CFD Simulations of the IHF Arc-Jet Flow: Compression-Pad/Separation Bolt Wedge Tests

Tahir Gökçen and Kristina A. Skokova
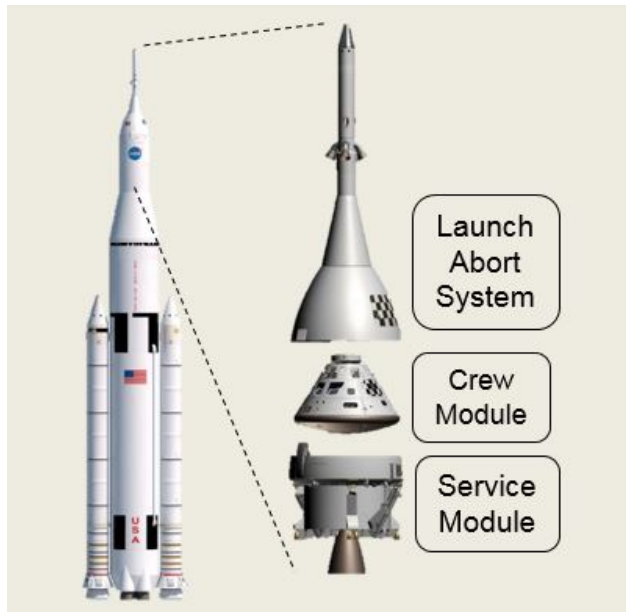
AMA Inc., NASA Ames Research Center, Moffett Field, CA 94035

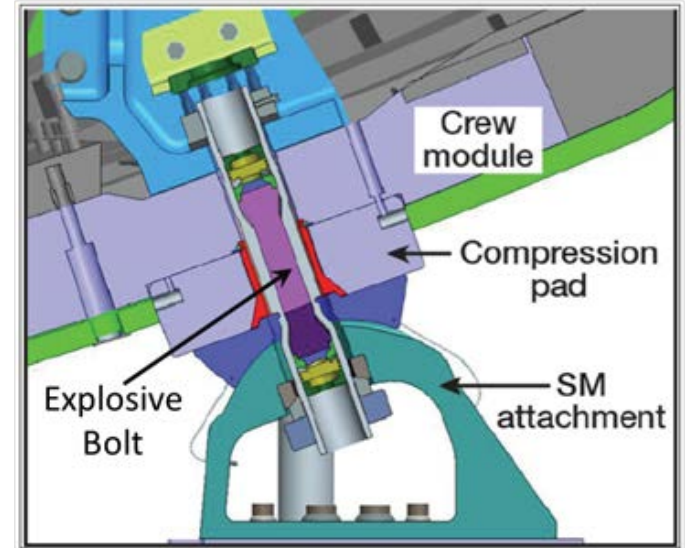This work is performed at NASA ARC Entry Systems and Technology Division

# What is a Compression Pad?

Compression pads on Apollo heatshield after reentry from Thompson et al., AIAA Paper 2009-1575

Expanded view of the compression-pad interface with the service module from NASA Facts, 3-D MAT, https://gameon.nasa.gov/

- Avcoat, the TPS for the Orion and Apollo spacecraft, does not have the mechanical strength to support loads between the crew module and service module during launch
- Densified materials (compression pads) are used to support these loads: as a result, recessed cavities are embedded in the heatshield
- Compression pads disturb the flow during reentry, producing augmented heating locally and downstream
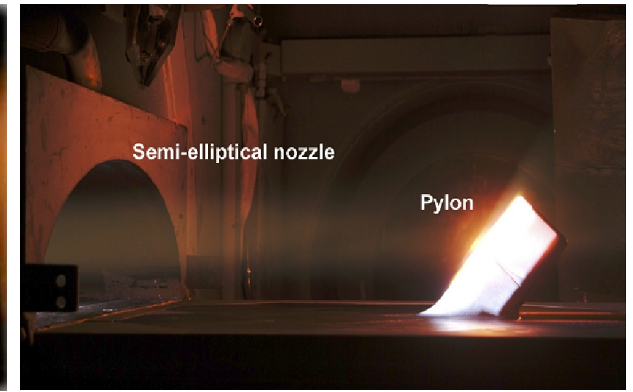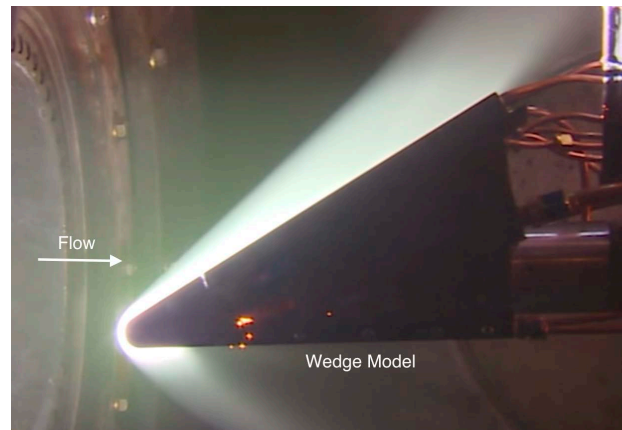
Introduction to Arc-Jets and Testing
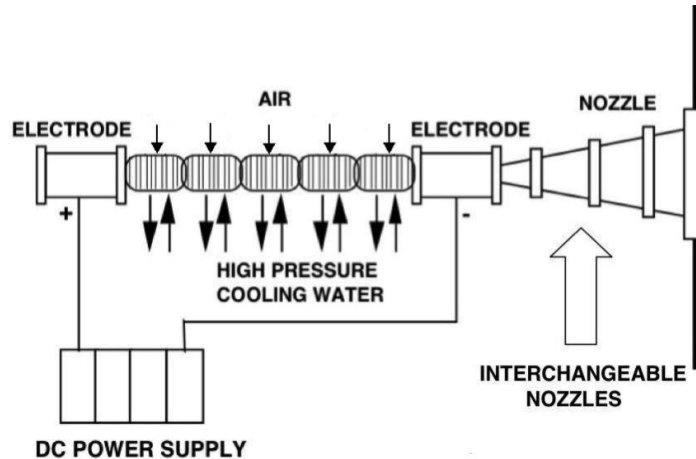
Arc-heater/nozzle sketch
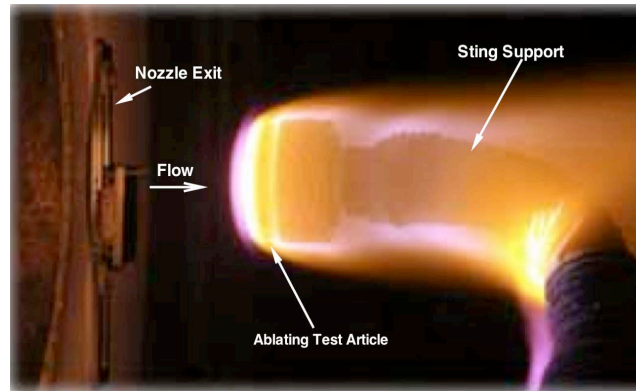
Stagnation coupon


IHF panel/pylon test

IHF wedge test

PTF panel test

- Arc-jets provide the primary means to test the performance of various types of thermal protection systems (TPS) in an aerothermodynamic heating environment

- Set of conical nozzles or semi-elliptical nozzles: free jet test configurations are suitable for stagnation coupon or wedge models while semi-free jet configurations are primarily for panel test articles

- Computational fluid dynamics (CFD) simulations are used to predict arc-jet test environment parameters and to provide input for material response and thermal stress analyses

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Objectives and Scope

- Primary objective is to report CFD simulations in support of two arc-jet wedge tests conducted in the NASA Ames 60-MW Interaction Heating Facility (IHF)

- Pretest CFD simulations were used to investigate the feasibility of arc-jet tests using two different wedge models in two different nozzles
  - Recommend changes for test article design and configuration

- Posttest CFD simulations are used to predict arc-jet test environment parameters consistent with the facility and calibration measurements, and to provide input for material response and thermal stress analyses
  - Complex flowfield features: shock-shock and shock-boundary layer interactions
  - Multiple augmented heating regions on the test plate

- Comparisons of computed results with the test data are presented
  - Calibration plate surface pressure and heat flux data
  - Qualitative comparisons with surface heating distributions of the compression-pad/separation bolt test article

# Arc-Jet Tests with Compression-Pad/Separation Bolts
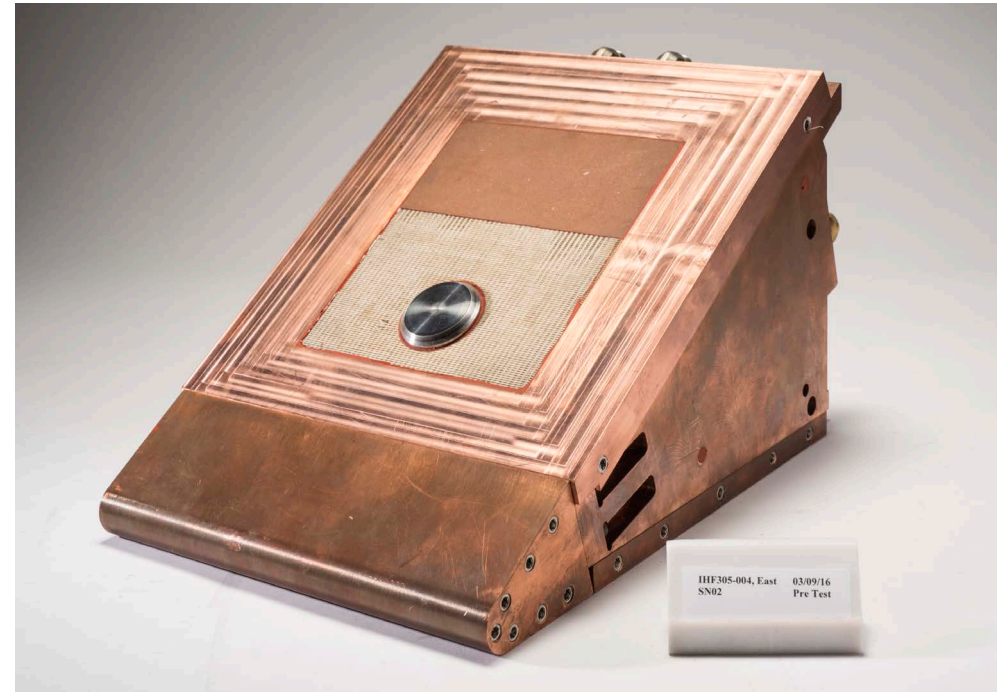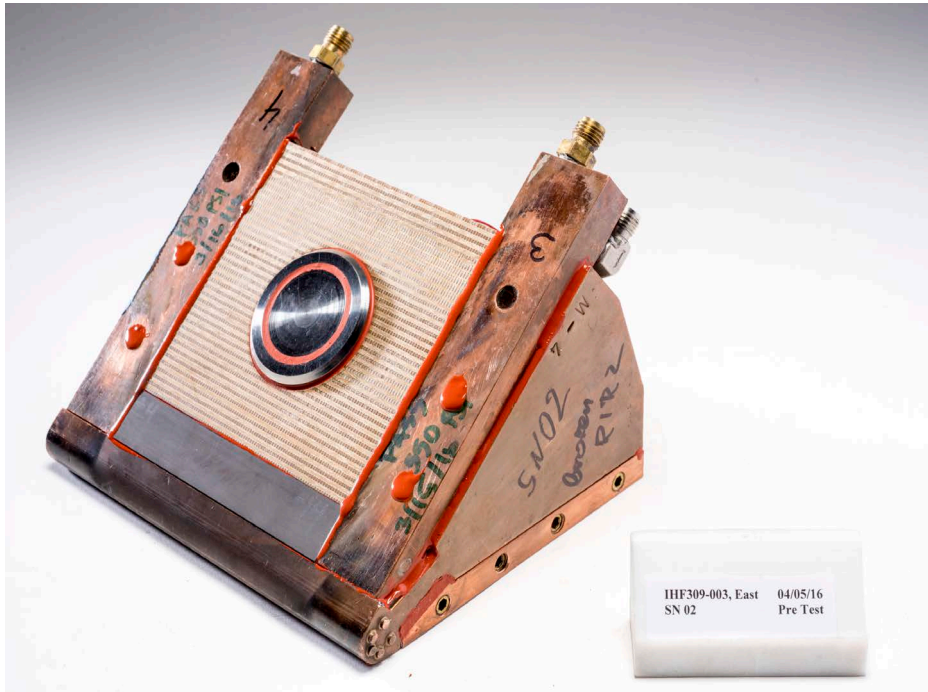
- Two arc-jet wedge tests were conducted in the NASA Ames 60-MW IHF to investigate the effects of the melting separation bolt used in a compression-pad system design
- Each panel test article included a metallic separation bolt imbedded in Orion compression-pad and heatshield materials, resulting in a circular protuberance over a flat plate
- The 7-in wedge model in the IHF 6-inch nozzle, IHF 309: effects of the melting separation bolt on performance of the compression-pad material (3-D MAT, woven TPS)
- The 9.2-in wedge model in the IHF 13-inch nozzle, IHF 305: effects of the melting bolt on performance of both compression-pad and heatshield (molded Avcoat) materials

Two Wedge Models: Calibration and Test Plates
IHF 309 and IHF 305 Tests

7-in wedge model with calibration plate (20º)
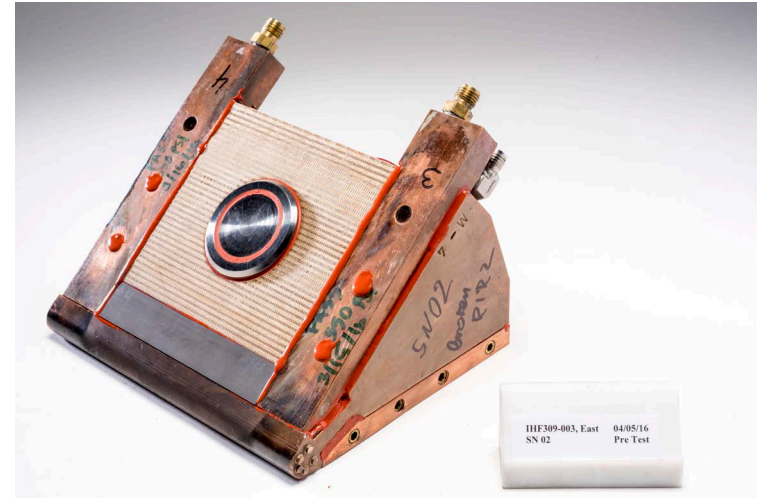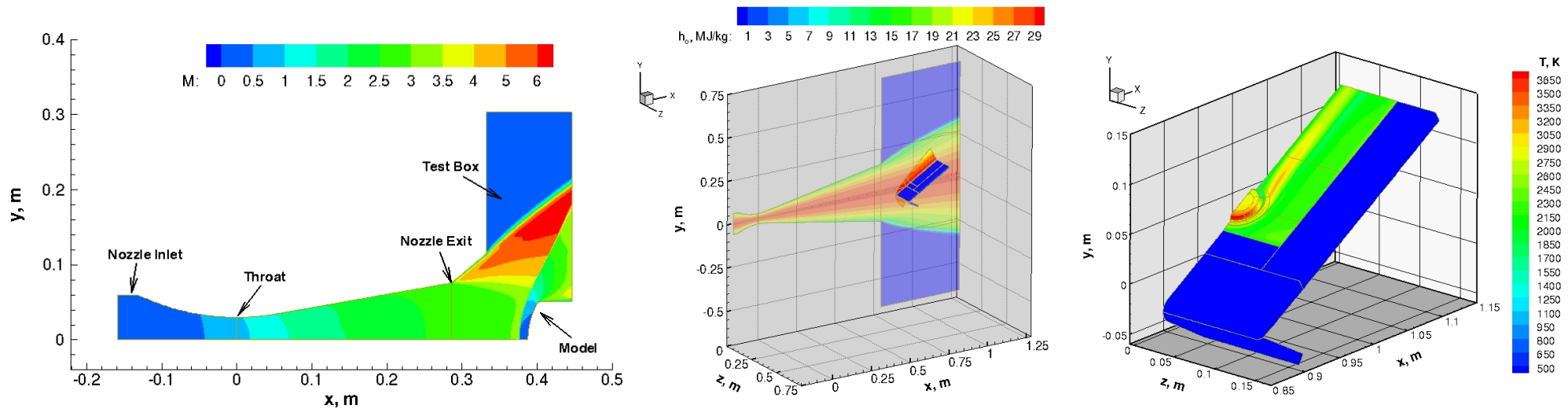

with test plate

9.2-in wedge model with calibration plate (30º)

with test plate

Computational Approach

- CFD analysis includes simulation of nonequilibrium flow in the arc-jet facility (the nozzle, test box, over the model)

- Prescribe flow profiles with chemical equilibrium composition at the nozzle entrance; Centerline total enthalpy is set to match the measured slug calorimeter and calibration plate data

- 2-D axisymmetric and 3-D Navier-Stokes equations with nonequilibrium processes

- Thermochemical model for arc-jet flow
  - Six chemical species: N_2, O_2, NO, N, O, Ar
  - Two-temperature model (Park): T -translational-rotational, T_v -vibrational-electronic

- Data-Parallel Line Relaxation Method –DPLR Code

Presentation of Results

- Stagnation calorimeter model simulations
  - IHF 6-inch and 13-inch nozzles
  - Estimate the centerline total enthalpy consistent with the facility and calorimeter measurements

- 7-in wedge model simulations, 20°, IHF 6-inch nozzle flow
  - With the water-cooled calibration plate
  - With the test article with the circular bolt protrusion

- 9.2-in wedge model simulations, 30°, IHF 13-inch nozzle flow
  - With the water-cooled calibration plate (in the paper)
  - With the test article with the circular bolt protrusion

- Discussion of protuberance induced flow features
  - Complex flowfield features over the test articles with a circular protuberance: shock-shock and shock-boundary layer interactions, multiple augmented heating regions

- Comparisons of qualitative heating patterns
  - HD and Infrared camera images

Stagnation calorimeter model simulations

# Example: Stagnation Calorimeter Model Simulation

IHF 6-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 20.9 MJ/kg, h_{ocl} = 31.7 MJ/kg, 6.4% Ar
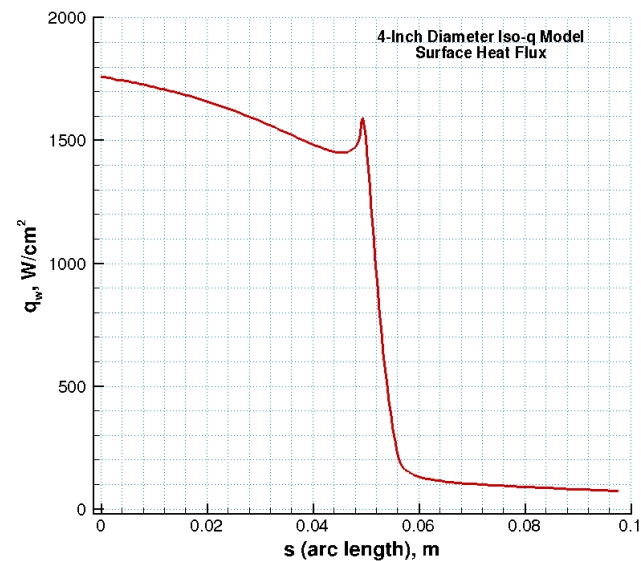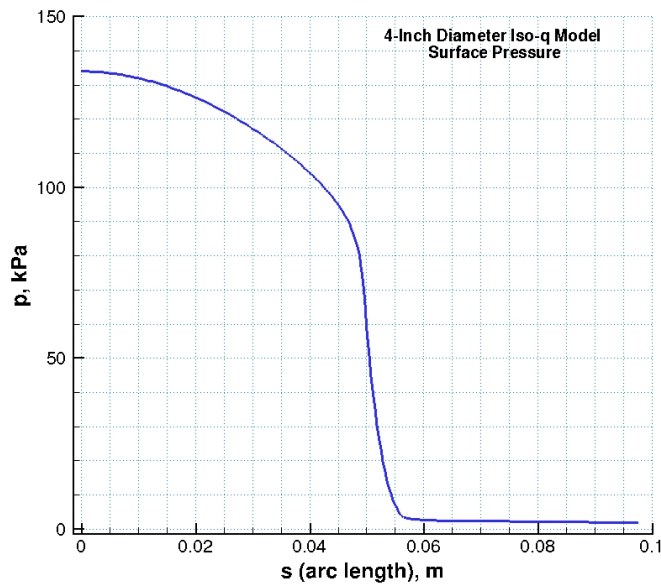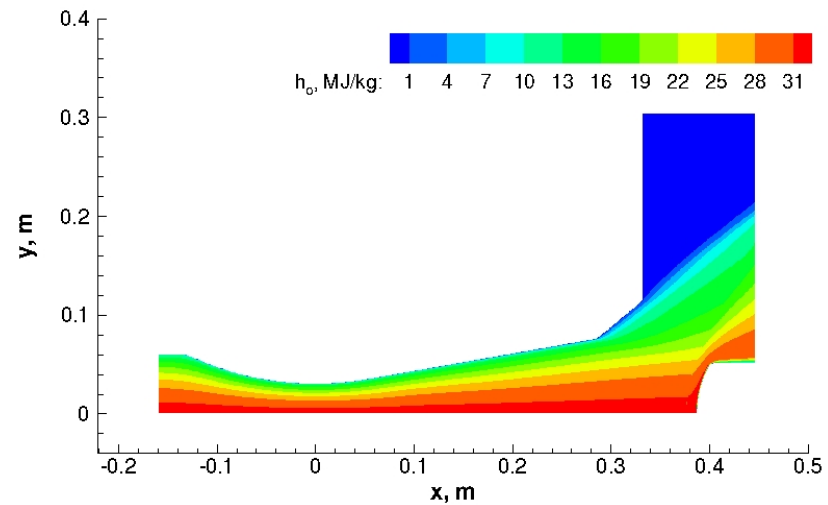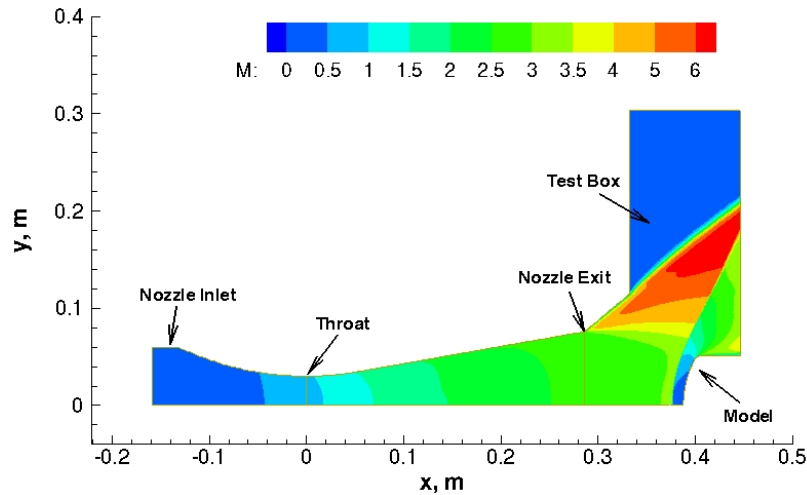
- Calorimeter data (IHF 309 Runs 1-1 and 2-1): 1759 W/cm^2 and 134 kPa
- Centerline total enthalpy is determined to reproduce the measured slug calorimeter data

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Example: Stagnation Calorimeter Model Simulation

IHF 13-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 22.8 MJ/kg, h_{ocl} = 26.7 MJ/kg, 6.4% Ar
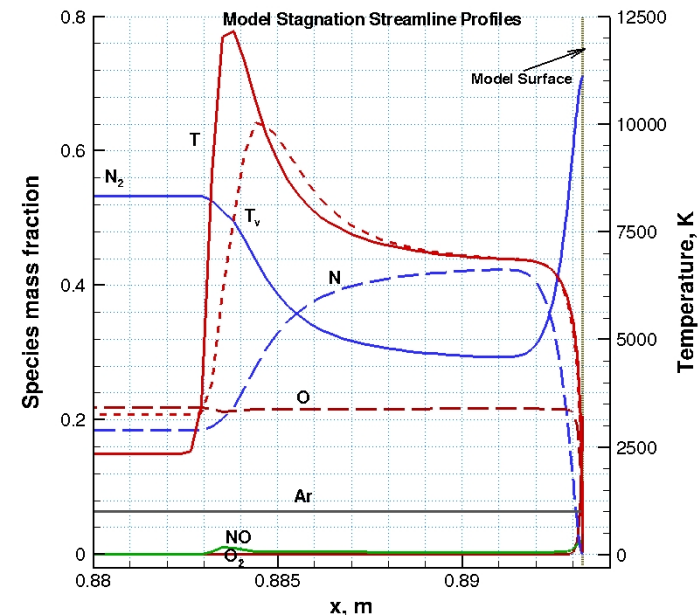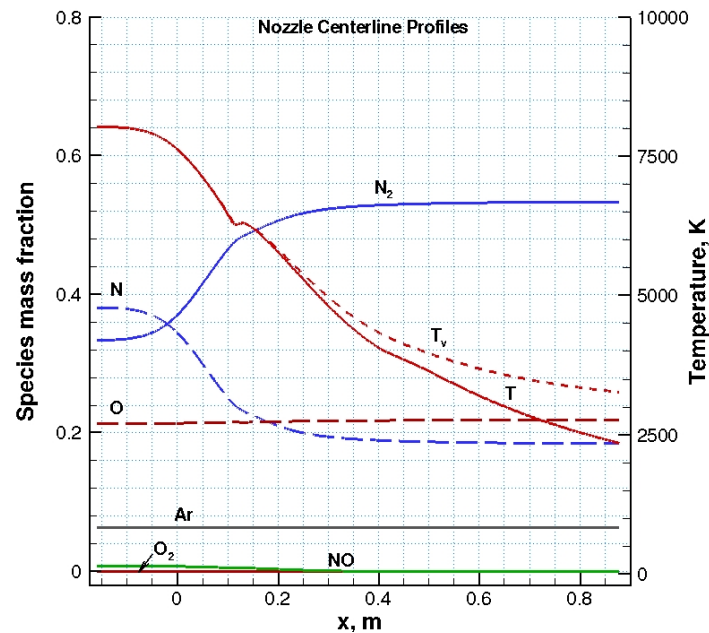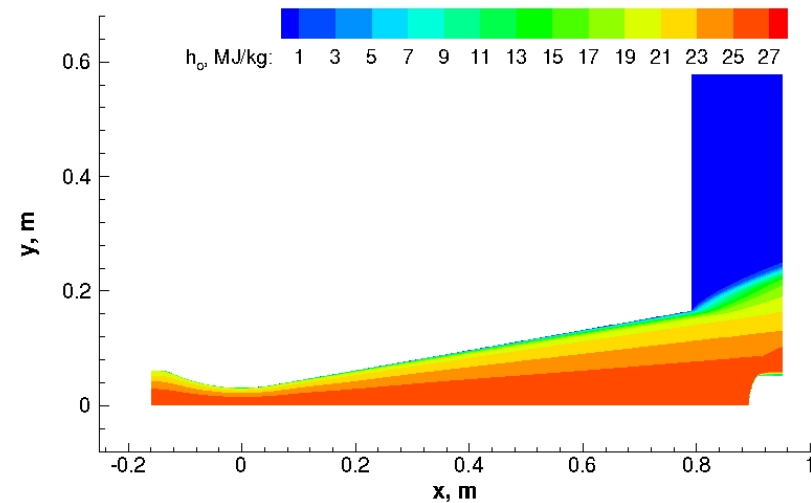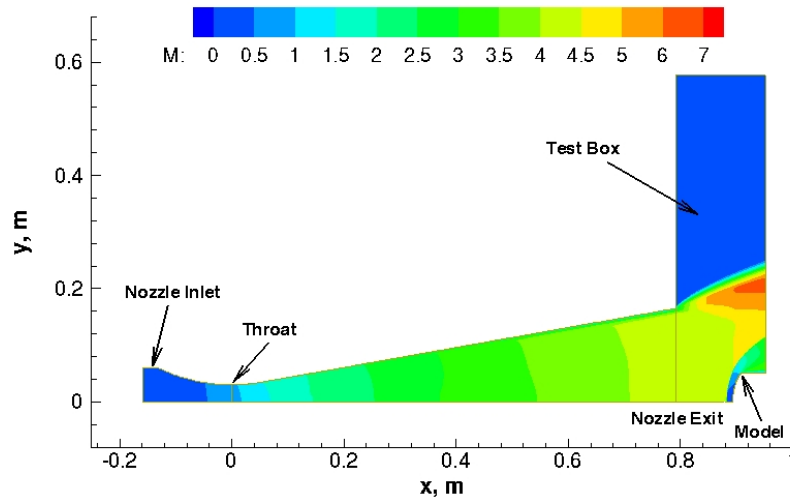
- Flow is in chemical and vibrational nonequilibrium
- Oxygen remains fully dissociated except in the boundary layer (and shear layer)
- Nitrogen is partially dissociated

7-in wedge model simulations, 20º, IHF 6-inch nozzle flow

7-in Wedge Model/IHF 6-Inch Nozzle –Arc-Jet Test Environment Summary
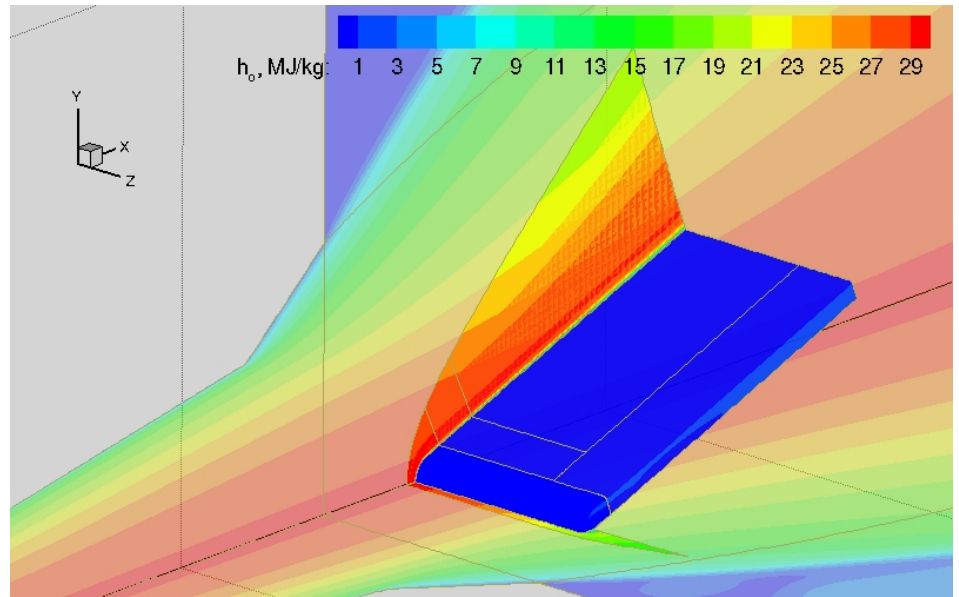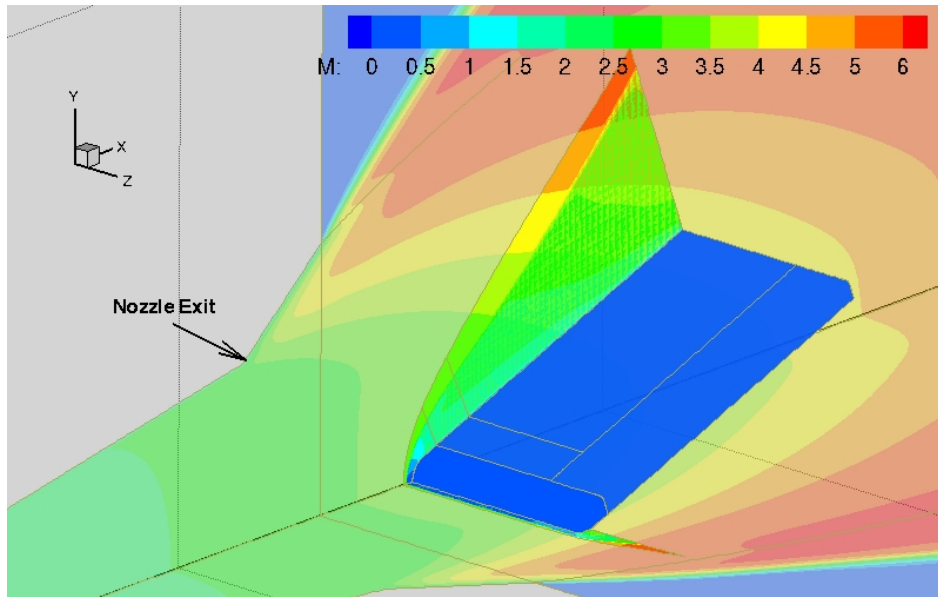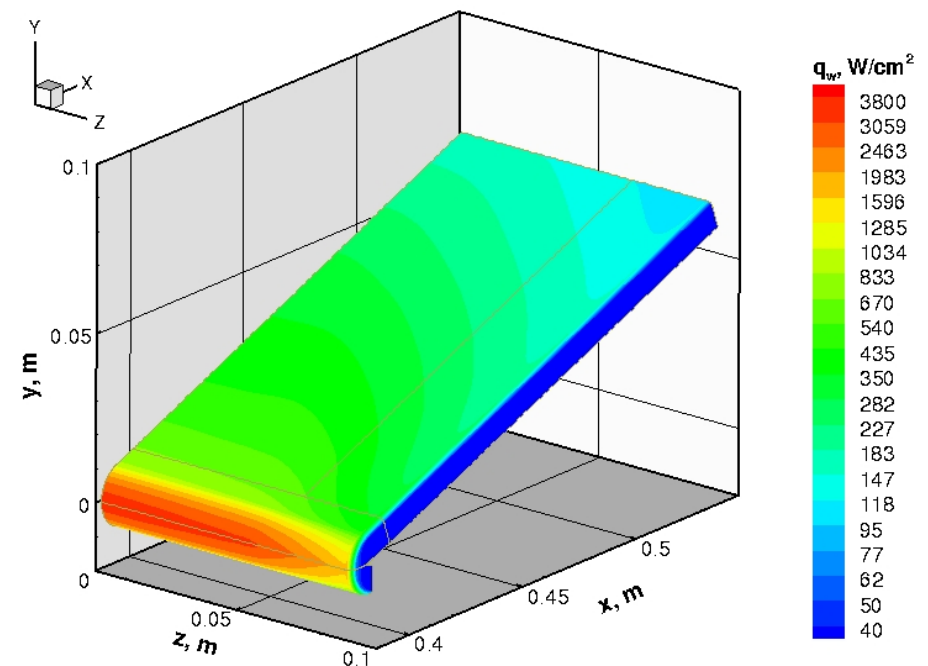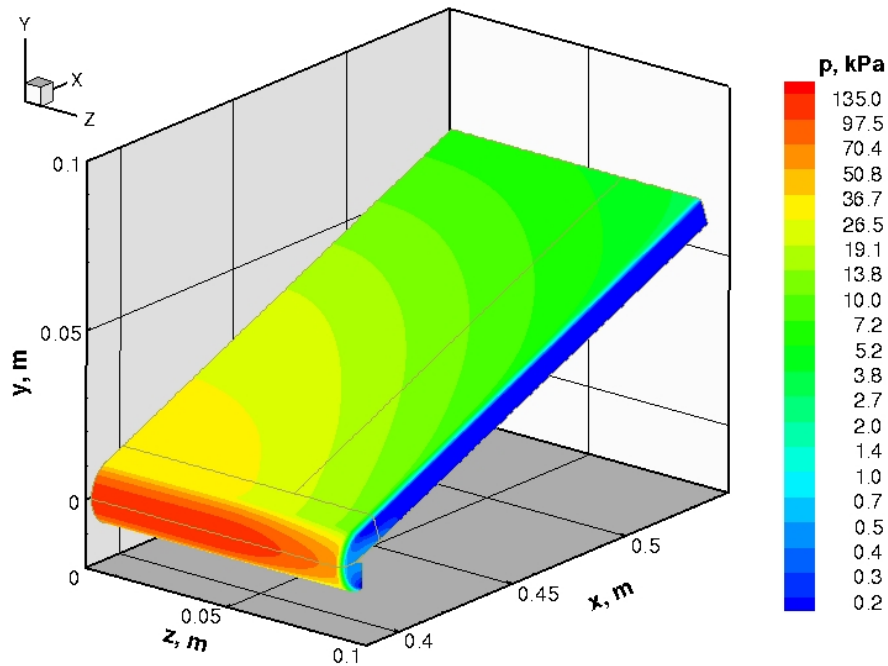

- 7-in wedge model, 20°, 10.2 cm downstream of the IHF 6-inch nozzle exit
  - IHF 309 cond 1
  - Calibration data: IHF 309 runs 1-1, 2-1, 3-1
  - Computations: $\dot{m}$ = 849 g/s, h_{ob} = 21.5 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar
  - q_s = 499 – 216 W/cm^2 (CWFC, from the plate LE to 10.2 cm downstream)
  - q_s = 417 – 203 W/cm^2 (HWFC)
  - p_s = 27.6 – 9.5 kPa
  - τ_s (shear) = 443 – 308 Pa
  - At the test plate LE: δ (BL thickness) = 0.25 cm; M_e = 1.56; Re_x = 8.1x10^3

Computed Surface Pressure and Heat Flux Contours

20° Wedge Model (r_n = 0.95 cm, w = 17.78 cm), CWFC

IHF 6-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 21.5 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar

- The wedge model leading edge is at ~10.2 cm downstream of the nozzle exit and on centerline
- Calibration plate configuration does not have a conditioning plate upstream
- Factors causing gradients in surface pressure: blunt nose, 3-D conical flow expansion, interaction of expansion waves from the nozzle exit with the bow shock wave of the wedge model

Comparisons with Calibration Plate Data –Surface Pressure

20° Wedge Model (r_n = 0.95 cm, w = 17.78 cm), CWFC

IHF 6-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 21.5 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar
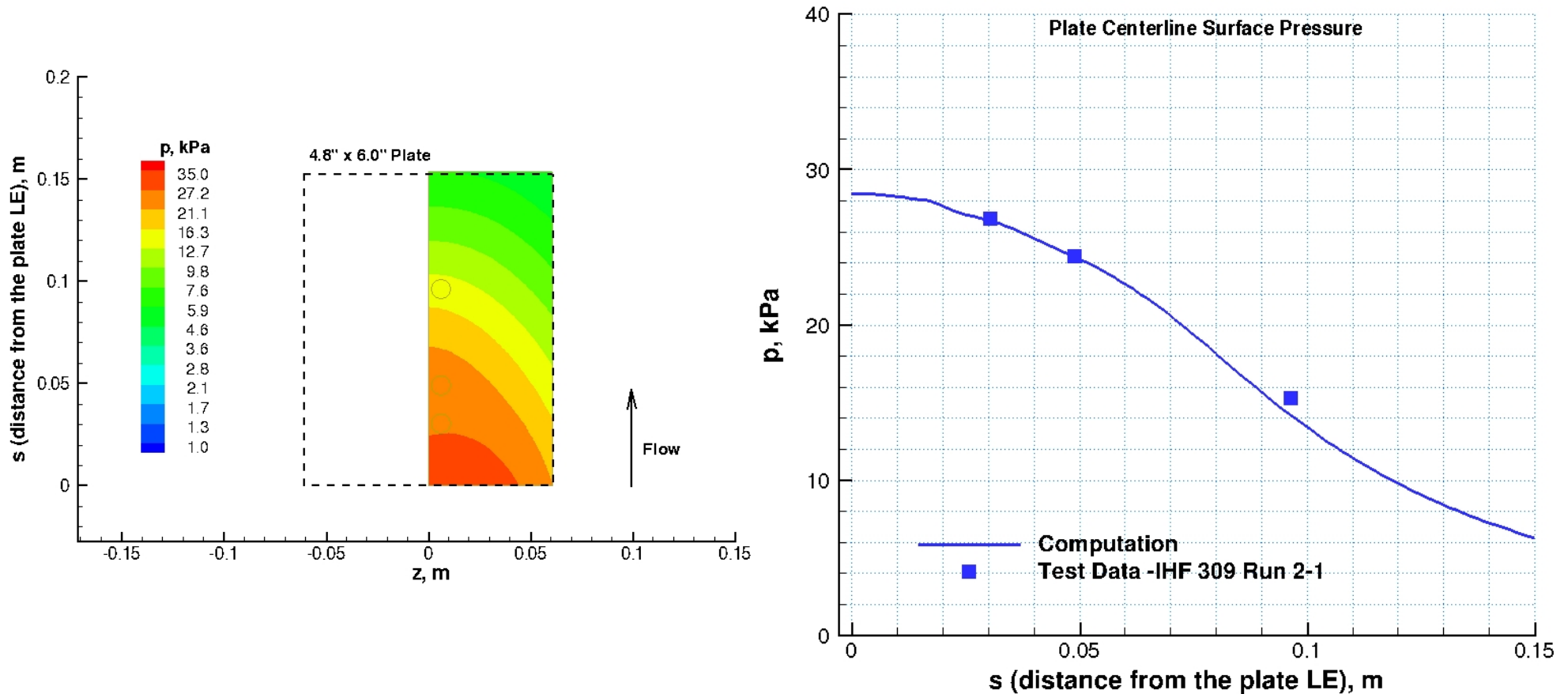
- Nominal plate surface conditions: 500 W/cm^2, 28 kPa
- Estimated uncertainty on pressure measurements: ±5% (based on historical facility data)
- Measurements are color-coded same as the computed contours

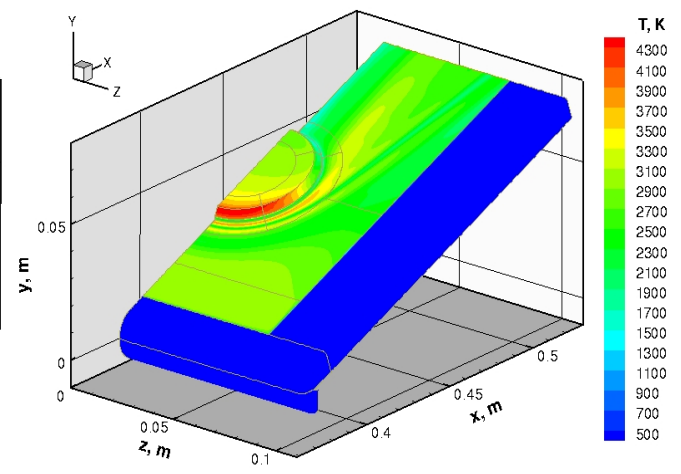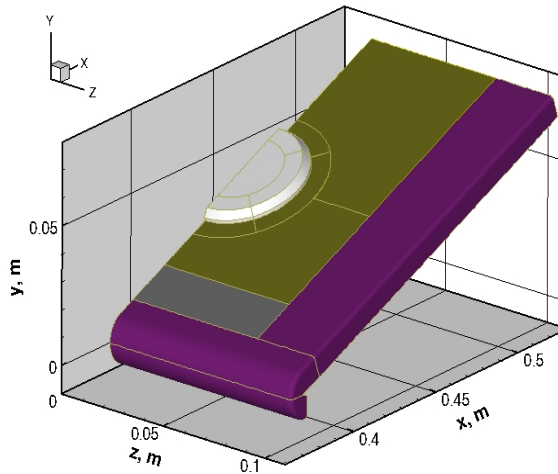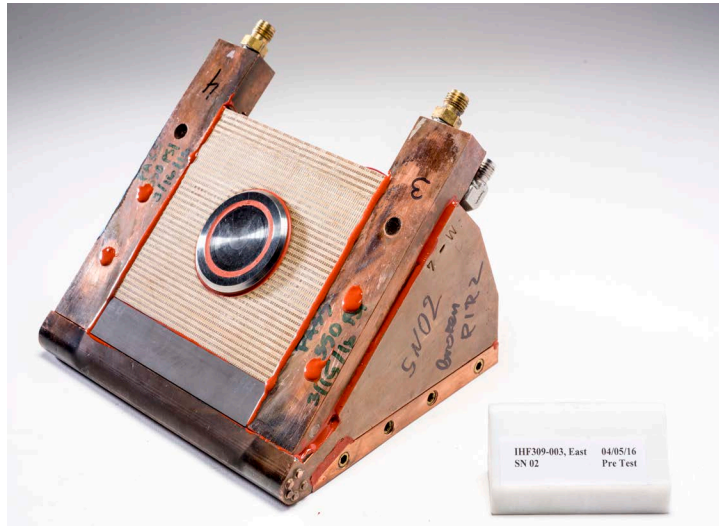# Comparisons with Calibration Plate Data –Surface Heat Flux

20° Wedge Model (r_n = 0.95 cm, w = 17.78 cm), CWFC

IHF 6-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 21.5 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar
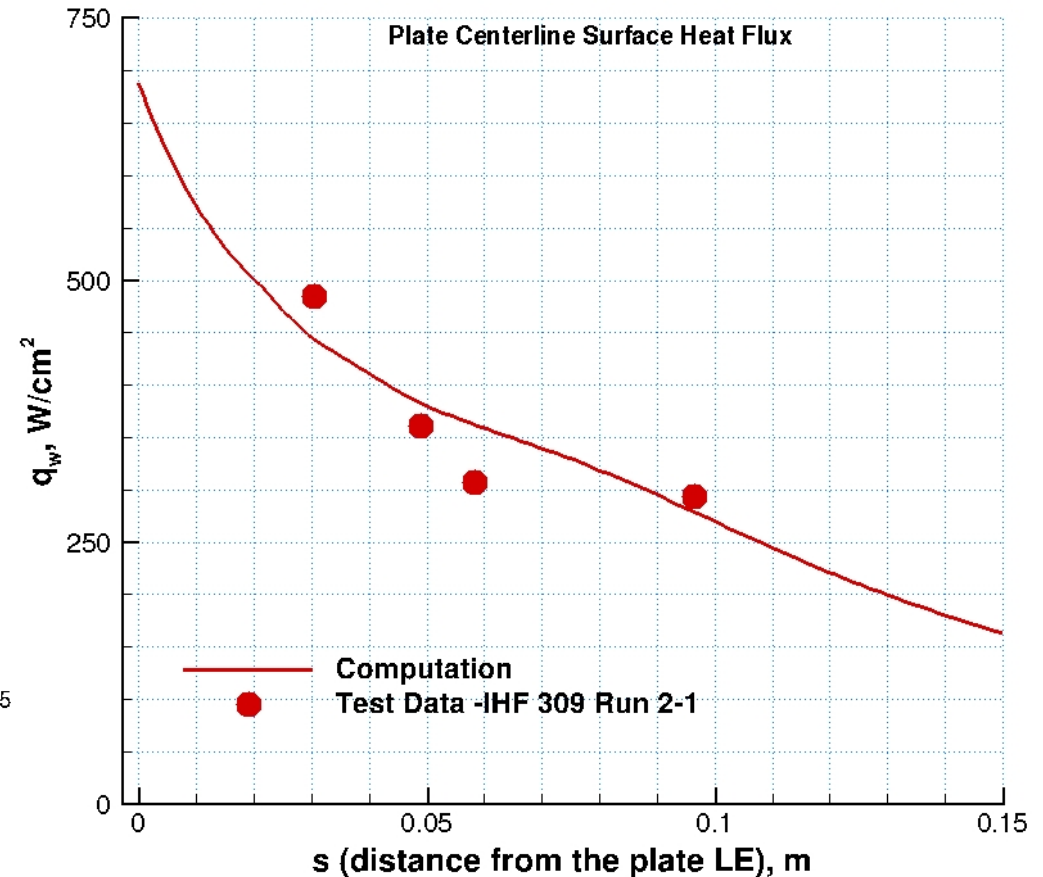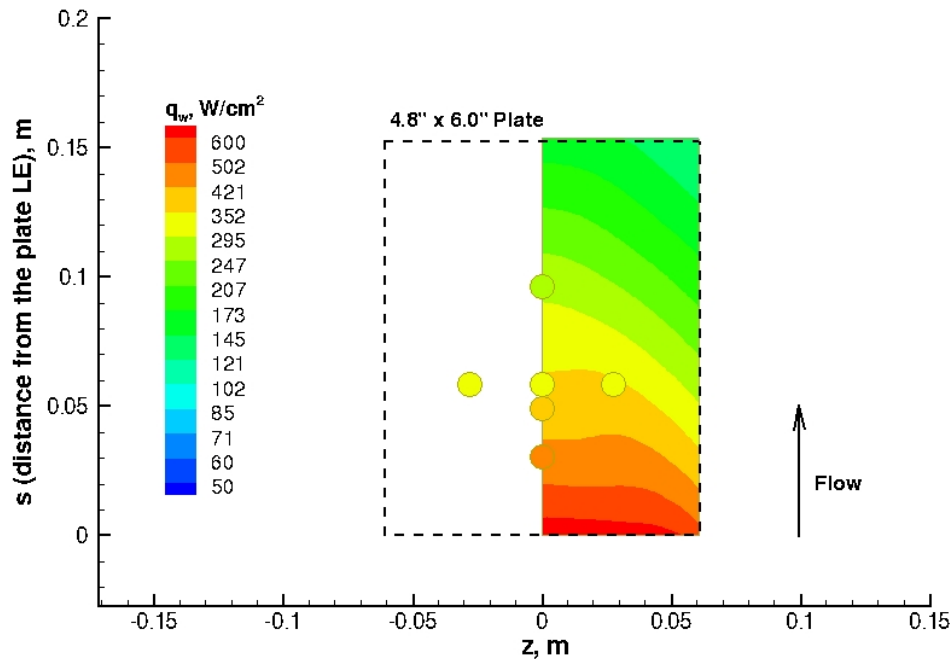
- Nominal plate surface conditions: 500 W/cm^2, 28 kPa
- Estimated uncertainty on the heat flux measurements: ±15% (based on historical facility data)
- Calorimeter data are color-coded same as the computed contours

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# Compression-Pad/Separation Bolt Test Simulations (IHF 309)

- NASA Ames 7-inch wide copper wedge holder is used
  - 20° wedge half-angle

- Test plate/bolt geometry details
  - Bolt parameters: D = 5.156 cm (2.03"), h_{bolt} = 0.381 cm (0.15"), h_{step1} = 0.127 cm (0.05"), 45° bevel angle
  - Distance from the test plate LE to the bolt LE: Δx_{boltLE} = 2.54 cm (1.0")

- Nominal test plate surface conditions: 500 W/cm^2 (CWFC), 28 kPa

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Computed Surface Pressure and Centerline Profile –Test Plate

20° Wedge Model (r_n = 0.95 cm, w = 17.78 cm), CWFC

IHF 6-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 21.5 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar
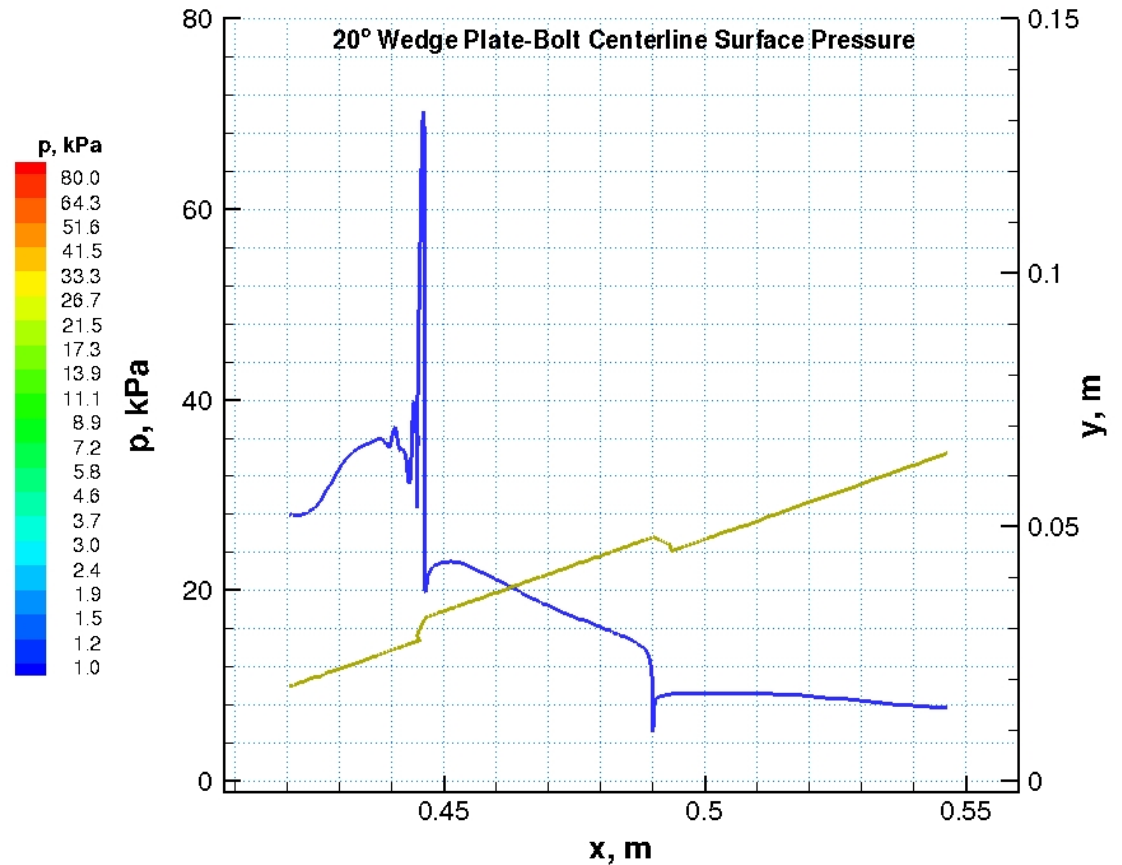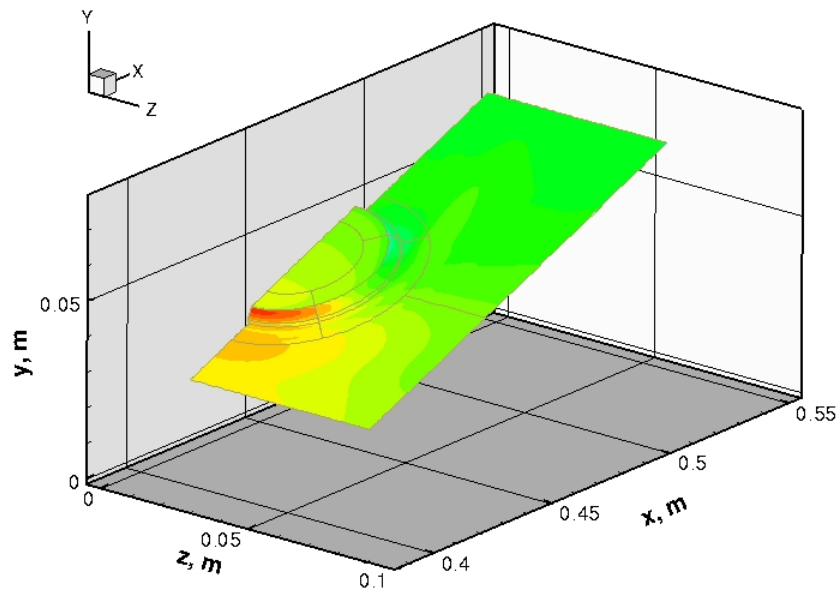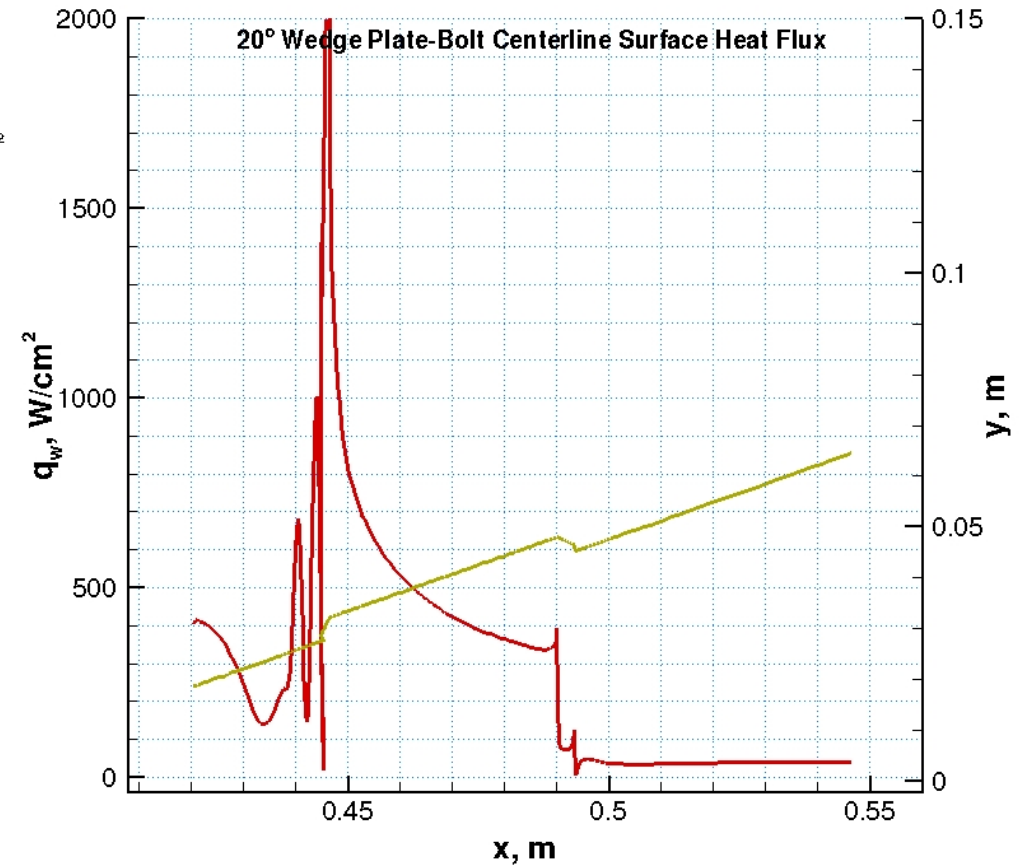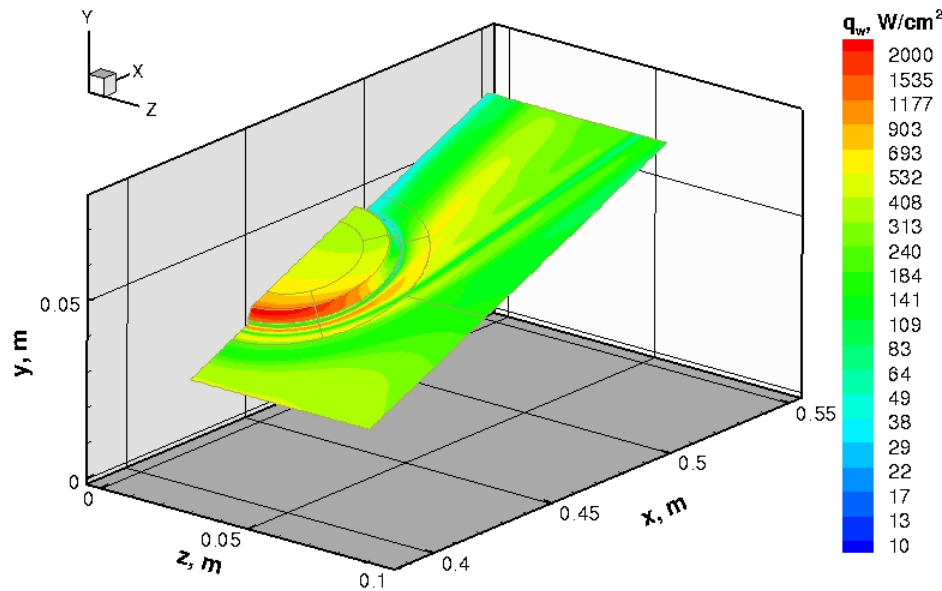

- Nominal plate surface conditions (CWFC): 500 W/cm^2, 28 kPa
- In order to make interpretation of the centerline profiles easier, the geometry of the test plate is also shown

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Computed Surface Heat Flux and Centerline Profile –Test Plate

20° Wedge Model (r_n = 0.95 cm, w = 17.78 cm), CWFC

IHF 6-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 21.5 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar

- Nominal plate surface conditions (CWFC): 500 W/cm^2, 28 kPa
- Two primary augmented heating regions upstream of the bolt and around the bolt are predicted

Computed Surface Shear and Centerline Profile –Test Plate

20º Wedge Model (r_n = 0.95 cm, w = 17.78 cm), CWFC

IHF 6-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 21.5 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar
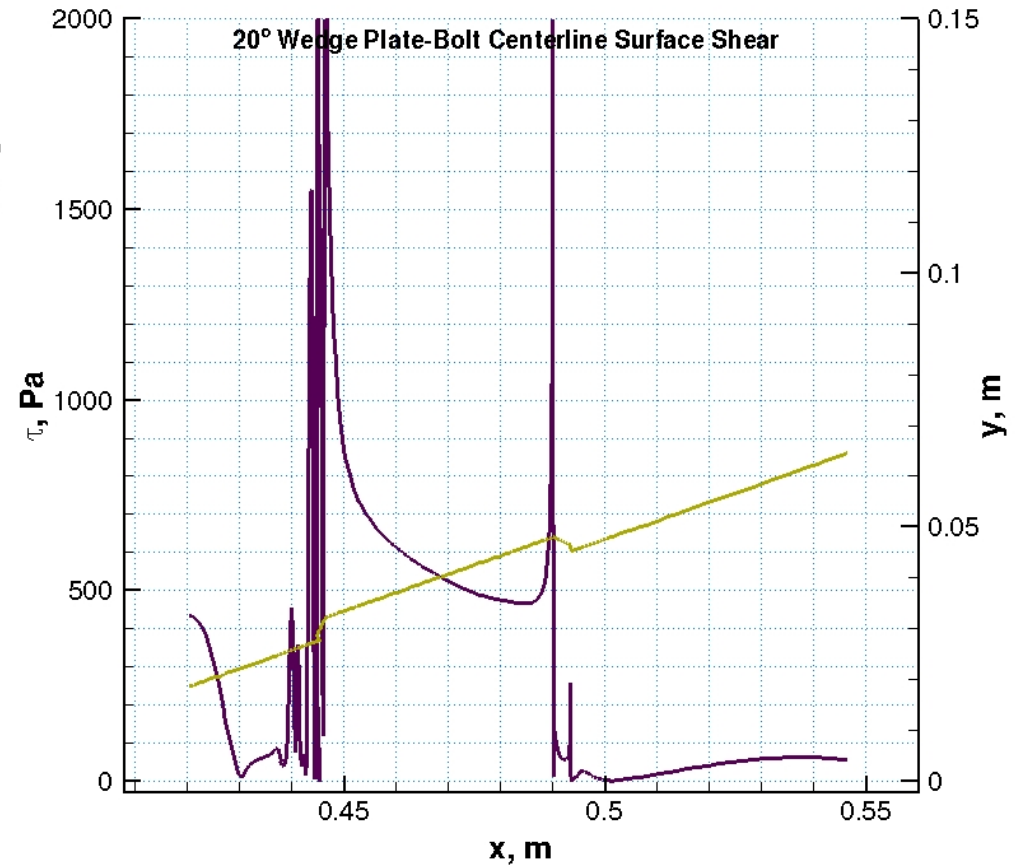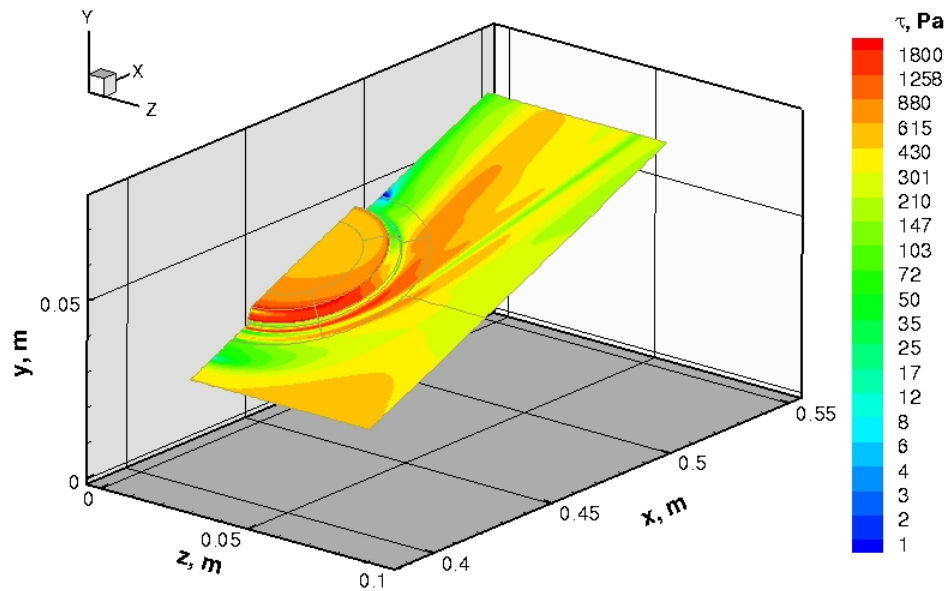
- The computed shear stress contours provide additional information about stagnant and separated regions in the flowfield, as these regions exhibit relatively low shear levels, e.g., both upstream and downstream of the bolt

9.2-in wedge model simulations, 30°, IHF 13-inch nozzle flow

9.2-in Wedge Model/IHF 13-Inch Nozzle –Arc-Jet Test Environment Summary
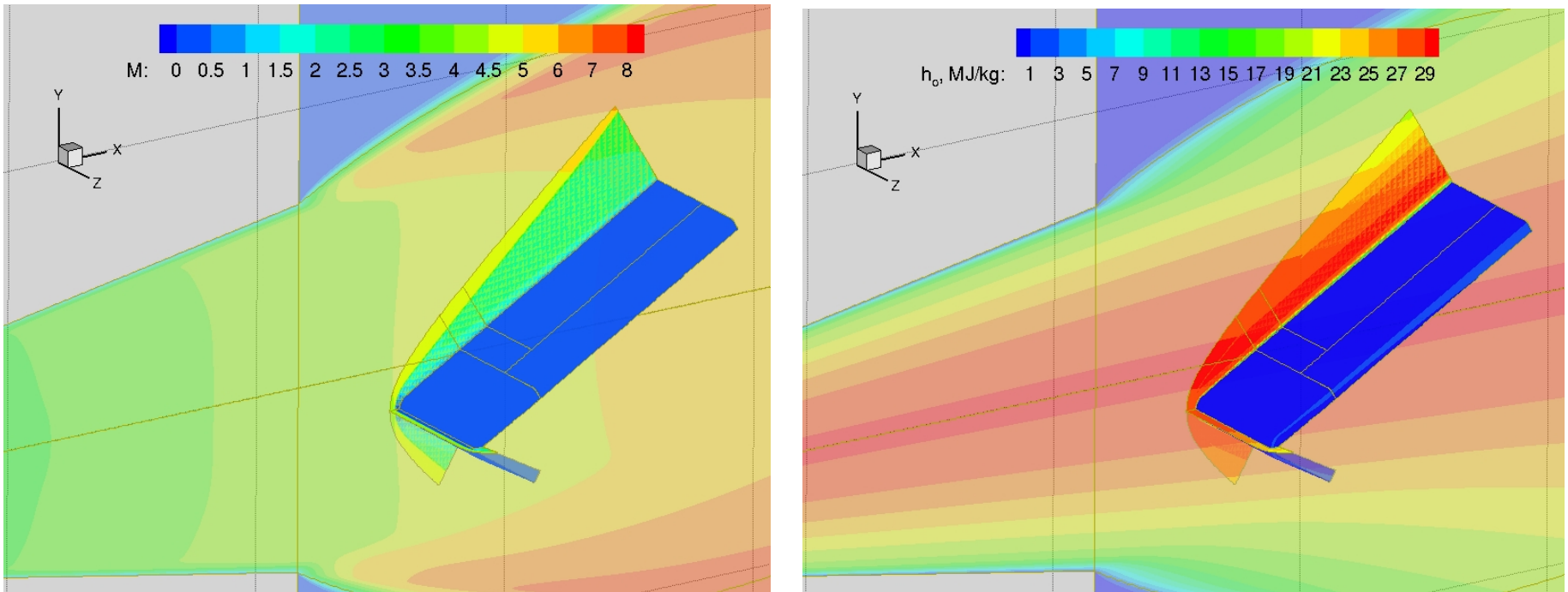
- 9-in wedge model, 30º, 10.2 cm downstream of the IHF 6-inch nozzle exit (~3.8 cm below nozzle centerline)
  - IHF 305 cond 1
  - Calibration data: IHF 305 runs 3-1, 4-1, 5-1
  - Computations: $\dot{m}$ = 849 g/s, h_{ob} = 22.8 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar
  - q_s = 221 – 139 W/cm^2 (CWFC, from the plate LE to 15.2 downstream)
  - q_s = 165 – 127 W/cm^2 (HWFC)
  - p_s = 12.9 – 8.4 kPa
  - τ_s (shear) = 191 – 155 Pa
  - At the test plate LE: δ (BL thickness) = 0.49 cm; M_e = 1.62; Re_x = 8.6x10^3
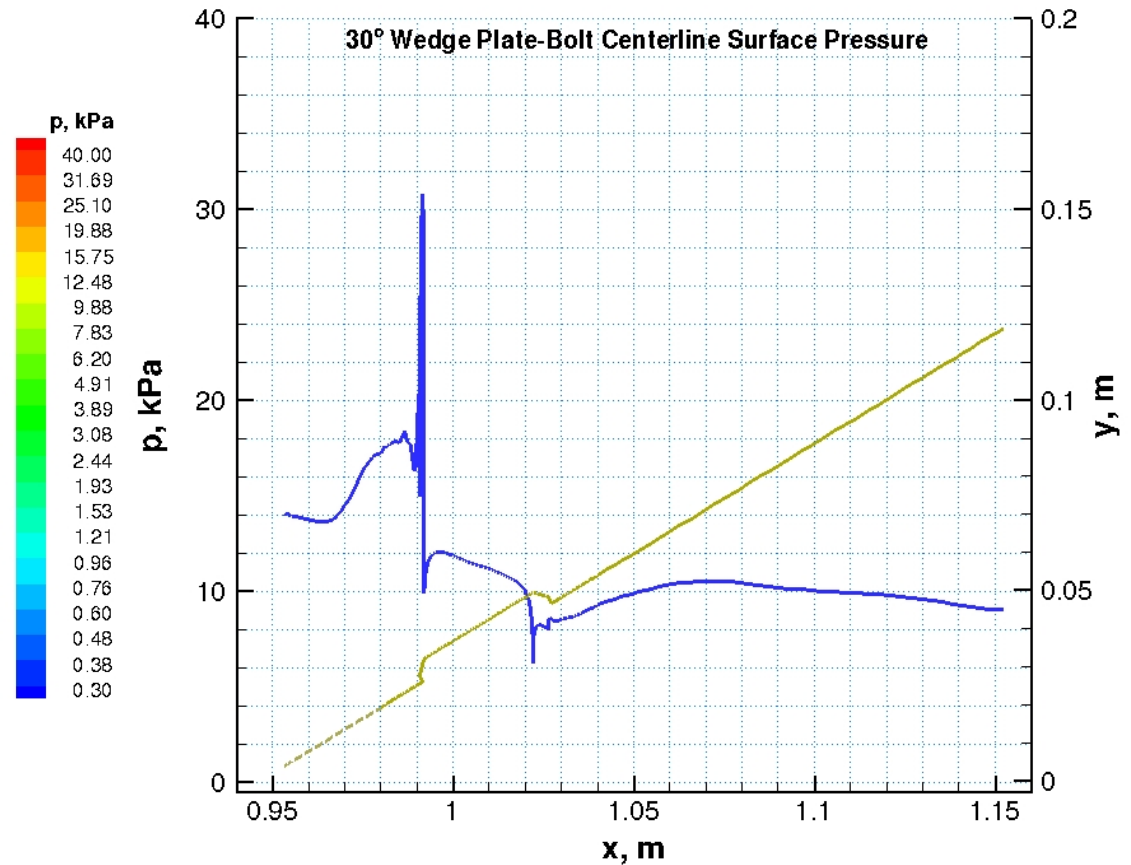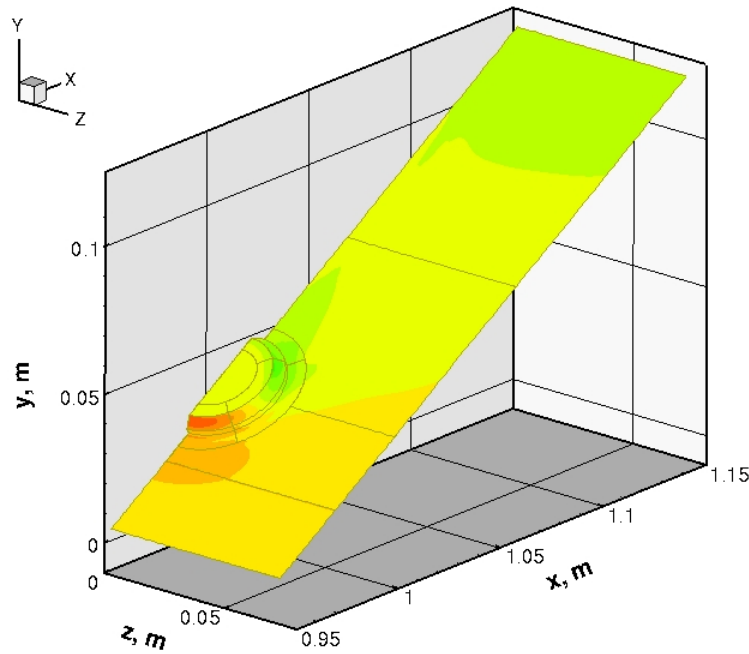
Compression-Pad/Separation Bolt Test Simulations (IHF 305)
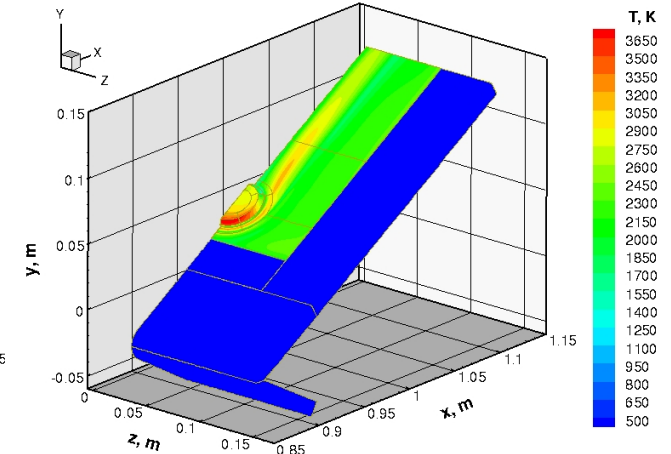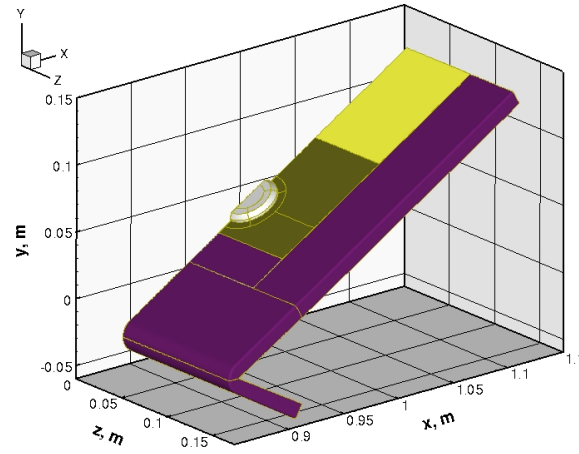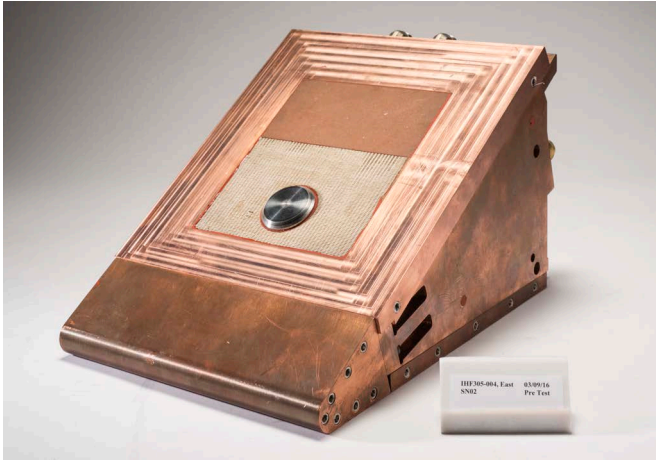
- NASA Ames 9-inch wide copper wedge holder is used
  - 30º wedge half-angle

- Test plate/bolt geometry details
  - Bolt parameters: D = 4.128 cm (1.625"), h_{bolt} = 0.508 cm (0.2"), h_{step1} = 0.191 cm (0.075"), 45º bevel angle
  - Distance from the test plate LE to the bolt LE: Δx_{boltLE} = 1.27 cm (0.5")

- Nominal test plate surface conditions: 200 W/cm^2 (CWFC), 13 kPa

Computed Surface Pressure and Centerline Profile –Test Plate

30º Wedge Model (r_n = 1.27 cm, w = 23.37 cm, l_{tp} = 21.59 cm), CWFC

IHF 13-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 22.8 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar
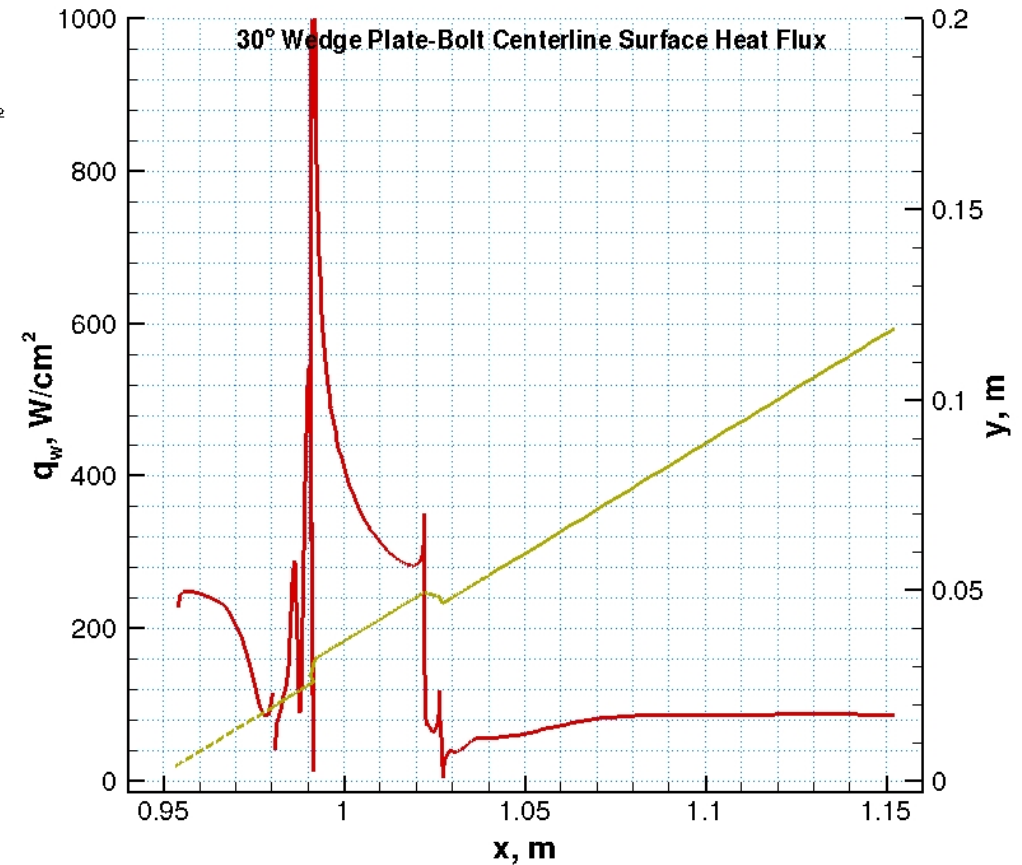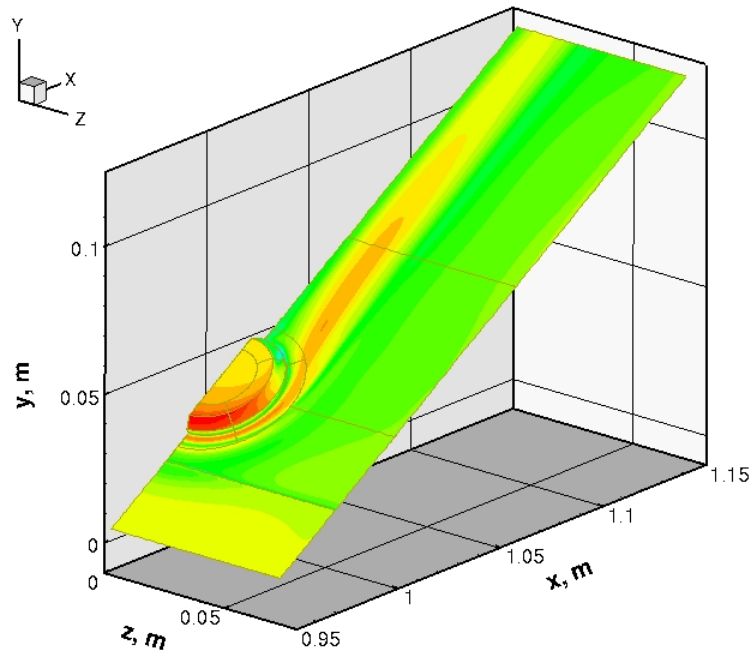

- Nominal plate surface conditions (CWFC): 200 W/cm^2, 13 kPa
- On the line plot, the dashed line represents the water-cooled copper plate surface upstream of the test plate

Computed Surface Heat Flux and Centerline Profile –Test Plate

30° Wedge Model (r_n = 1.27 cm, w = 23.37 cm, l_{tp} = 21.59 cm), CWFC

IHF 13-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 22.8 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar
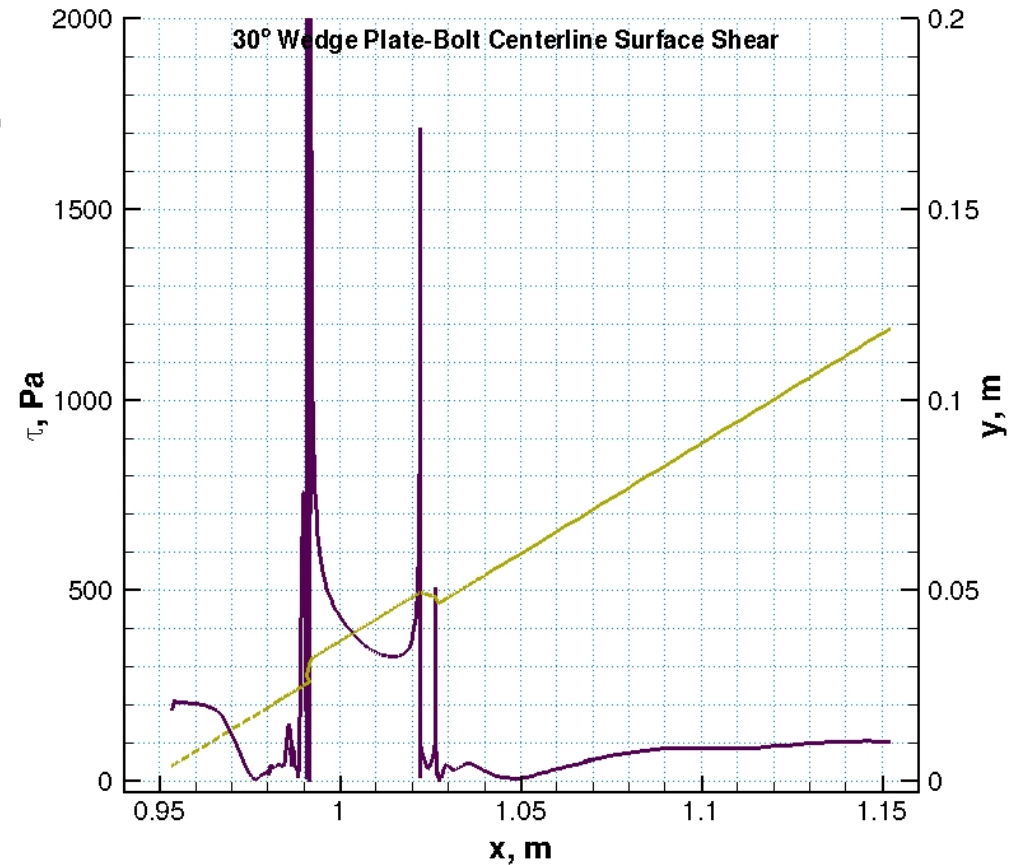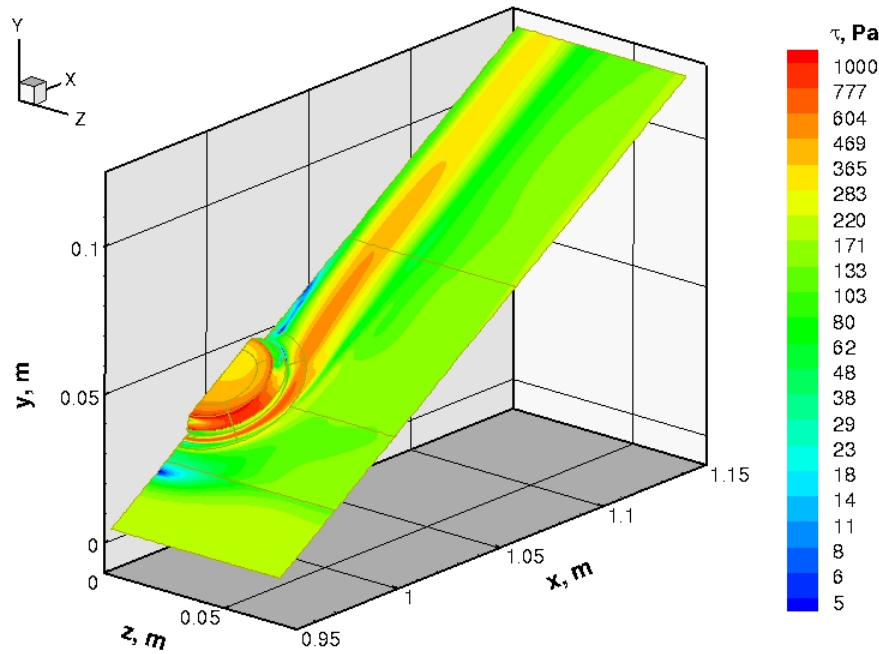

- Nominal plate surface conditions (CWFC): 200 W/cm^2, 13 kPa
- On the line plot, the dashed line represents the water-cooled copper plate surface upstream of the test plate

Computed Surface Shear and Centerline Profile –Test Plate

30° Wedge Model (r_n = 1.27 cm, w = 23.37 cm, l_{tp} = 21.59 cm), CWFC

IHF 13-Inch Nozzle Flow: $\dot{m}$ = 849 g/s, h_{ob} = 22.8 MJ/kg, h_{ocl} = 29.2 MJ/kg, 6.4% Ar
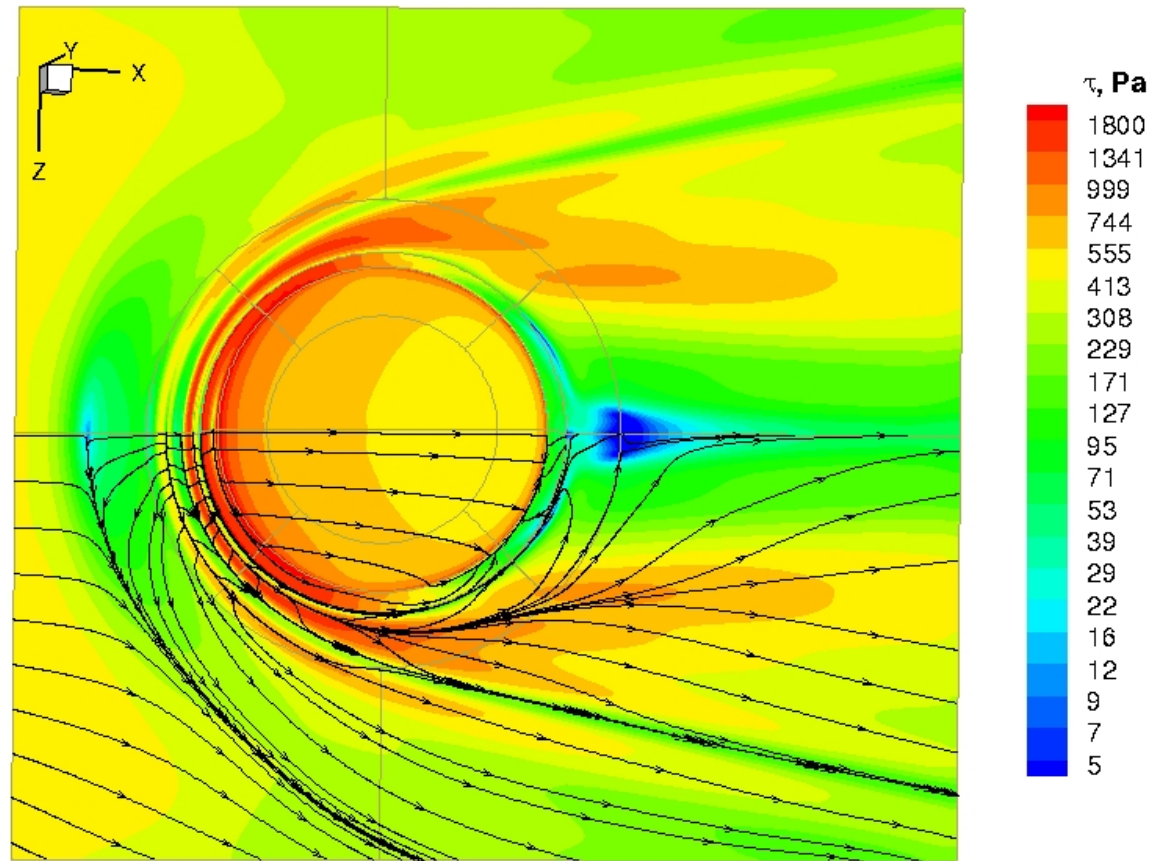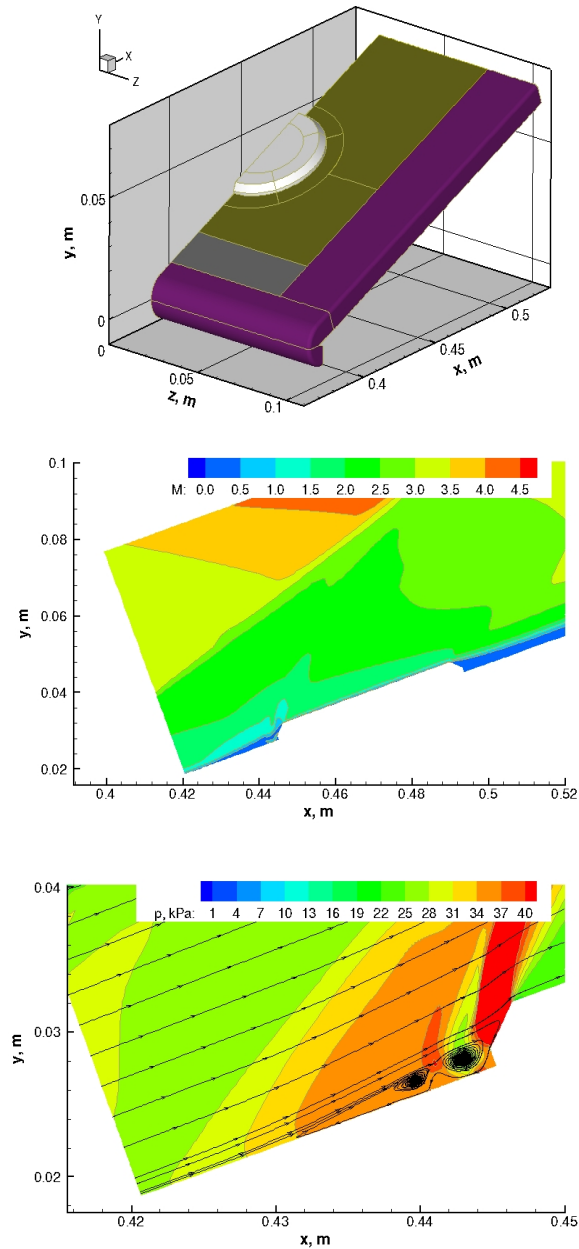

- The computed shear stress contours provide additional information about stagnant and separated regions in the flowfield, as these regions exhibit relatively low shear levels, e.g., both upstream and downstream of the bolt

Protuberance Induced Flow Features

Protuberance Induced Flow Features
## 20º Wedge Test Plate, IHF 6-Inch Nozzle Flow

- Many factors affect flowfield structure over a flat plate with a circular protuberance in a supersonic flow: boundary-layer thickness, protuberance diameter, step height and its geometry, edge Mach number, Reynolds number, pressure gradient over the plate, etc.
- Surface shear contours are very informative to map out important flow features

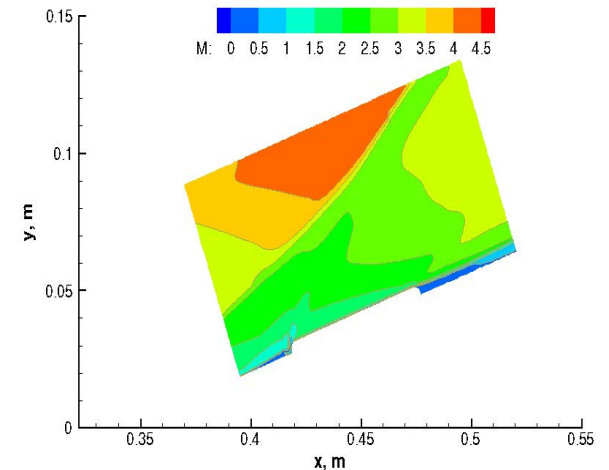# Effect of Bolt Step Height and Shock-Shock Interaction

20° Wedge Model, IHF 6-Inch Nozzle, Pretest Simulation: $p_o = 894$ kPa, $h_{ob} = h_{ocl} = 26.3$ MJ/kg, 6.4% Ar
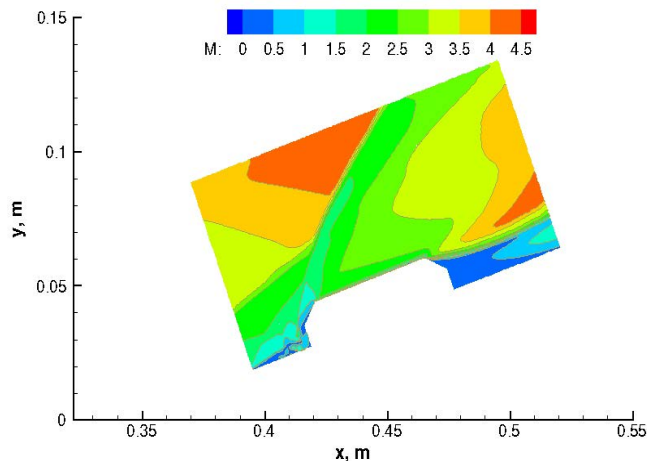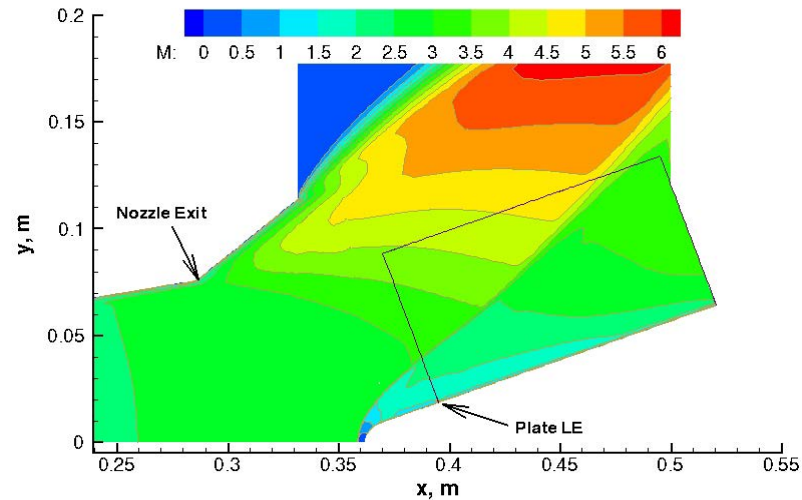
$h_{bolt} = 1.54$ cm, $h_{step1} = 0.82$ cm
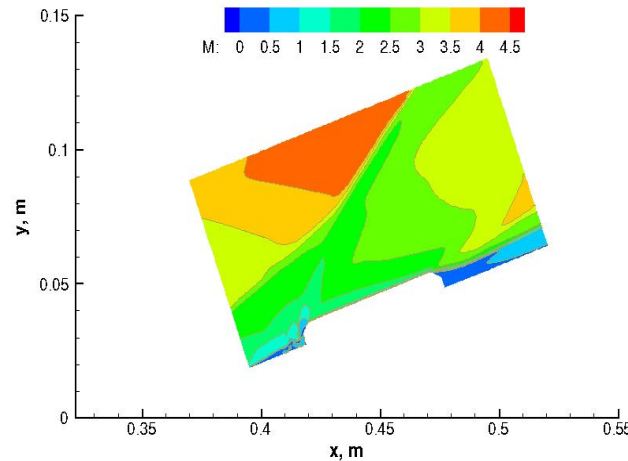
$h_{bolt} = 0.77$ cm, $h_{step1} = 0.41$ cm

$h_{bolt} = 0.38$ cm, $h_{step1} = 0.21$ cm

- The highlighted rectangular frame on the top Mach number contour plot represents the area of interest, namely the flowfield over the test article

- With increasing bolt height, interaction of the primary bolt shock with the bow shock of the wedge model increases, and as a result, steeper wedge bow shocks form, creating concerns for the facility test box and flow capture
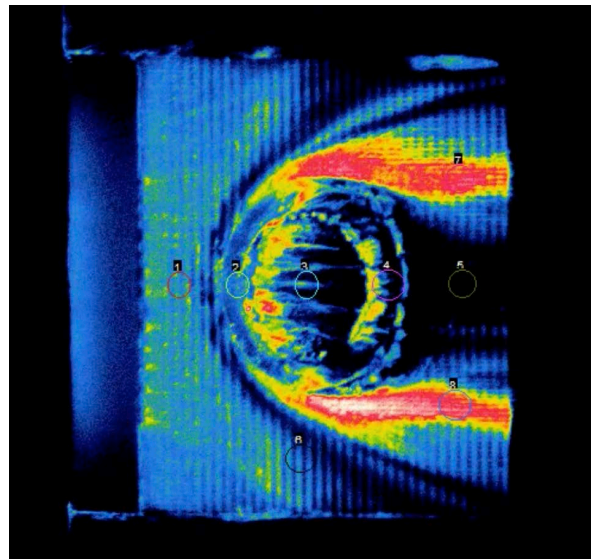
Comparisons of Qualitative Heating Patterns
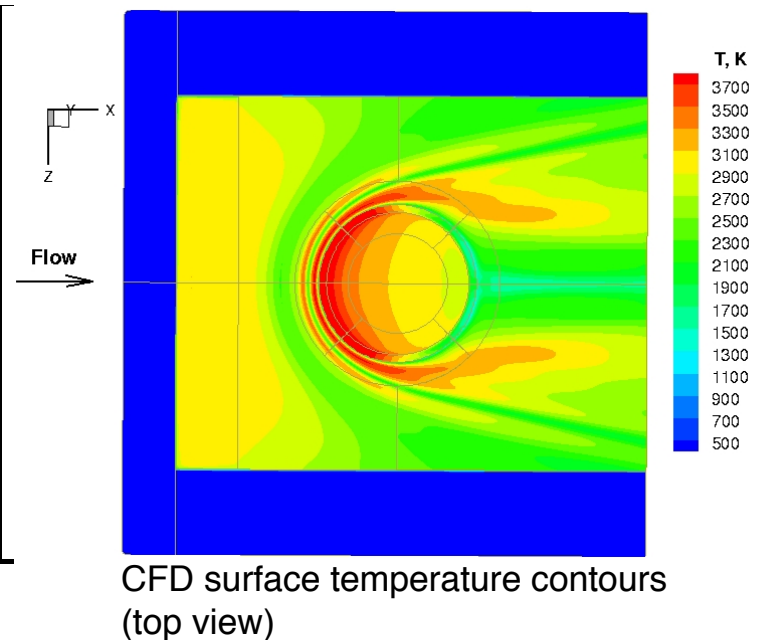
Qualitative Comparisons
20º Wedge Model, IHF 6-Inch Nozzle Flow
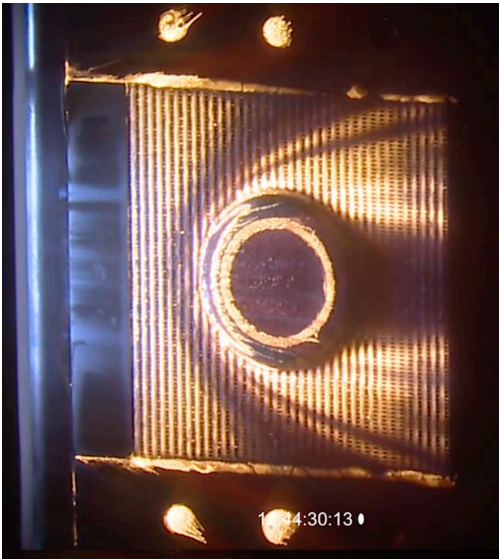
HD camera, IHF 309 Run 3

IR camera, IHF 309 Run 2

CFD surface temperature contours
(top view)

- HD and IR camera images, taken right before the separation bolt started to melt and soon afterwards, are similar to the computed surface temperature contours
- Darker regions on the HD and IR images represent colder regions (separated flow)
- Two primary augmented heating regions around the bolt are clearly observed and predicted by CFD simulations

Qualitative Comparisons
30º Wedge Model, IHF 13-Inch Nozzle Flow

HD camera, IHF 305 Run 3
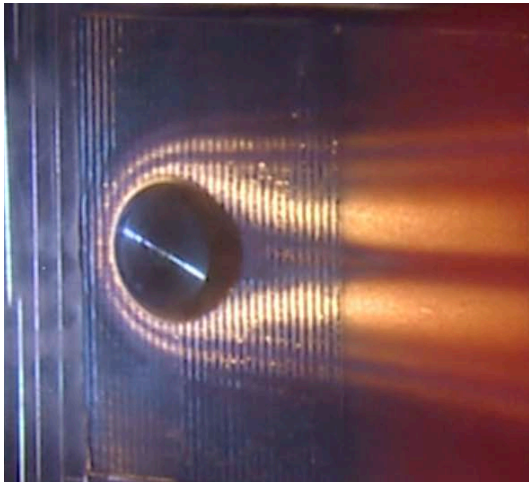
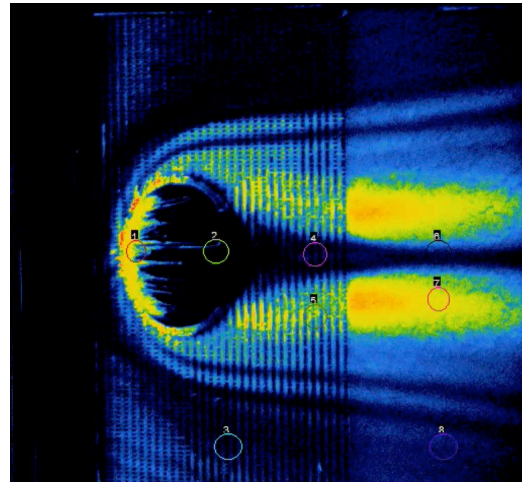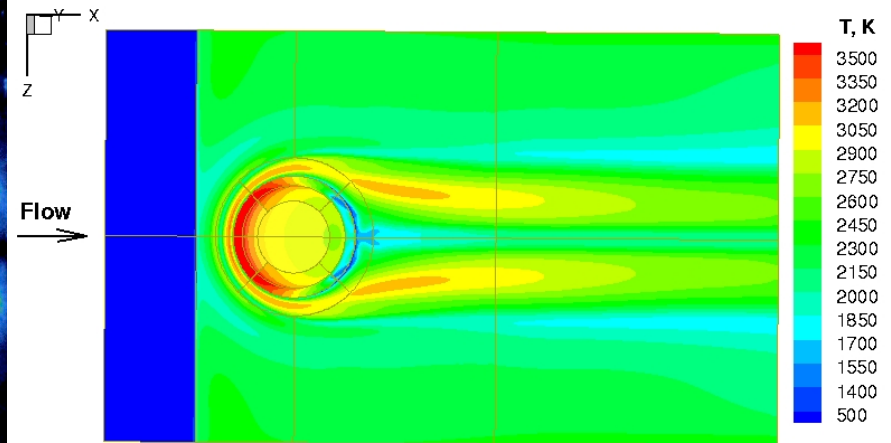IR camera, IHF 305 Run 5

CFD surface temperature contours (top view)

- HD and IR camera images, taken right before the separation bolt started to melt and soon afterwards, are similar to the computed surface temperature contours
- Darker regions on the HD and IR images represent colder regions (separated flow)
- Note that the separated flow region and subsequent reattachment upstream of the bolt remain intact as the flow goes around and passes the bolt
- Two primary augmented heating regions around the bolt are again clearly observed and predicted by CFD simulations

Summary and Concluding Remarks

- CFD simulations in support of two arc-jet wedge tests in the NASA Ames 60-MW IHF arc-jet flow are presented
  - Two different wedge models: 7-in wedge in the IHF 6-inch nozzle, and 9.2-in wedge in the IHF 13-inch nozzle
  - Panel test articles included a metallic separation bolt imbedded in the compression-pad material, resulting in a circular protuberance over a flat plate

- CFD simulations, through comparisons with the test data, provide estimates of arc-jet test environment parameters, the centerline total enthalpy being the most important test parameter
  - Hot-wall full-catalytic heat flux, boundary layer thickness, edge Mach number, and surface shear

- For the test articles with the separation bolt, CFD simulation is the only reliable tool to provide surface heating and pressure distributions
  - Predicted heating distributions are qualitatively in good agreement with images from HD and infrared cameras
  - Both camera images and computations show that surface heating distributions of the test articles have multiple augmented heating regions due to complex flow interactions, such as shock-shock and shock-boundary layer interactions

- As demonstrated in our earlier work for other arc-jet facilities, these CFD simulations of the IHF flow can assist test planning, define arc-jet test environments for surface properties of TPS, reduce exploratory testing, and provide a framework for tracing the TPS performance from this ground test facility to flight

Acknowledgments