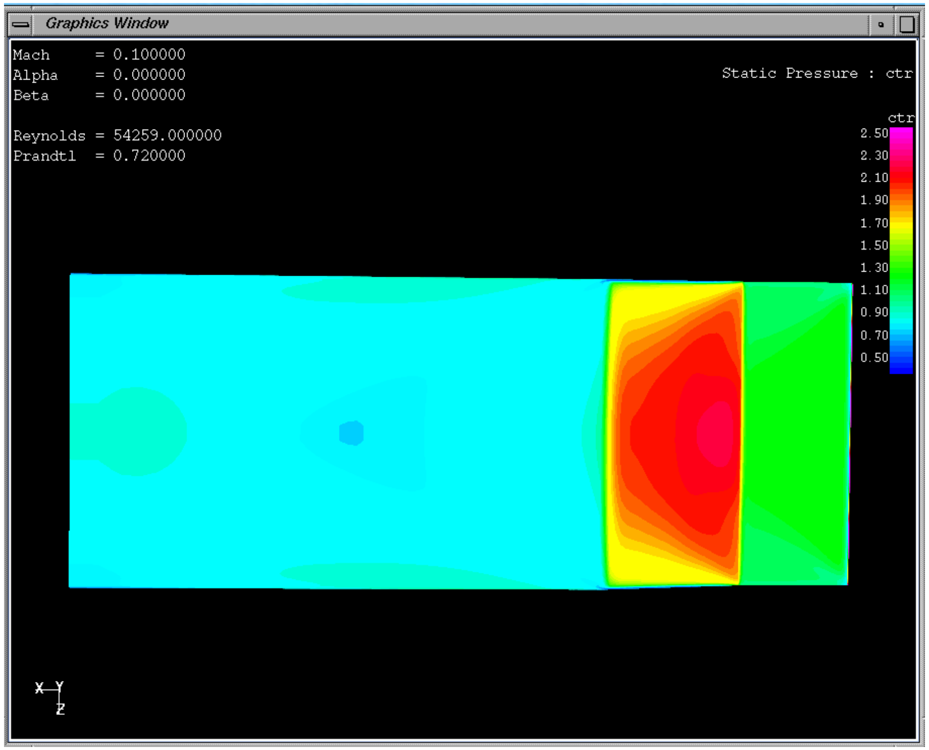


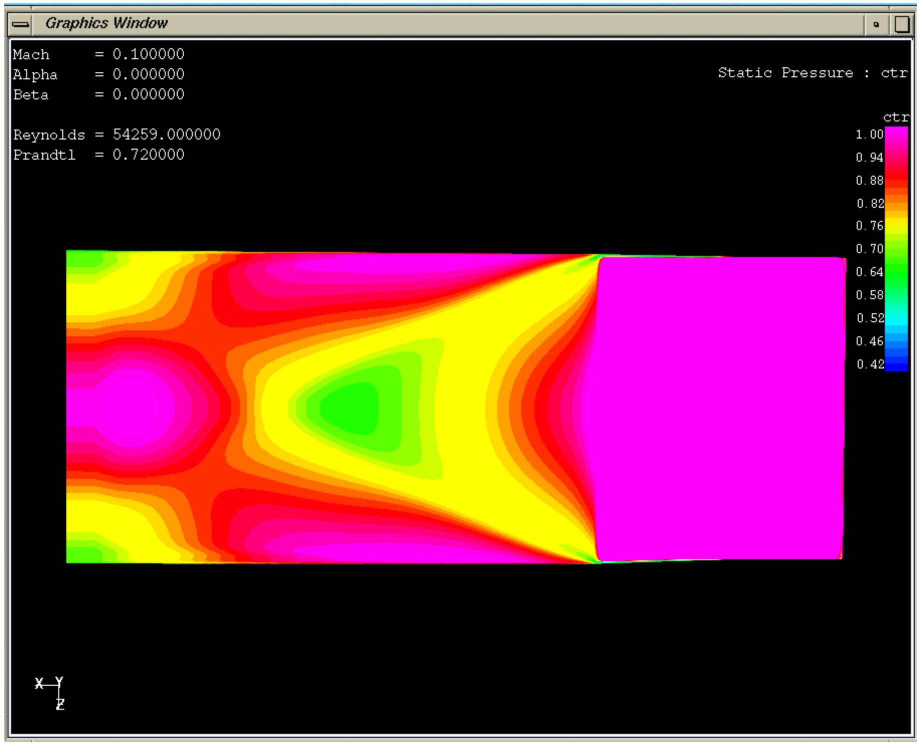
Low pressure on the bottom, flat, surface

Static Temperature (T amb. = 511R).



CFD Static Pressure on Flat Test Fixture



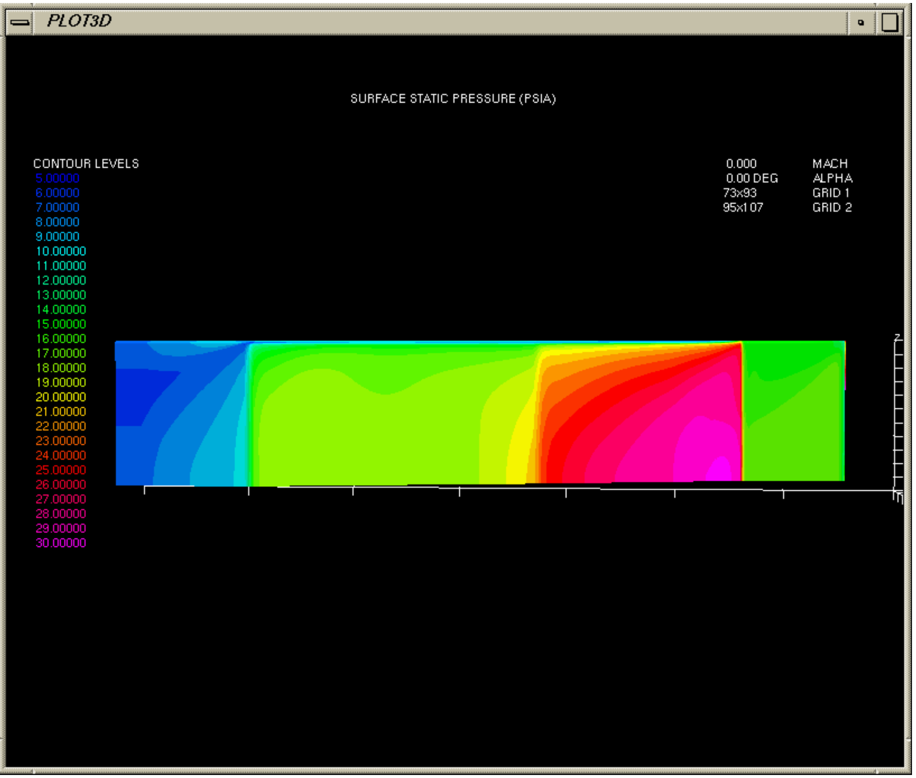


0.5<Ps (atm)<2.5

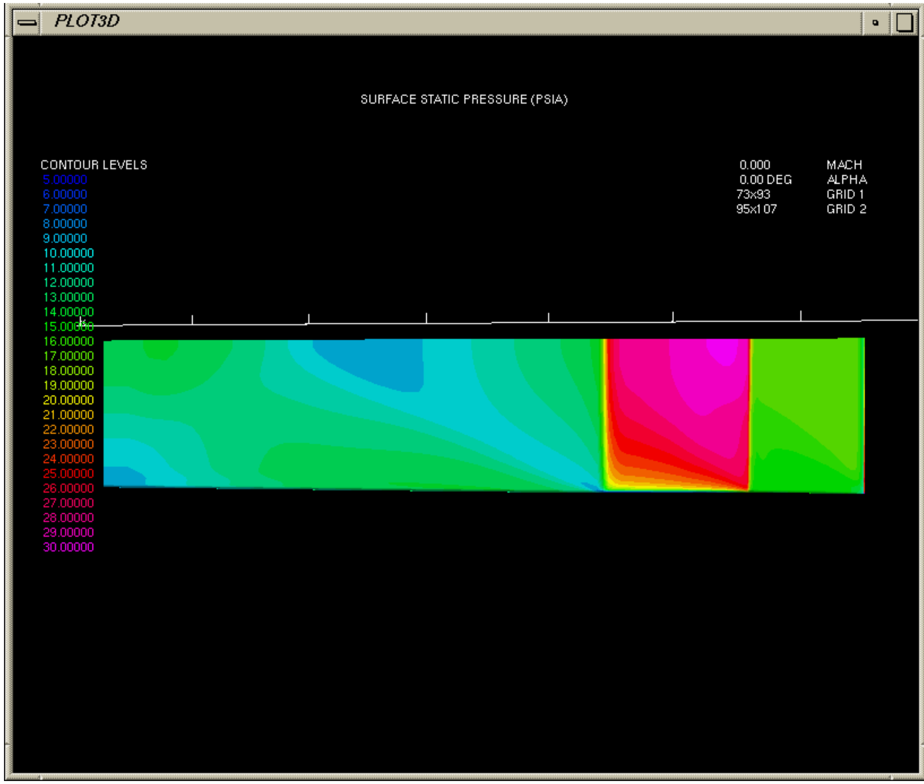
0.5<Ps (atm)<1.0

Sub-ambient and variable pressure at calorimeter station

CFD Surface Static Pressure (psia)

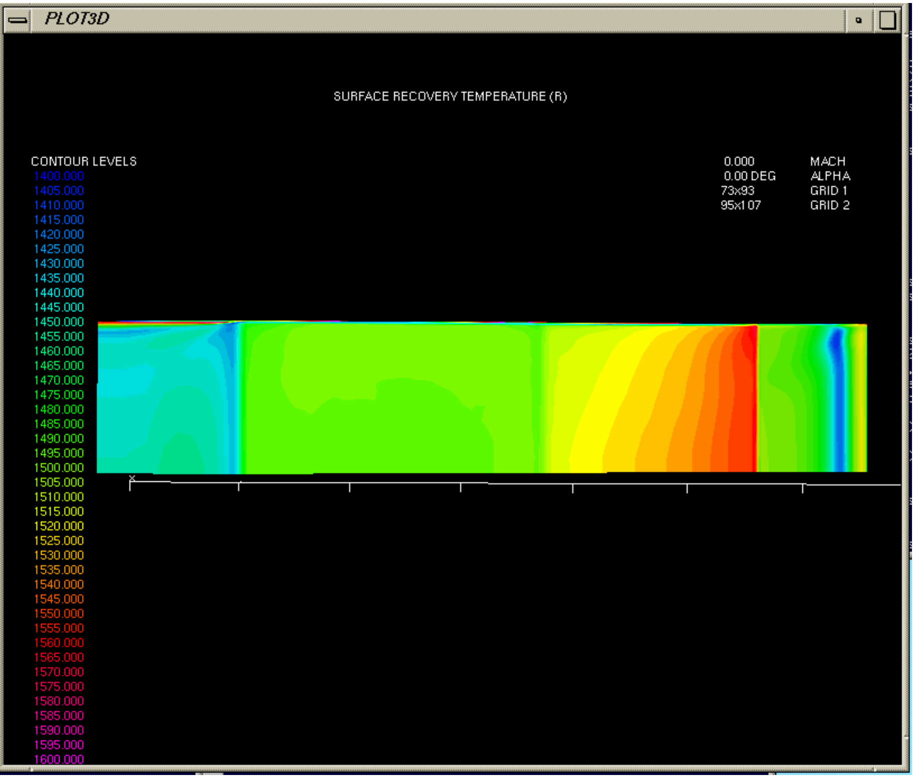


WEDGE

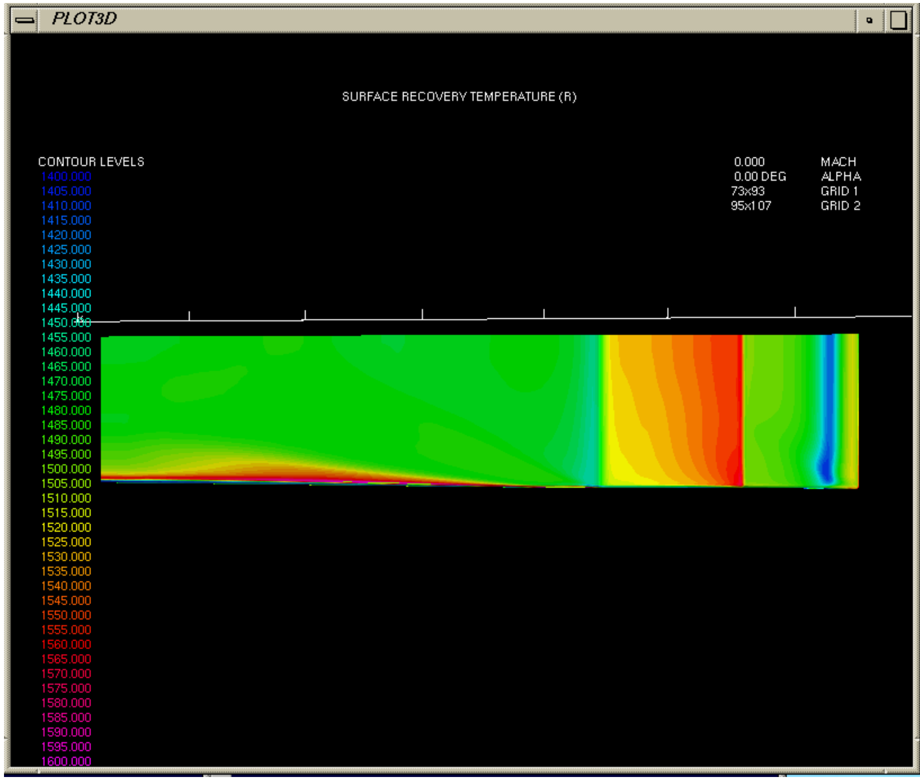


FLAT

CFD Surface Recovery Temperature



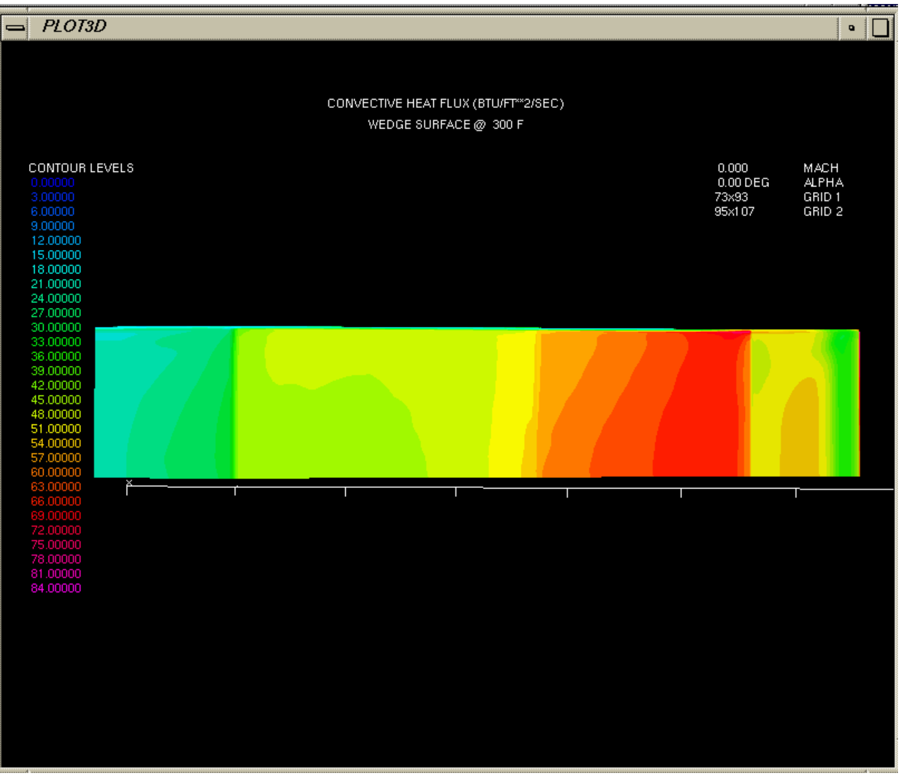
WEDGE



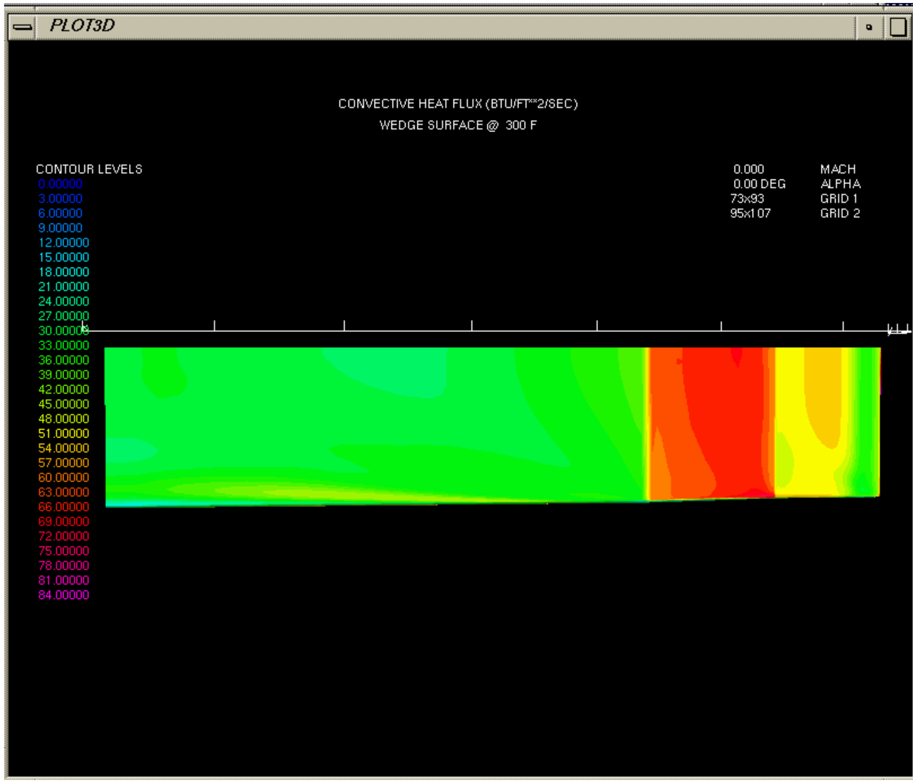
FLAT

Note: Trec is computed by extrapolating from two isothermal wall solutions (300F and 600F) to the adiabatic wall temperature.

CFD Convective Heat Flux at Twall = 300°F

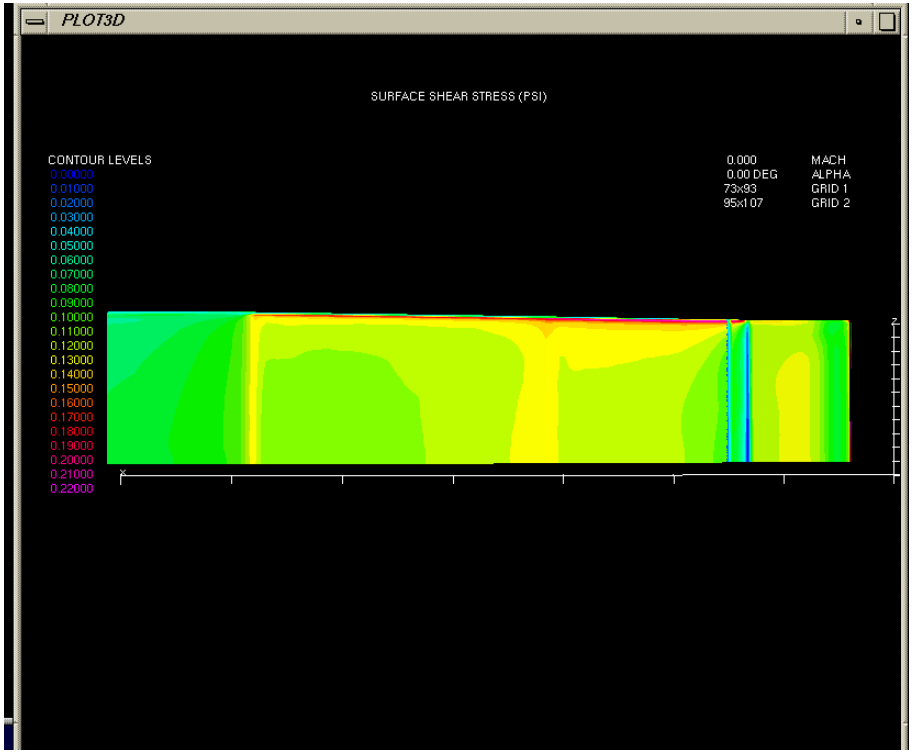


WEDGE

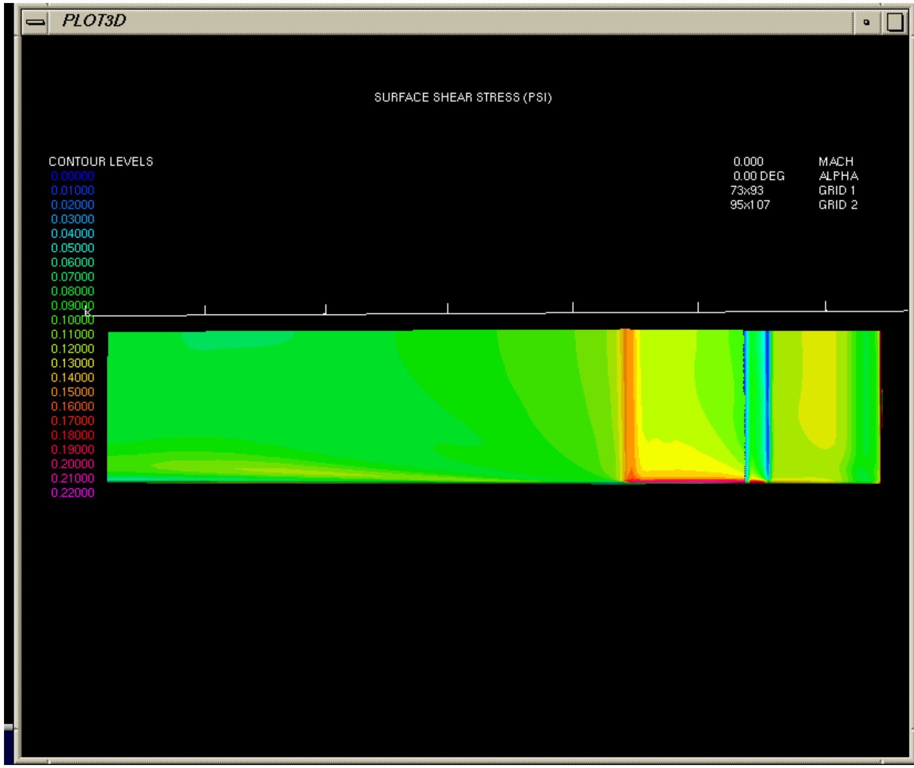


FLAT

CFD Shear Stress

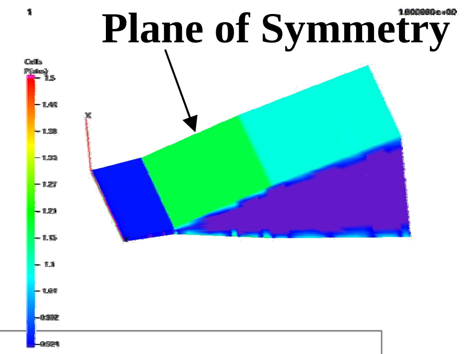


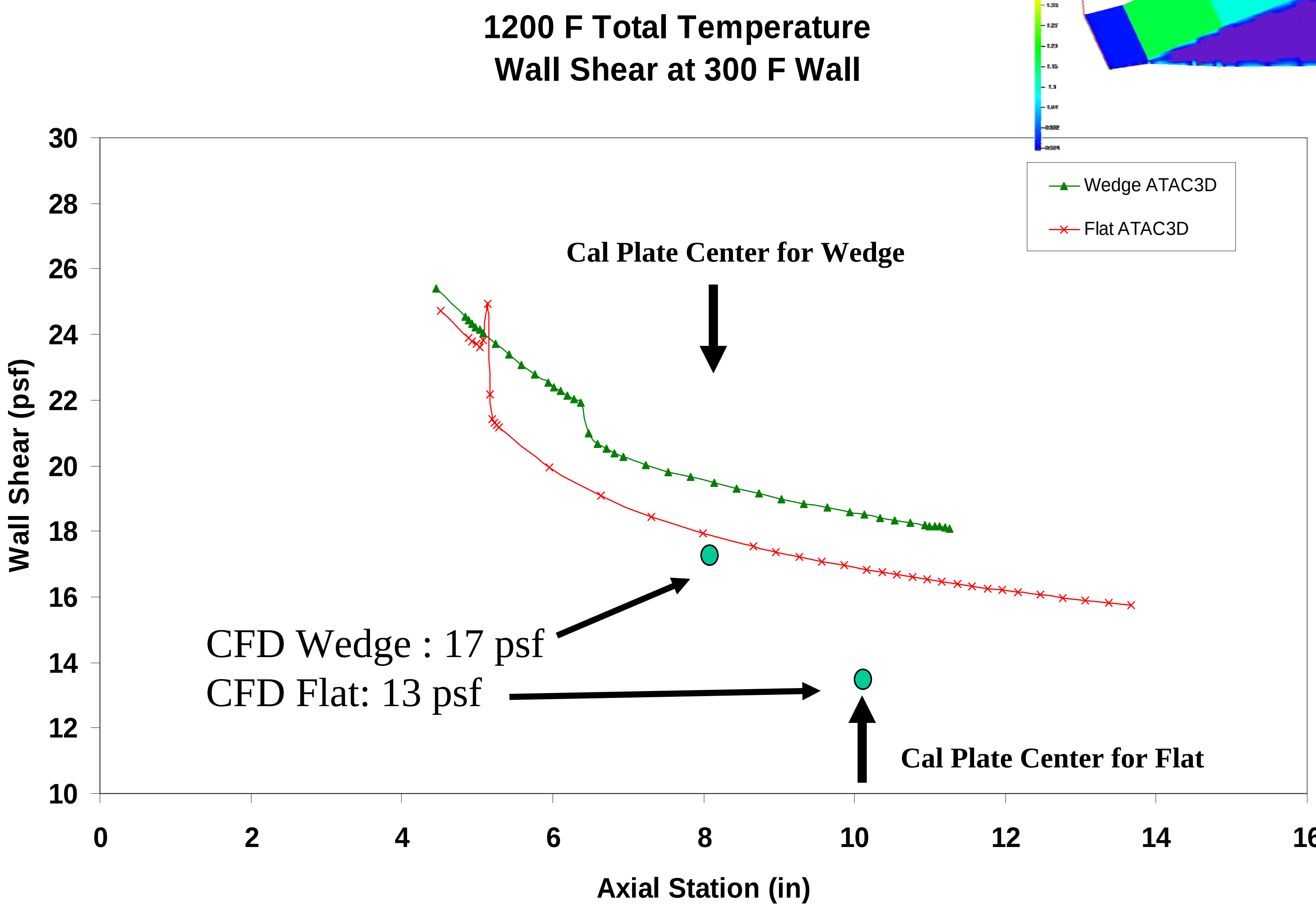
WEDGE



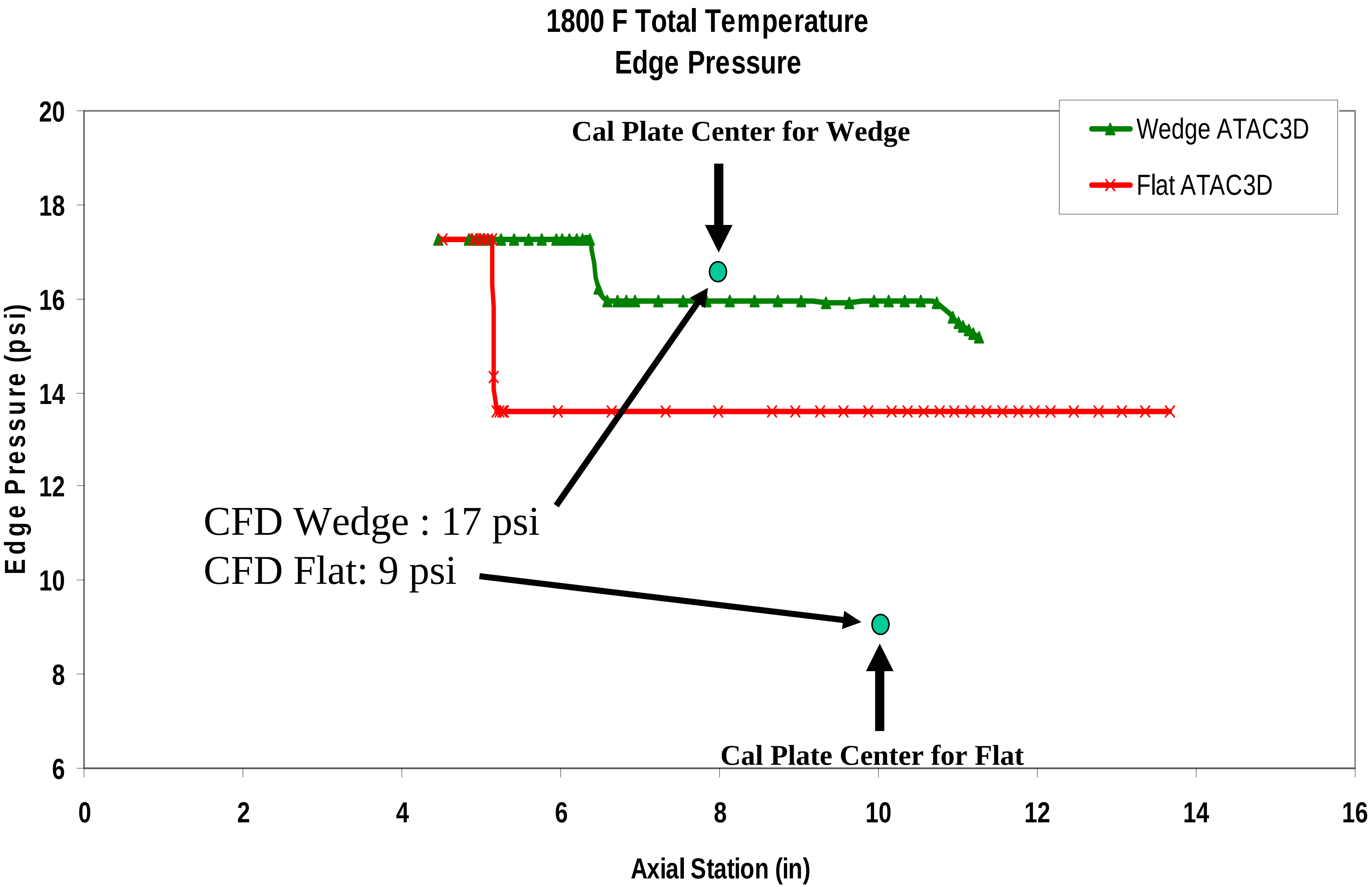
FLAT

ATAC3D Shear Stress

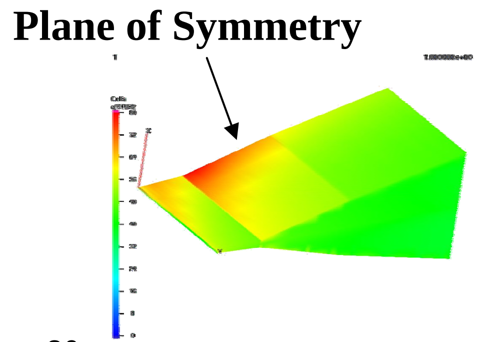


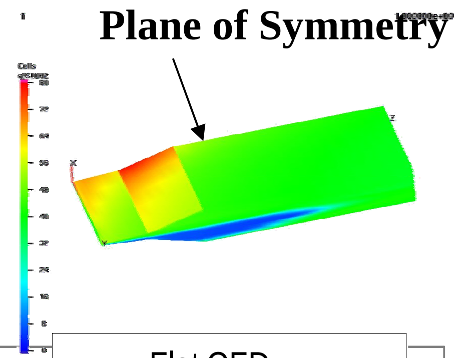


ATAC3D Edge Pressure

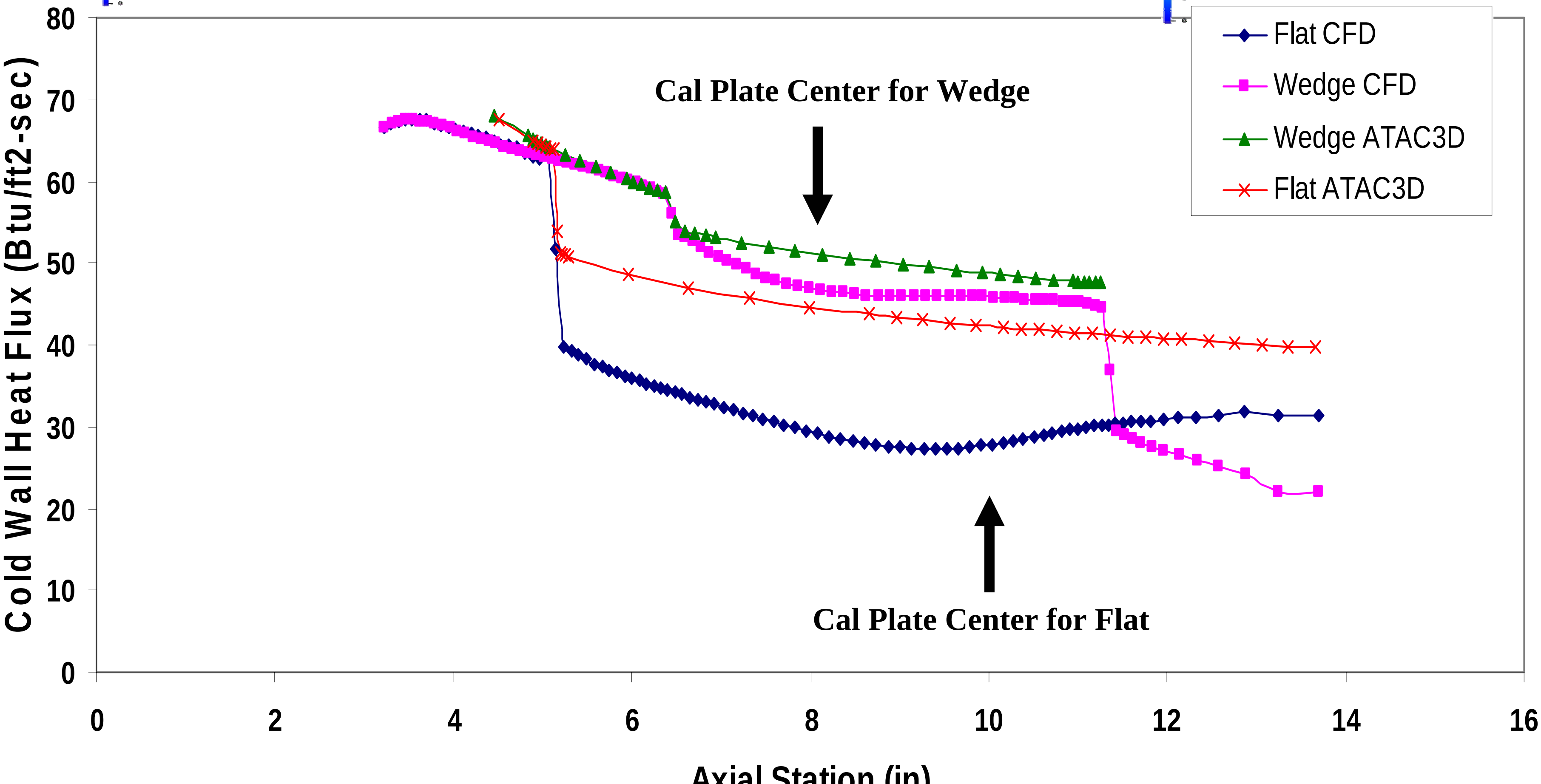


Heat Flux Comparison of ATAC3D and CFD

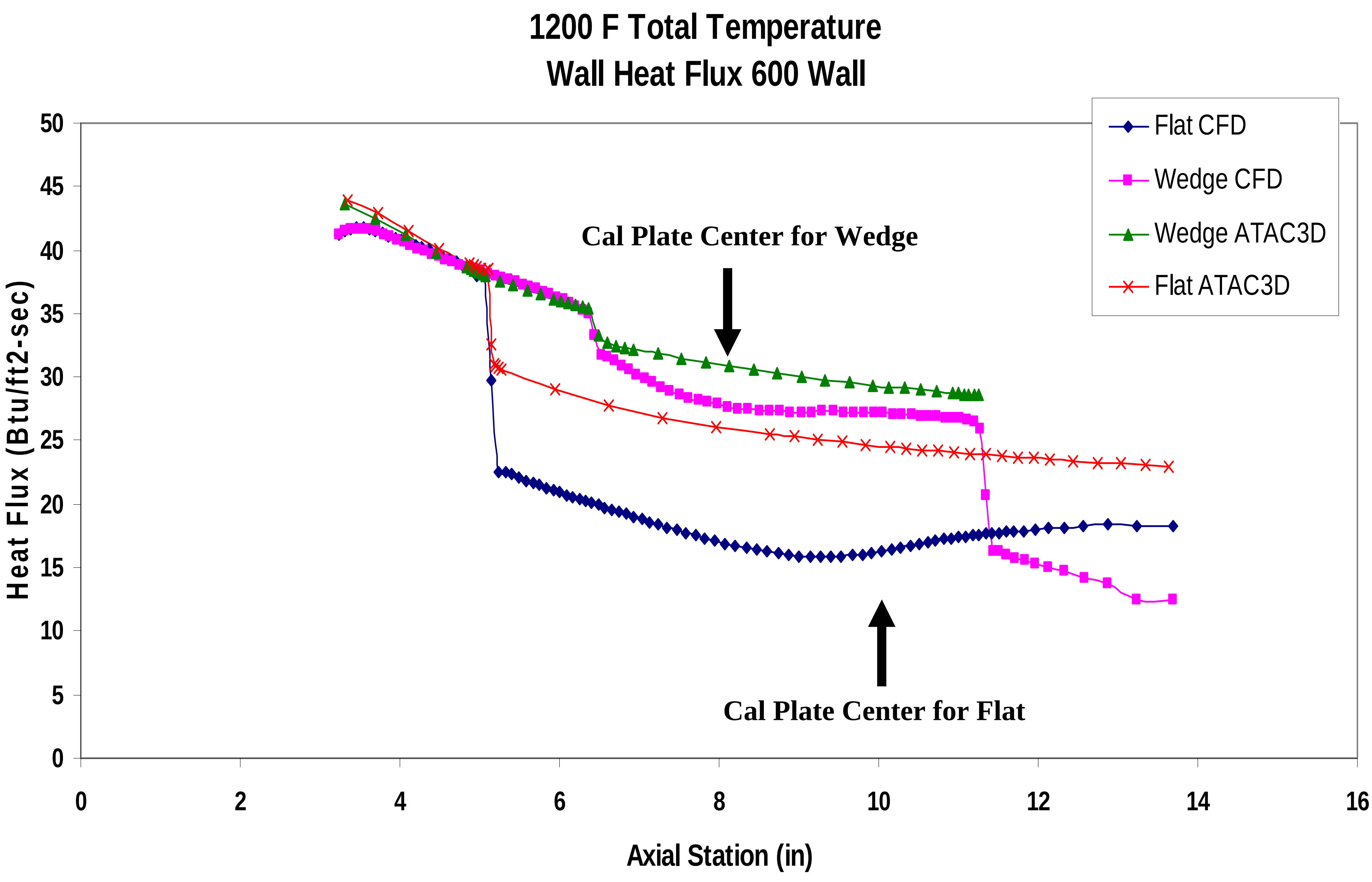




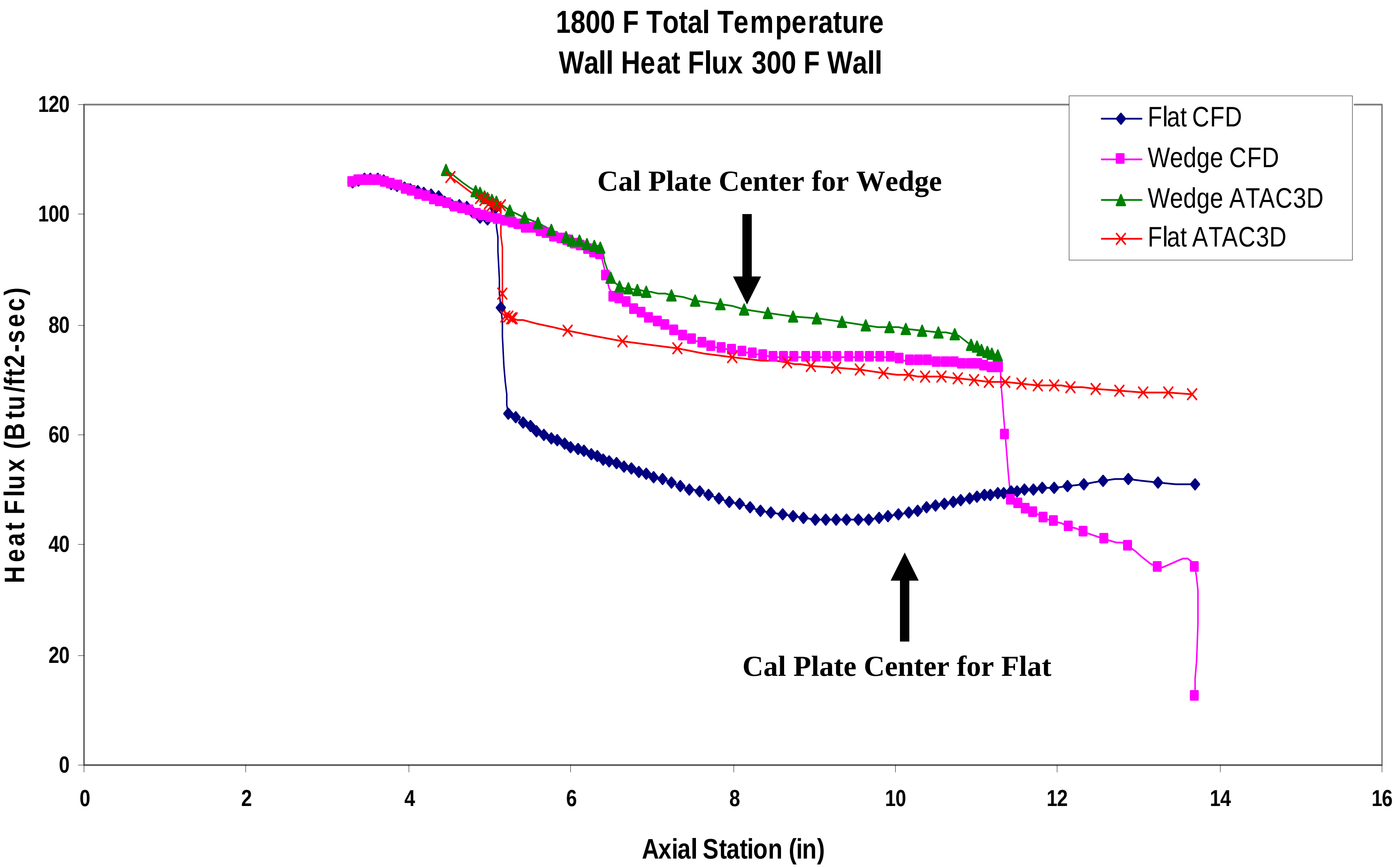
1200 F Total Temperature
Heat Flux 300 F Wall



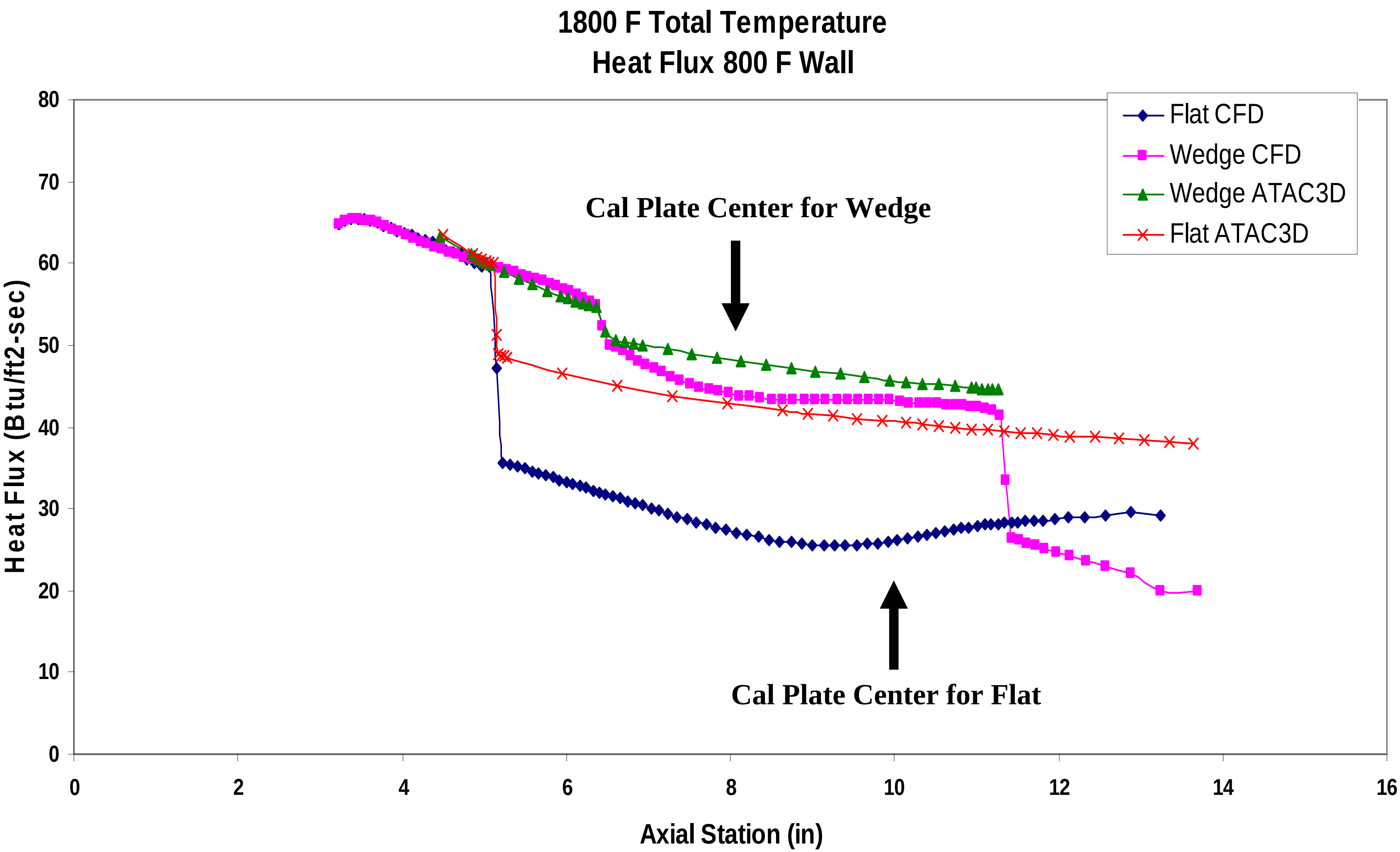
Heat Flux Comparison of ATAC3D and CFD



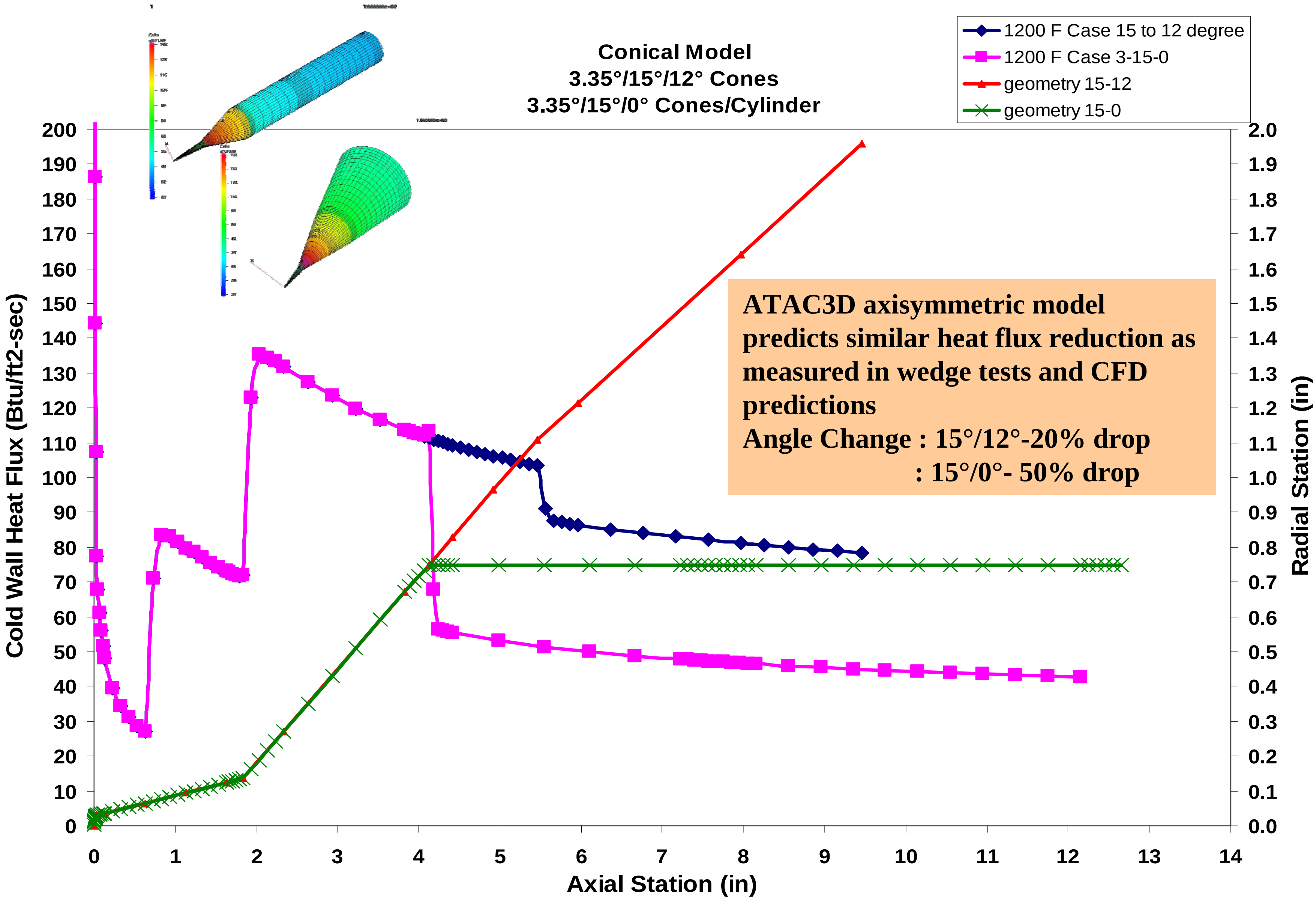
Heat Flux Comparison of ATAC3D and CFD



Heat Flux Comparison of ATAC3D and CFD



Assessment of ATAC3D Cone/Cylinder Heat Flux



Summary

- An aerothermal test series was conducted and calorimetry was utilized to verify boundary conditions delivered by the NAWC T-Range Facility to a wedge test fixture
- This effort is representative of the process which should be used for all aerothermal test and evaluation efforts
  - Quantify flight boundary conditions
  - Select appropriate aerothermal test facility/facilities
  - Design and analyze appropriate test fixture to ensure predictable environments are imparted to test specimens
  - Design and test calorimeters in position of interest
  - Verify predicted conditions with measured calorimeter data
  - Utilize CFD if flow fields are complex or uncertainties exist in aerothermal boundary conditions

Summary Continued

- Calorimeters
  - Thin skin calorimeters provided accurate thermal response data for quantifying convective boundary conditions
  - Pressure gages provided verification of uniform flow for wedge configuration (were not integrated into flat test fixture)
- Boundary Condition Predictions
  - Wedge: ATAC3D provided reasonable agreement for 12 degree wedge configuration where angle change between the two wedges was small (15 degree to 12 degree)
  - Flat Plate: ATAC3D predictions over predicted the calorimeter data by approximately 45%
  - Overflow Code (CFD) provided detail predictions of flowfield variation over test fixture in agreement with measured data and verified reduced ATAC3D boundary condition prediction were necessary
  - ATAC3D axisymmetric model for a cone/cylinder provided more realistic heat flux drops for the given angle changes suggesting confidence in the ATAC3D predictions for missile shapes
  - The ATAC3D 3-dimensional wedge model predictive techniques needs to be investigated and modified

Future Efforts

- Verify/modify ATAC3D analytic method for predicting aerothermal environments on wedges
- Modify ATAC3D to support stagnation lines on cylinders in cross-flow
- Continue simplification of geometry builder for ATAC3D
- Couple ATAC3D with CFD solutions for corrected edge conditions in complex flow regimes
- Continue development of material database interface for ATAC3D
- Provide guidance to T-Range customers on test fixture requirements to ensure acceptable and predictable flow fields and aerothermal environments