Conjugate Fluid Flow/ Solid Heat Transfer Simulations of the Flame Deflector Thermal Environment

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MOTIVATION

- Main Flame Deflector (MFD) re-directs the plume
  - Direct plume impingement → harsh stress and thermal loads
  - Coated with the Fondu-Fyre refractory material
- Shuttle era design required frequent and costly repairs:
  - Average cost of repair, per launch, is roughly **$500K*** (for MFD only)
  - **2-3 weeks** of repair time
- MFD re-design for the new launch complex:
  - Compatibility with Space Launch System (SLS) and **commercial** launch vehicles

* *NASA/TM-2013-216321*

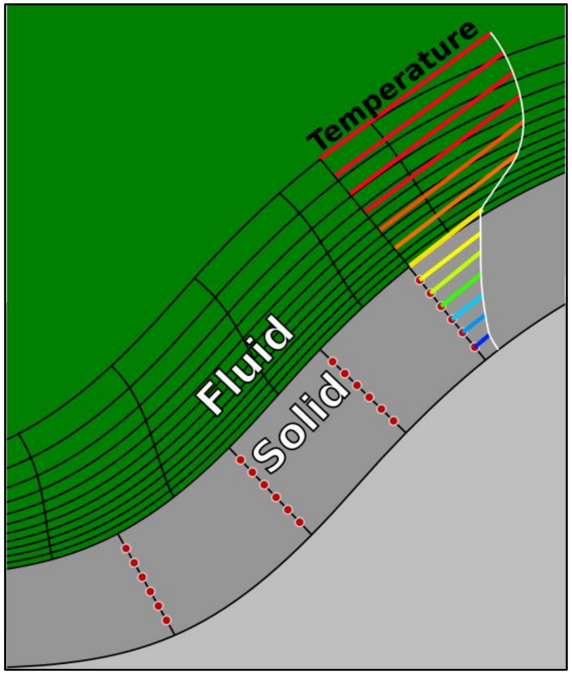
MOTIVATION

- Guide MFD re-design with CFD
  - Fast simulation turn-around time
    - Support fast-paced design iterations
  - Reasonably accurate, time-dependent predictions of
    - Pressure loading
    - Heat flux
- Traditional CFD analysis of wall heat flux
  - Isothermal wall assumption
    - Vast over-prediction (with hot plume impinging on cold wall)
  - Adiabatic wall + post analysis with empirical correlations
    - Dubious predictions for complicated flows
  - Lack of time-dependent response of the surface temperature
  - Thus, CFD thermal analysis of MFD was not used

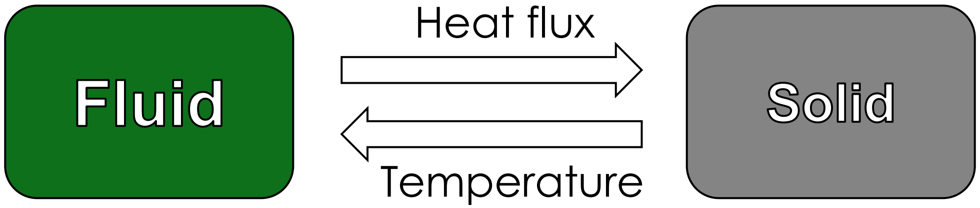
- LAVA CFD code introduced conjugate simulations:
  - Tightly coupled fluid flow & surface material heat transfer
  - Predictive capability for MFD thermal environment
- Developed by the authors at NASA ARC
- High performance oriented
- Handles Cartesian, arbitrary polyhedral unstructured & curvilinear meshes
  - Hybrid meshes are possible via an overset coupling
  - Adaptive mesh refinement for Cartesian meshes
- 2nd order spatial and temporal accuracy
- SST, SA and SA-DES turbulence models

Conjugate Simulation Method

- Fluid domain:
  - Arbitrary polyhedral unstructured mesh
  - Polygonal prism boundary layer mesh
  - 3D Navier-Stokes equations
- Solid domain:
  - 1D, unsteady heat conduction equation
  - Along rays for each fluid mesh face on the surface
  - Solid back assumed insulated

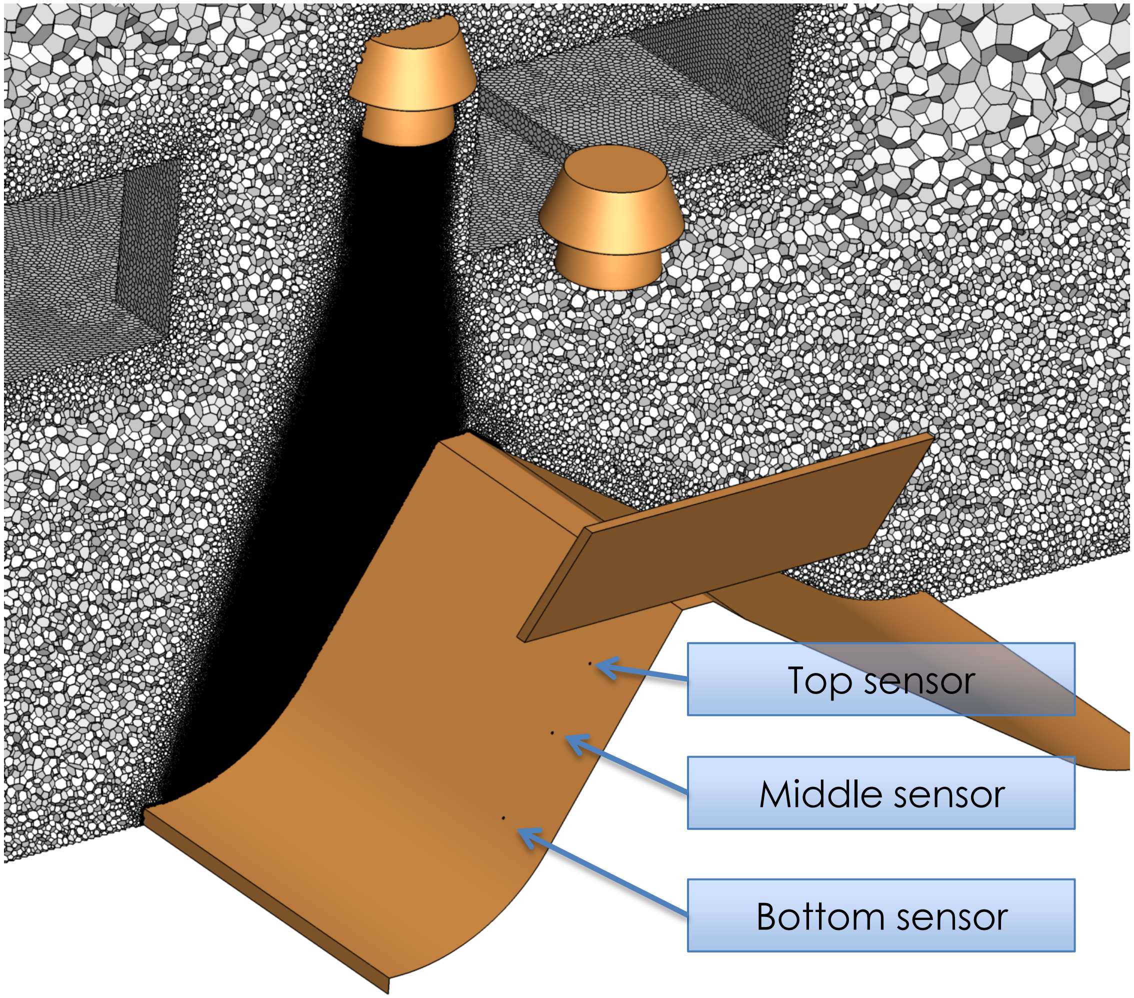


- Coupling:
  - Two-way information exchange at each iteration



Test Application – STS-135

- MFD pressure and heat flux measured during launches
  - STS-133-134-135
  - 3 locations instrumented with COTS sensors which feature
    - Kulite – High speed pressure
    - Medtherm – Heat flux
    - Nanmac – Heat flux
    - Sensors were embedded in stainless steel encasing



21 million polyhedral unstructured elements

Orbiter, external tank were omitted

Only nozzles of SRB's included

Time step of 3.5e-5 seconds

20 sub-iterations each time step

Prismatic boundary layer mesh ($y^+<1$)

STS-135 :: Computational Setup

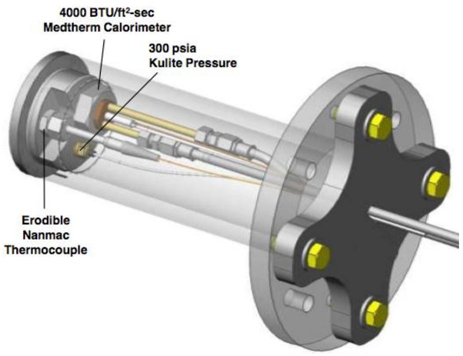
- SA-DES turbulence model
- Unsteady SRB plenum data was used from STS-1
  - Likely inconsistencies with STS-135 (current case)
- Non-reacting, single species plume exhaust gas
  - Not expected to affect impingement heating
- Water sound suppression system is neglected
  - Not expected to affect impingement heating
  - Affects wave propagation speed
- These assumptions all contribute to temporal error
- Solid particles from SRB's omitted
- MFD surface irregularities neglected
- No MFD refractory material recession and surface reactions
- Solid heat transfer is modeled as 1-dimensional

STS-135 :: Surface Material Properties

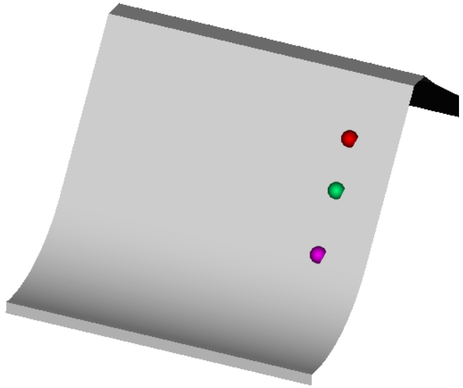
- MFD surface material (Fondu Fyre) properties:

Thickness	6 in
Density	2000 kg/m^3
Specific Heat	Temperature dependent*
Melting Temperature	1373 K
Thermal Conductivity	1 W/(m.K)

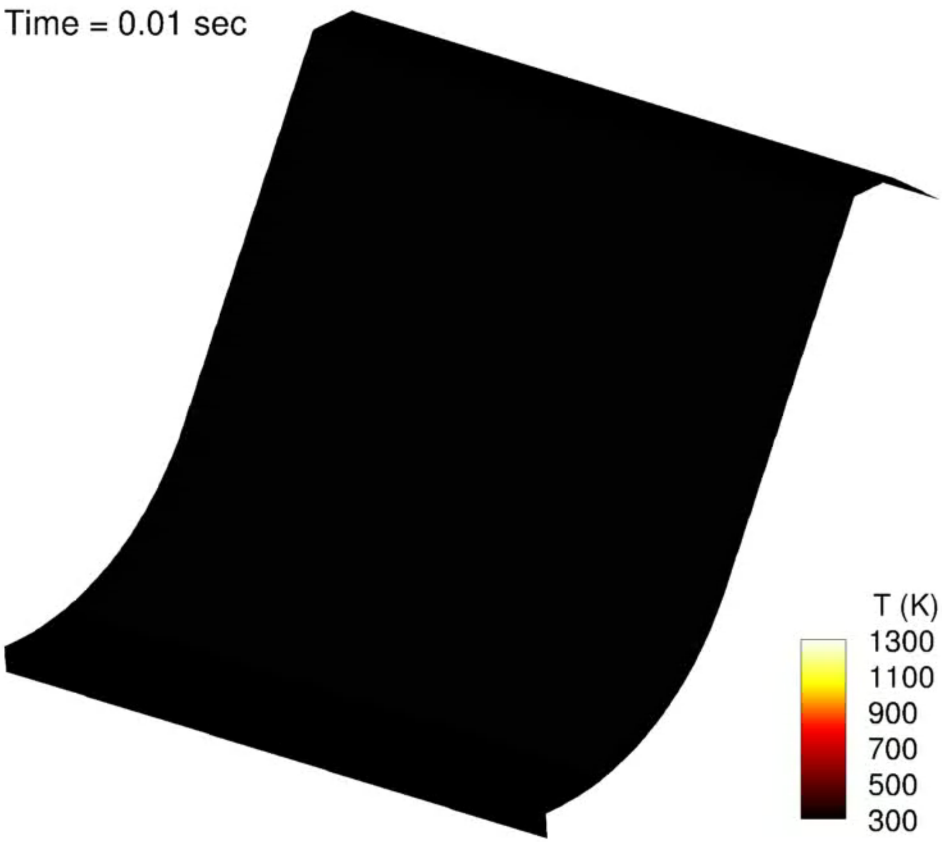
- Sensors are embedded in stainless steel structures
- Encasing is modeled as 3.5" diameter discs
- Sensor encasing material (stainless steel) properties:

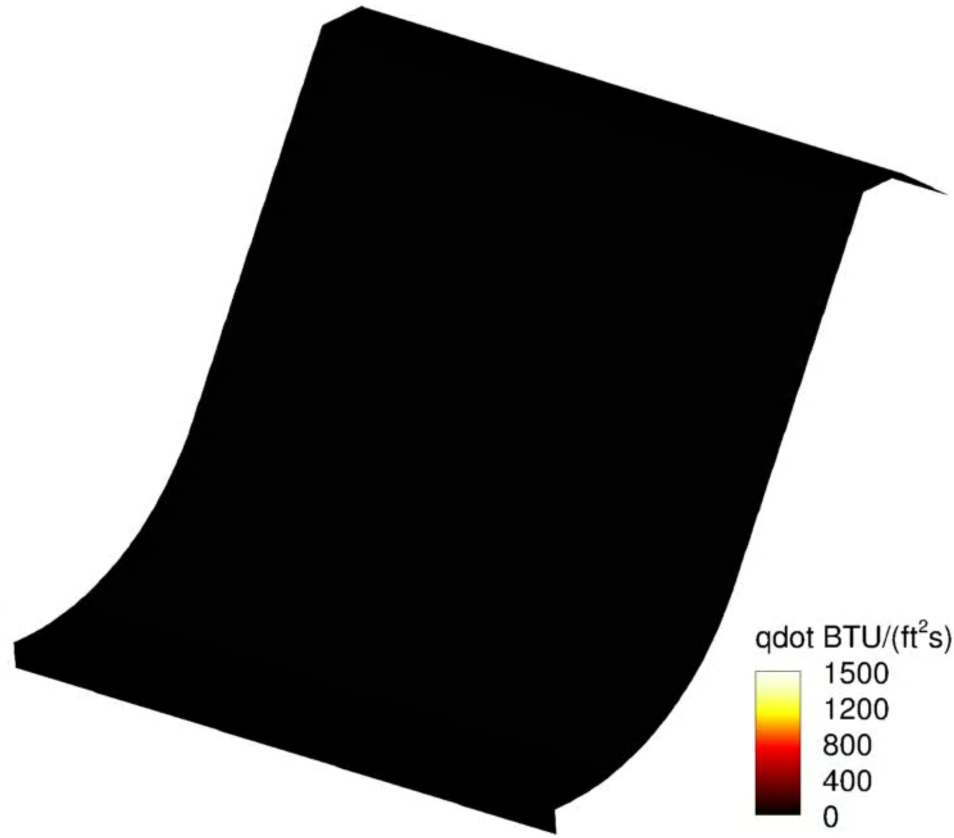


Thickness	1 in
Density	8030 kg/m^3
Specific Heat	500 J/(kg.K)
Melting Temperature	1700 K
Thermal Conductivity	21.4 W/(m.K)



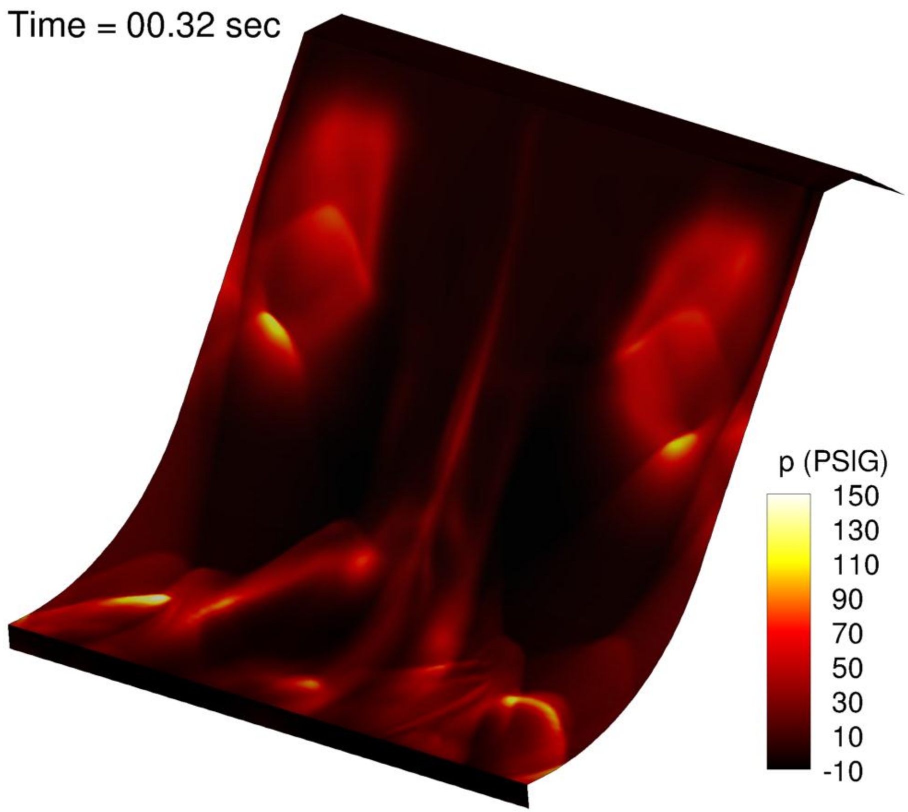
STS-135 :: MFD Temperature & Heat Flux

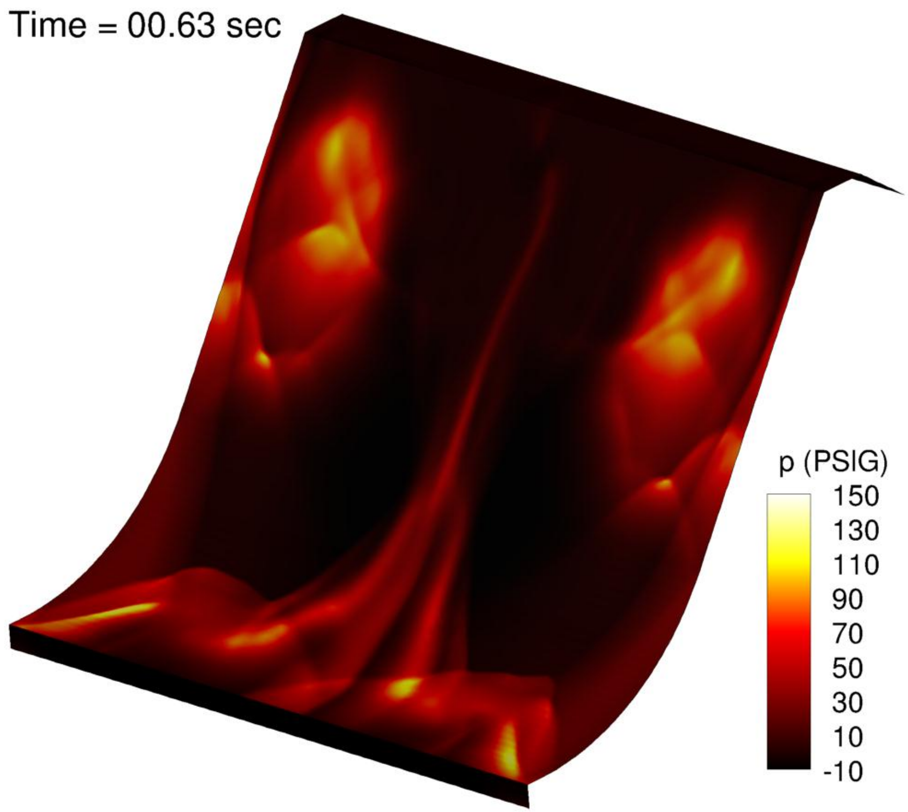




STS-135 :: MFD Pressure

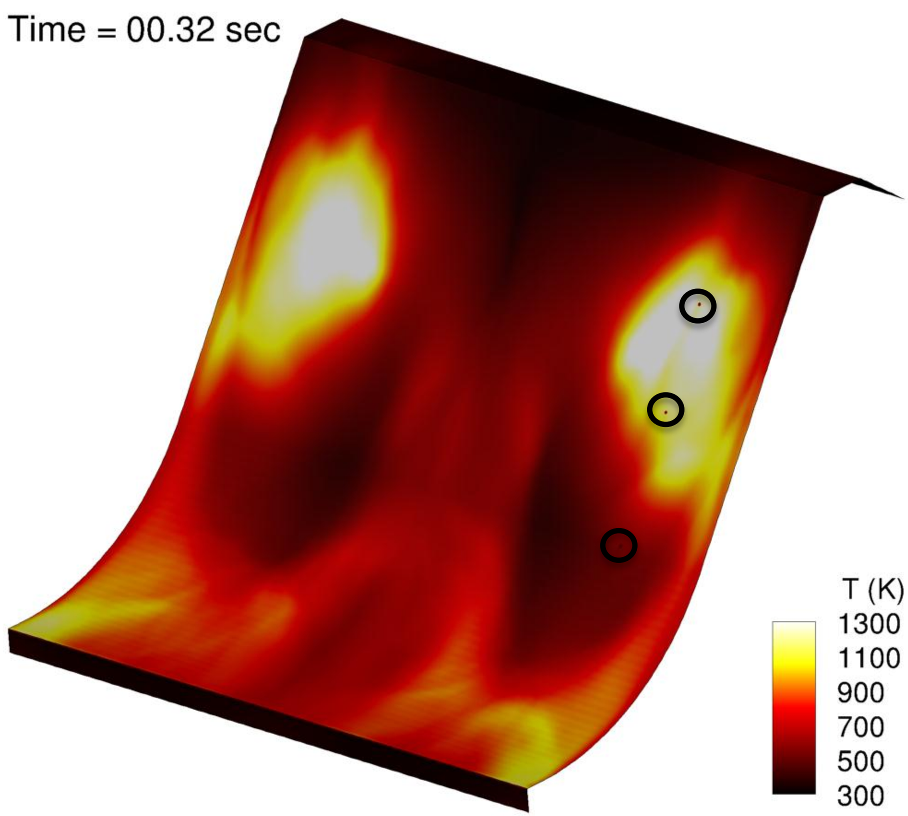
- Instantaneous pressure distribution over MFD
  - High pressure regions at the primary and secondary impingement locations
  - Near quasi-steady conditions reached around 0.6 sec

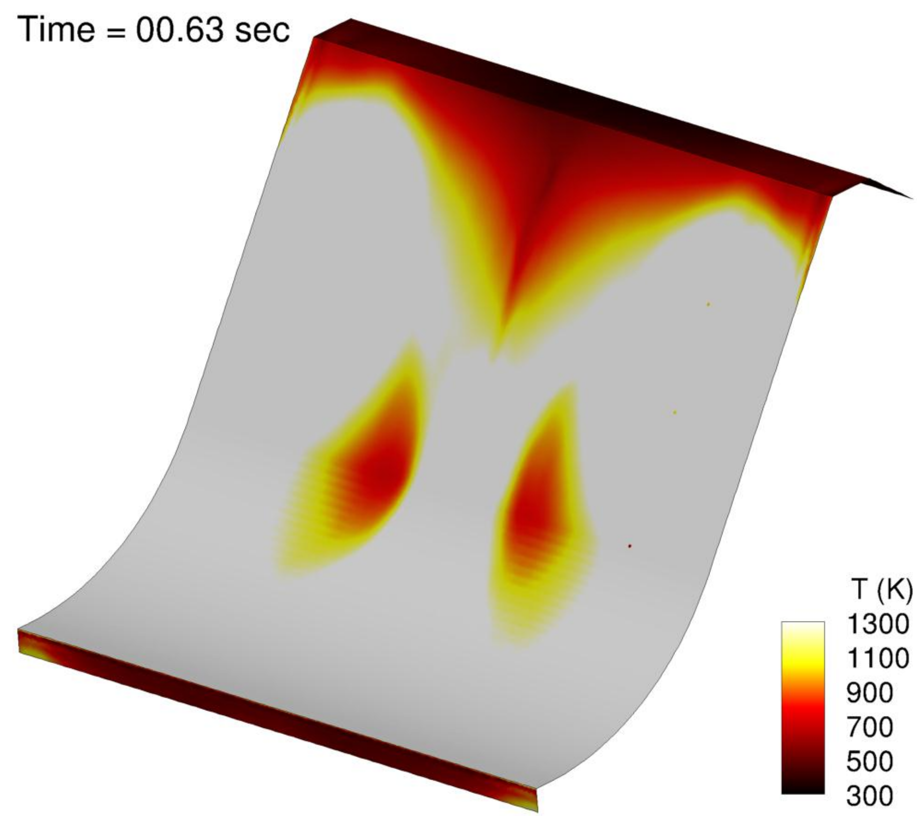




STS-135 :: MFD Temperature

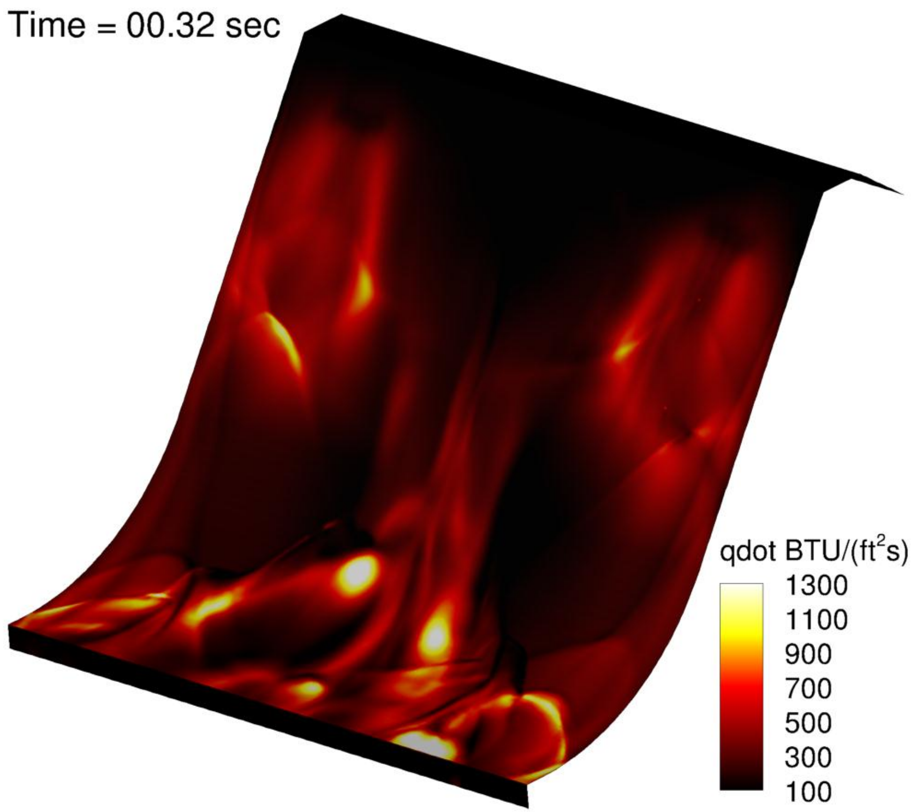
- Instantaneous temperature distribution over MFD
  - Temperature builds-up over time
  - Relatively cooler sensor locations (stainless steel) identified
  - Lack of water cooling results in wide spread melting

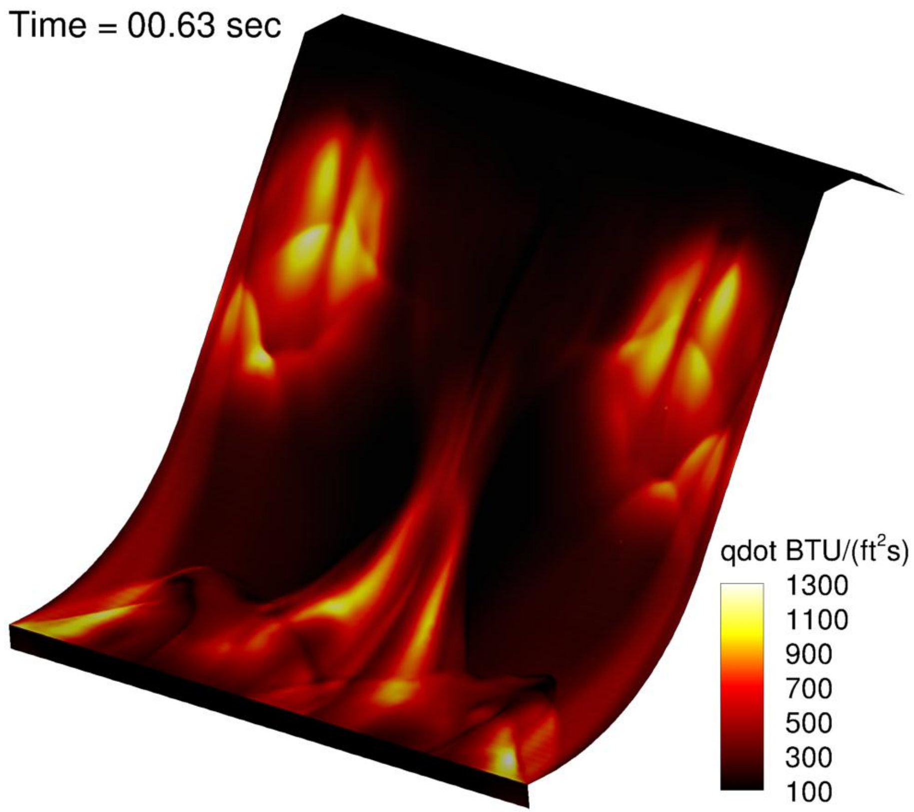




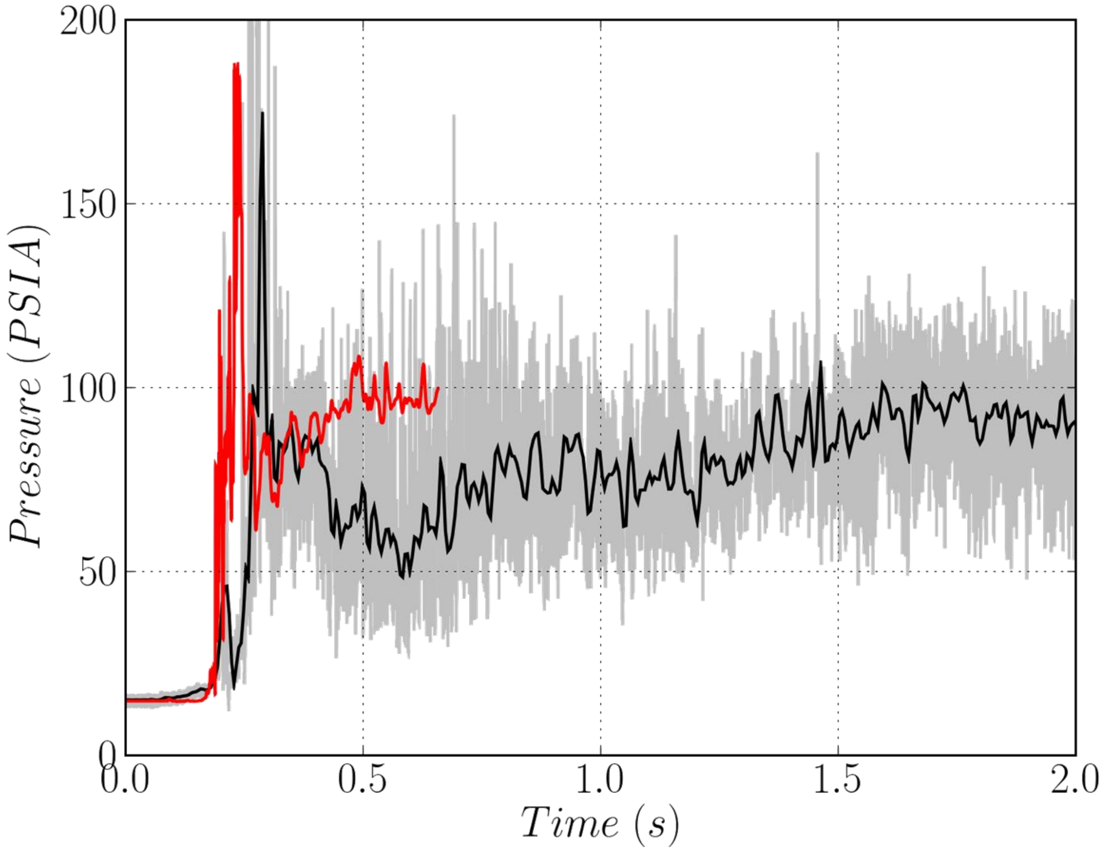
STS-135 :: MFD Heat Flux

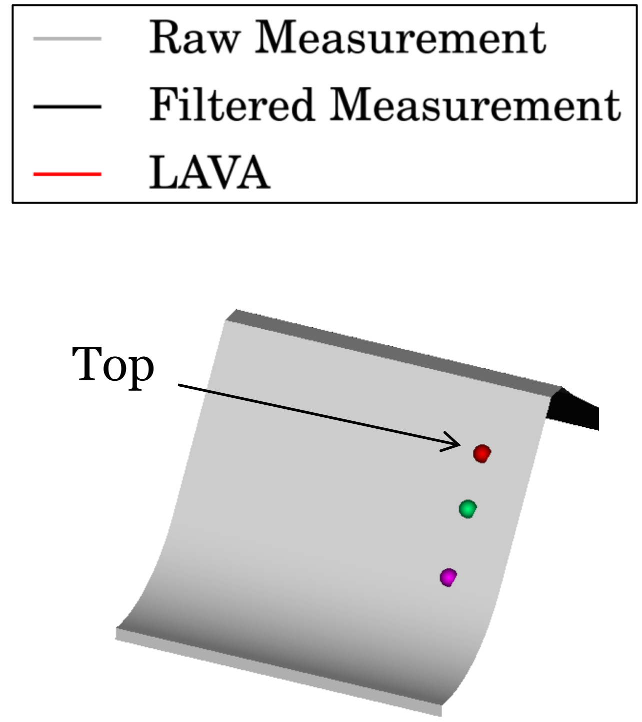
- Instantaneous heat flux distribution over MFD
  - High heat flux regions at the primary and secondary impingement locations
  - Similar pattern as the pressure distribution





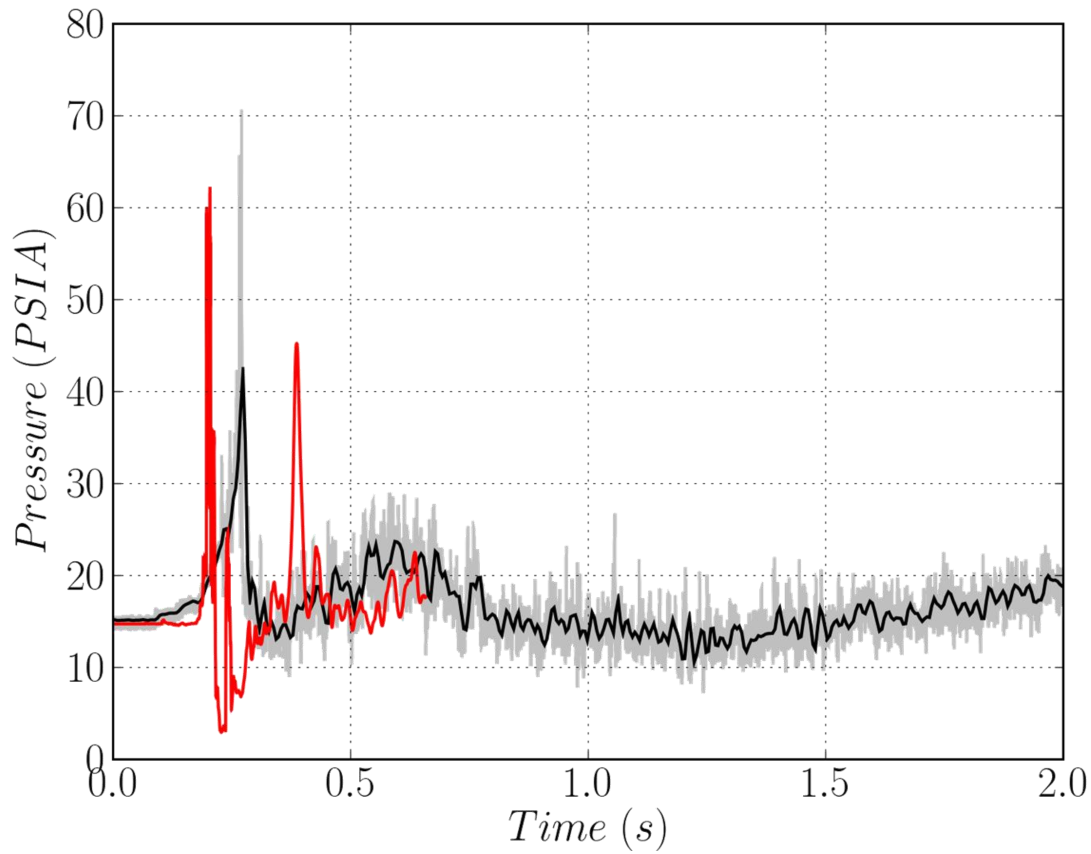
STS-135 :: Top Pressure Sensor

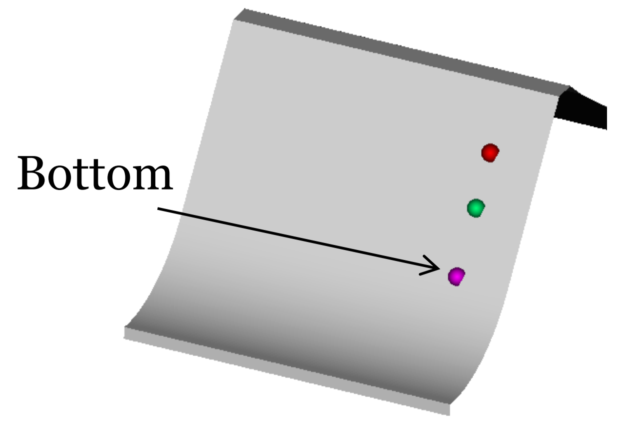




- Peak Ignition Over Pressure (IOP) well predicted
- CFD simulation seems to precede measurement by ~0.05 sec.
  - Difference maybe attributed to assumptions emphasized earlier
  - Particularly, the omission of water sound suppression system

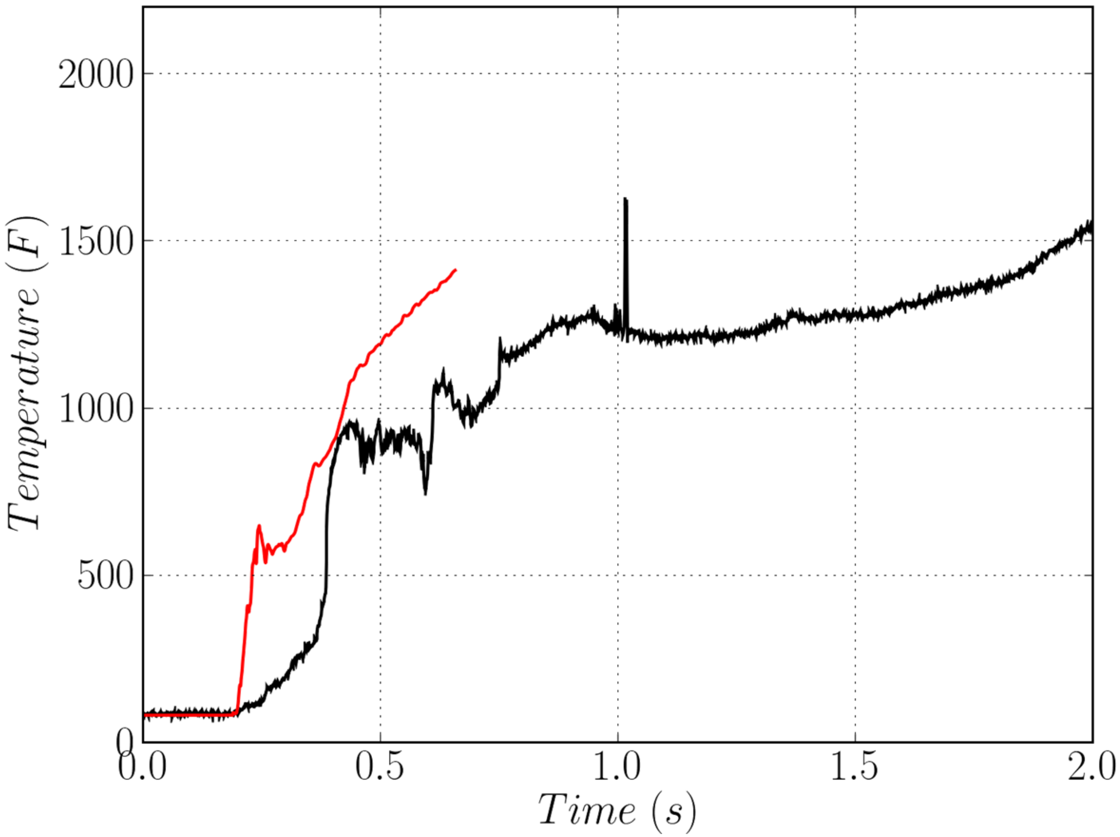
STS-135 :: Bottom Pressure Sensor

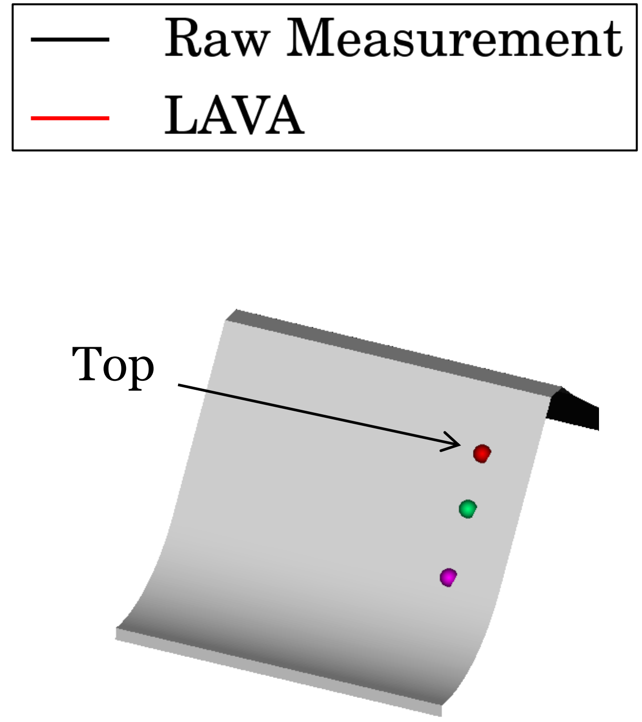




- Similar time shift as in the top sensor
- CFD shows a dip, followed by a secondary peak (~0.4 sec)
  - Not observed in measurements
  - Reason is to be investigated (possibly also due to water system suppressing the IOP)

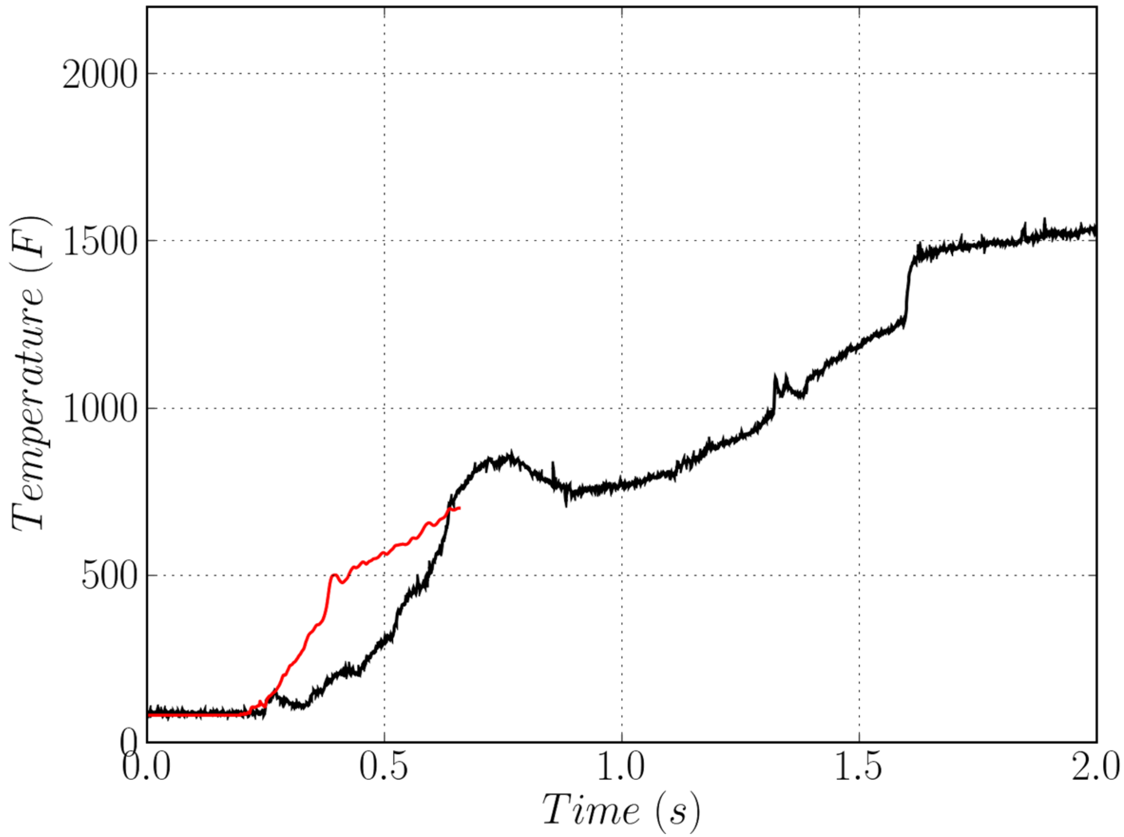
STS-135 :: Top Temperature Sensor

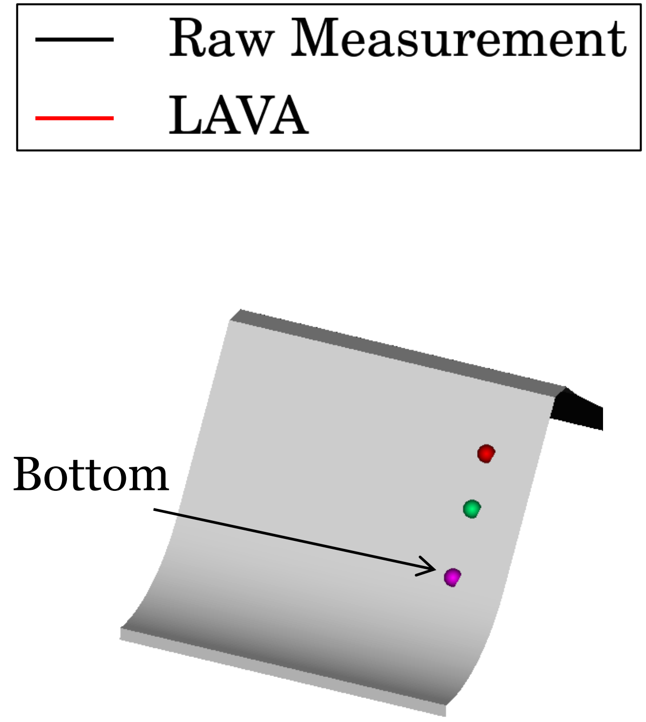




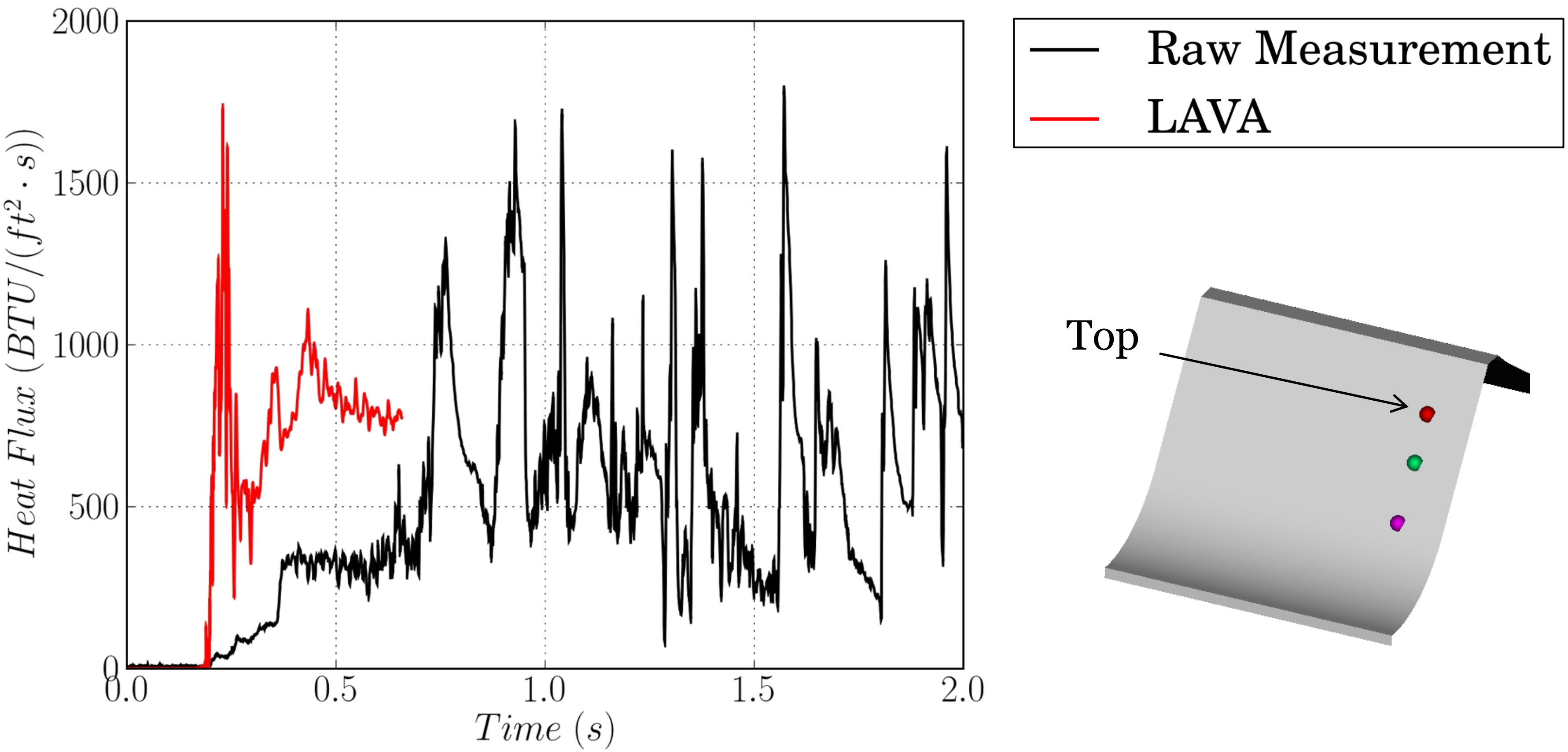
- Same time shift issue appears for temperature and heat flux
- Overall, well matched temperature climb profiles

STS-135 :: Bottom Temperature Sensor



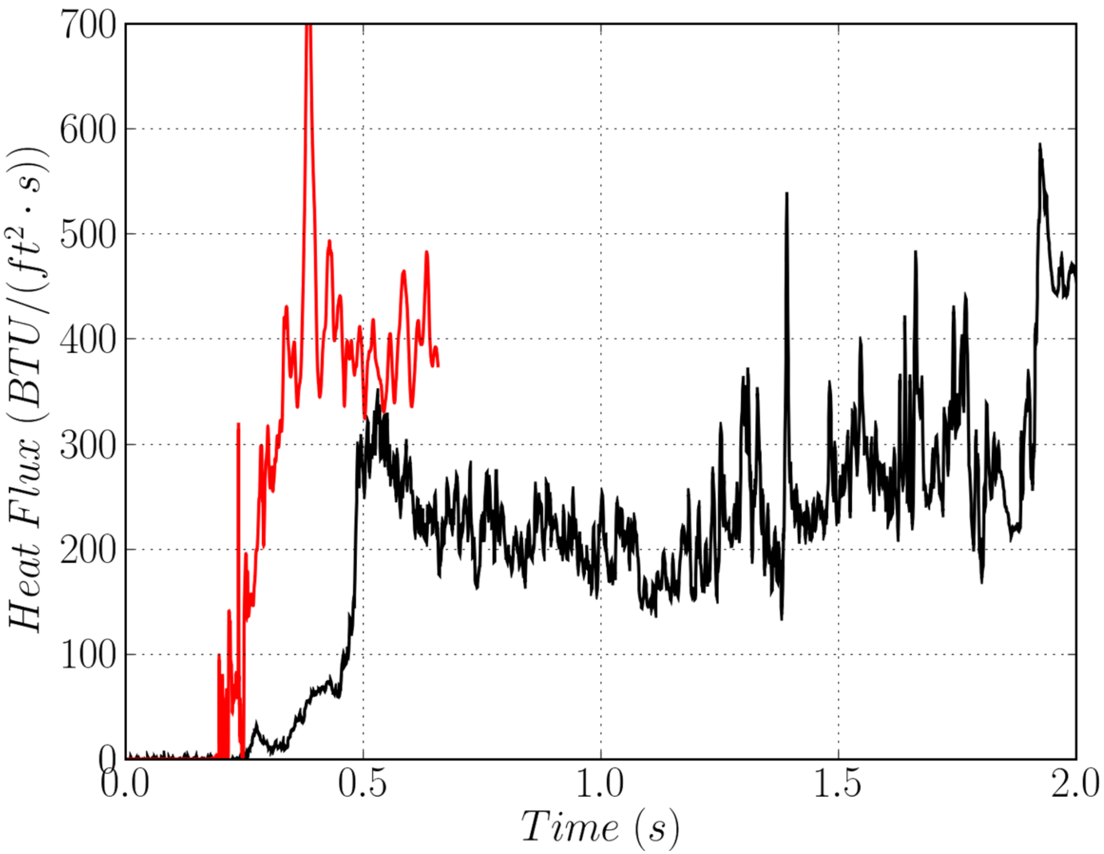


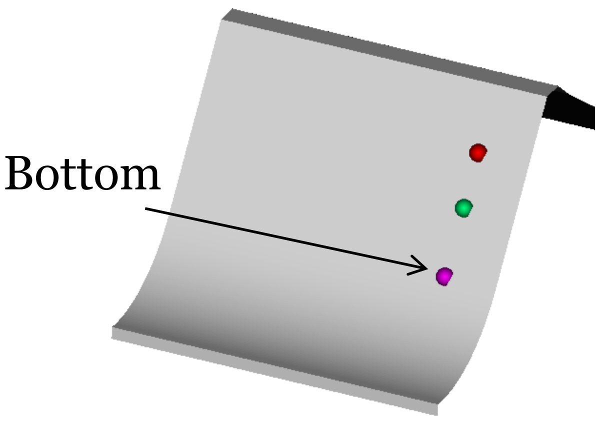
STS-135 :: Top Heat Flux Sensor



- The initial heat flux peak (~0.3 sec) not observed in measurements
- Spikes in measurements were attributed to particle impingement
- CFD prediction is conservative within reasonable margin
  - Heat flux is difficult to measure and simulate
  - Large uncertainties in both

STS-135 :: Bottom Heat Flux Sensor





Summary & Conclusions

- A first-principles based analysis of MFD heating
  - Conjugate fluid flow/ solid heat transfer CFD simulation
- Many simplifying assumptions were made
  - Physical and geometrical complexities/unknowns
- Reasonable agreement with the measurements
  - Temporal discrepancy is observed, possibly due to water exclusion
  - IOP wave amplitude is accurately captured
  - Temperature predictions are very consistent
  - Heat flux predictions are conservative within reasonable margin
    - Keeping in mind the large measurement uncertainty in heat flux
- Present method is:
  - Computationally affordable
  - Can be practically used to guide design process
- Would benefit from further validation in simpler cases
  - Investigation of sensitivity to modeling simplifications