Plume Impingement Heating on the International Space Station: Challenges and Opportunities

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INTRODUCTION

Objective

- Provide plume heating environments for the ISS during rendezvous proximity operations based on a summary of plume impingement heating studies performed for ISS visiting vehicles
- Challenge: Predicting plume impingement
  - Modeling exhaust plumes in space
  - Modeling impingement heating on complex geometries
- Opportunity: Locate keep-out zones for sensitive payloads and prime locations for experiments studying plume exhaust gases and their effects

Spacecraft Docking/Berthing

Rendezvous Proximity Operations

ISS Plume Heating Requirement

From SSP 50808:

- **3.3.10.1 VEHICLE PLUME HEATING ON ISS**
  - During approach/separation, the COTS RCS thruster thermal plume impingement heat fluxes and heat flux integrals on ISS hardware shall not exceed the heat flux and integral heat flux values in Table 3.3.10.1-1, Plume Impingement.
- **TABLE 3.3.10.1-1 PLUME IMPINGEMENT**

Component	Heat Flux (kW/m^2)	Heat Flux Integral (kJ/m^2)
SSRMS	242	68.5
Other ISS Elements	**133**	**119.6**

  - **Identical table appears in SSP 50273 for HTV**
- Per 4.3.3.10.1, thermal analysis may be used for verification for cases where heat flux integral exceeds values in Table 3.3.10.1-1

METHODOLOGY

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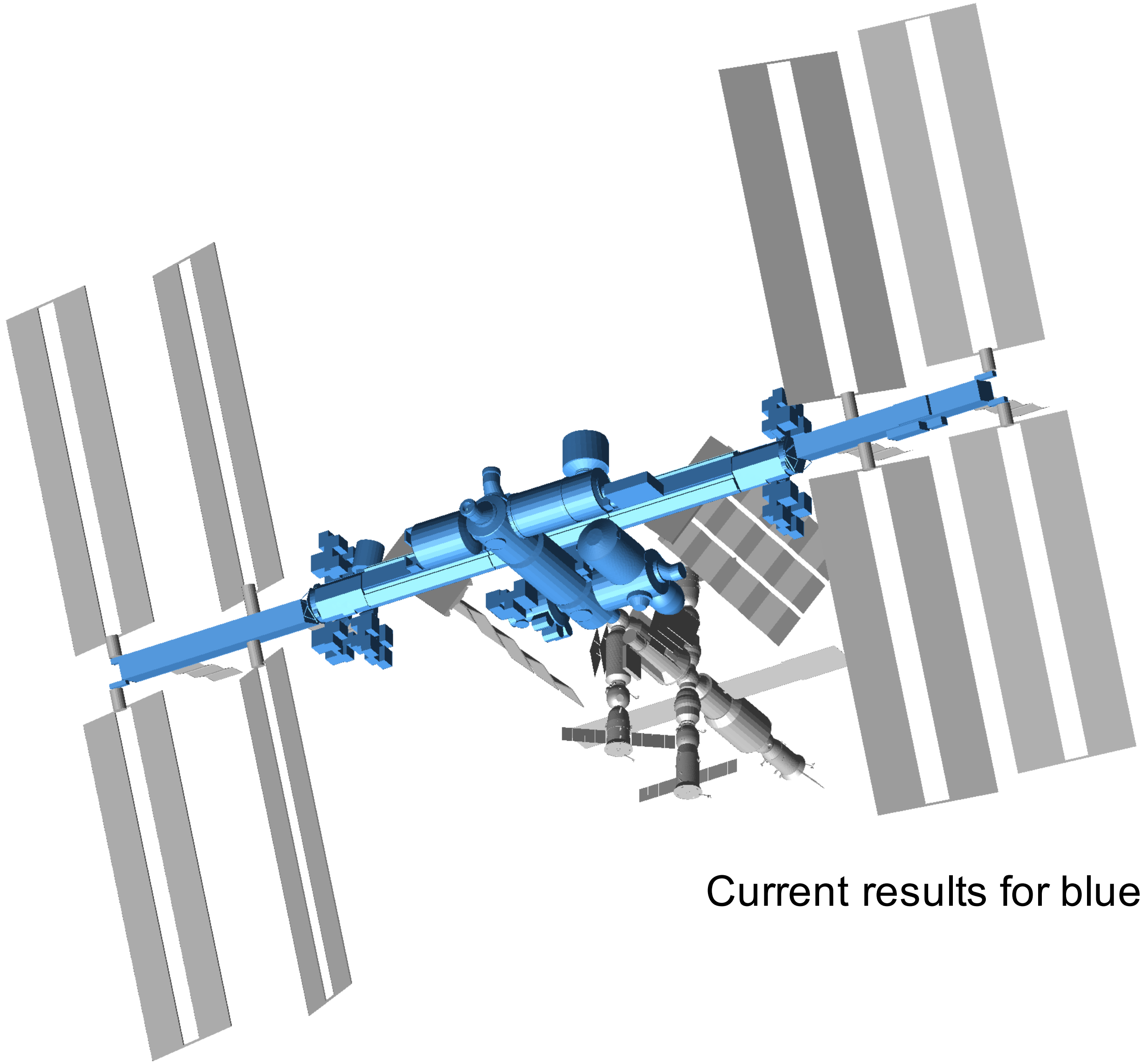
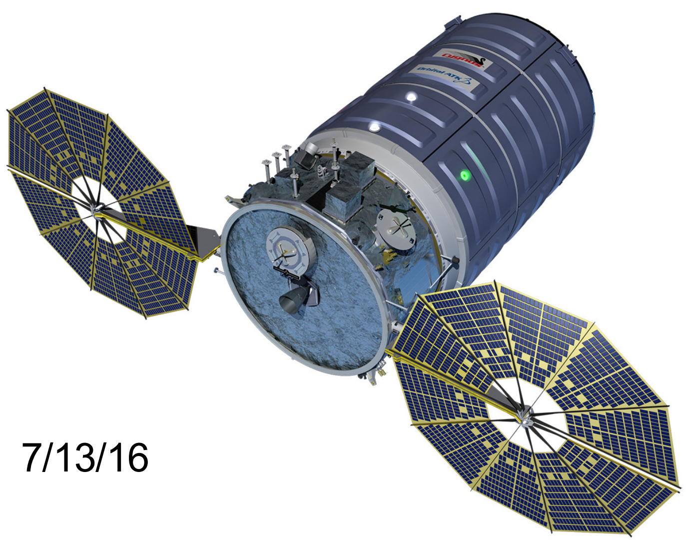
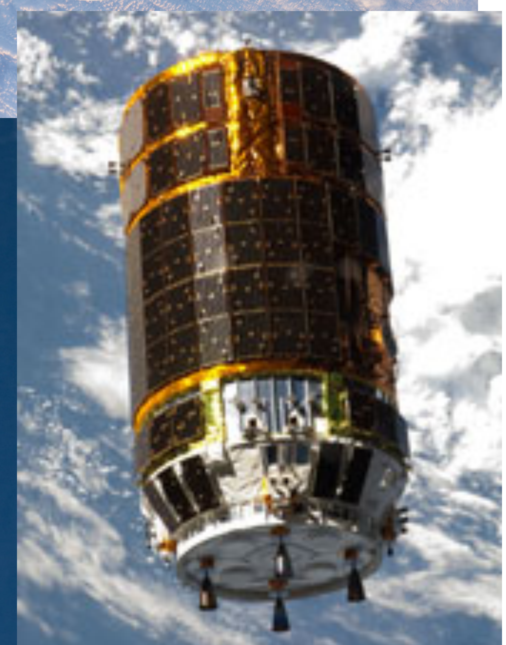


Current results for blue sections

Visiting Vehicles

- Each VV has a different thruster type, thrust level and number/configurations of jets
- Developed VV modules contain locations and orientations of each thruster on vehicle body





Tools

- **Reaction Control System (RCS) Plume Model (RPM3D)**
  - Engineering analysis tool that analyzes 6DOF vehicle trajectories to determine plume impingement to 3D geometries based on plume source flow model
- Computational Fluid Dynamics (CFD)
- Direct Simulation Monte Carlo (DSMC) Analysis Code (DAC)
  - NASA JSC high fidelity DSMC tool for simulating rarefied gases
  - Loosely coupled with CFD
- NASA heritage engineering codes

Calculation of Heating

- Plume Modeling with Source Flow Models (SFM)
  - SFM provides density and velocity
    - Single/multi- engine models for scarfed/axisymmetric nozzles
    - Developed with various methods
      - Heritage engineering codes
      - CFD and CFD/DSMC
- Impingement Modeling
  - Maximum Energy Heating Method
  - Other Methods
    - Bridging Function Heating Method
    - CFD/DSMC simulation
  - Total heat load is computed for each VV trajectory and compared to ISS requirement to check for exceedances

Analysis Process

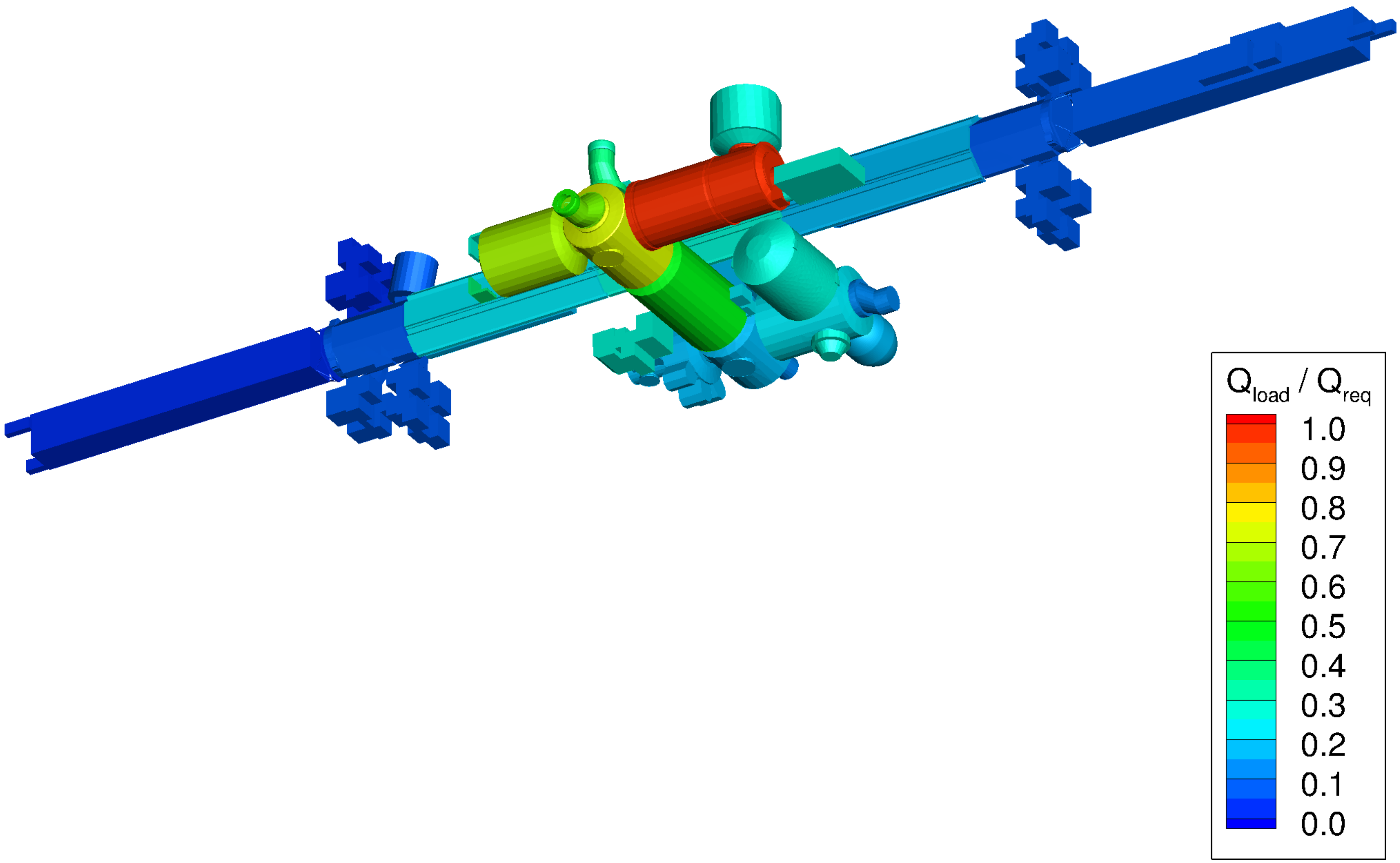
- Analysis performed with Maximum Energy heating method
- Screening for all thruster firings within 100 m of ISS based on the trajectory database for each VV
  - Current VV includes Dragon, HTV, Cygnus, and Soyuz
  - Over 25,000 simulated and as-flown trajectories
  - Nominal and off-nominal trajectories considered
- Component shading is not included
- Final results presented are based on the worst-case peak heat loads for each US segment component
  - Each component classified as zone
  - Each zone has a corresponding worst-case peak heat load that is applied to entire zone
  - The worst-case heat load for each zone corresponds to a worst-case trajectory from one of the VV trajectory databases

RESULTS

Results Summary

- Majority of worst-case results (for payloads) come from Dragon trajectories
  - Scarfed (100 lbf) thrusters used for on-orbit and reentry maneuvers
- Most severe heating occurs near docking and berthing locations
- Peak heat load occurs on JEM Module
  - From an off-nominal HTV trajectory
- Peak approaches maximum set by plume impingement heat load requirement for ISS

Heat Load Map



Summary

- Over 25,000 VV pre-flight and as-flown trajectories have been analyzed since 2004 (HTV)
- The results database has been used to develop external payload heating environments for equipment that uses passive thermal protection
- Based on the resulting heat load map, keep-out zones can be implied along with areas of interest for studying plume exhaust gases and their effects
- Future Work: Results will be updated as more and more vehicle data becomes available