Thermal & Fluids Analysis and the NASA Launch Services Program

John F. Kennedy Space Center

Abstract

THERMAL & FLUIDS ANALYSIS AND THE NASA LAUNCH SERVICES PROGRAM

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ABSTRACT

This presentation provides the What, Where, Why, and How of the thermal and fluids analysis disciplines within the Launch Services Program (LSP). The LSP manages all commercial launch services to match NASA science mission payloads to the appropriate launch system. The Flight Analysis Division within the LSP provides multi-disciplinary analysis support of these flight systems to characterize payload and launch vehicle environments from payload mate to upper stage through on-orbit separation. The Thermal Analysis and Fluids Analysis teams are two distinct groups within the Flight Analysis Division of the LSP who cover a wide array of standard and non-standard analytical tasks. These teams offer a significant benefit to both the payload design and integration team and the launch vehicle supplier. These benefits, along with the tools and methods are described in this talk to inform engineers and analysts from both sides of the launch system interface how the LSP Thermal and Fluids Analysis teams can benefit the success of their mission.

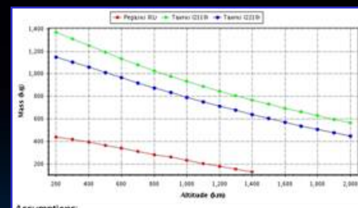
What is the Launch Services Program?

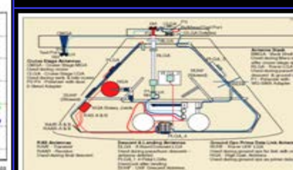
- Established in 1998 to support NASA's science and robotic missions with commercial launch vehicles
- Brings together technology, procurement, engineering best practices, strategic planning, studies, and cutting edge techniques
- Housed primarily at the Kennedy Space Center
  - Administratively a segment of KSC
  - Technical and programmatic reporting to Human Exploration & Operations at HQ

What is the Launch Services Program?

Acquire commercial launch services

Verify and validate mission engineering





Insight and approval of production, integration, testing and processing

Provide technical, operational, contractual, budget and business knowledge and expertise to future missions

Perform NASA launch management activities

Certify launch systems for NASA use

Establish strategic partnerships and make investments to satisfy Agency Launch Service needs

Perform Spacecraft launch site operations

Why the Launch Services Program?

Principal objectives

Provide safe, reliable, cost effective, and on-schedule processing, mission analysis, spacecraft integration and launch services

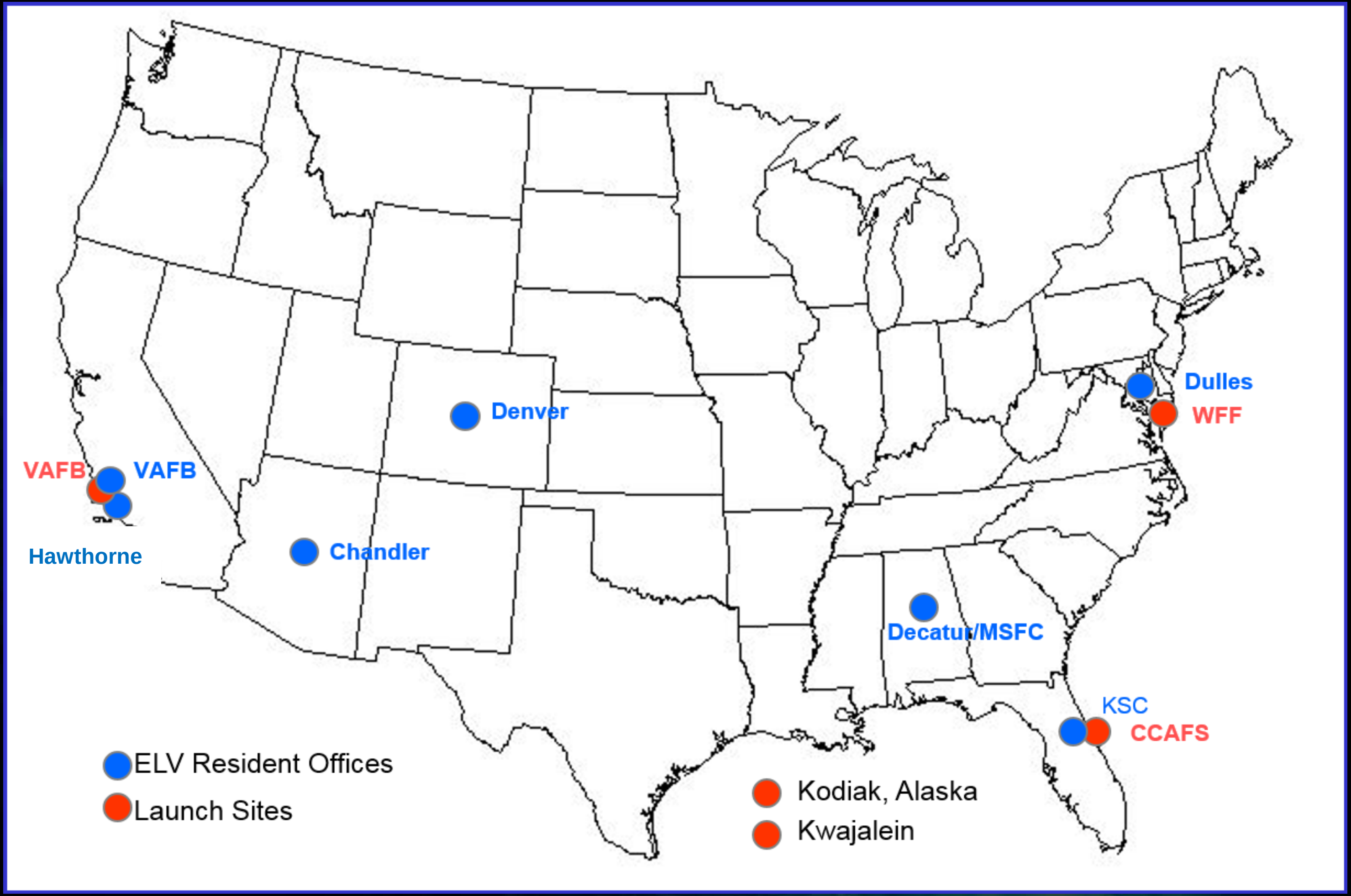
Vision:

Science and discovery through unlimited access to the universe

Mission:

Uniting customers, capabilities, and culture to explore space through unparalleled launch services

Where is the Launch Services Program?



NASA Launch Services (NLS) II Contract

How long does it take to award a mission's launch service and get to launch?

- ***The average time to award a competitive launch service is six months***
- ***Once awarded, the nominal integration cycle is about 30 months.***

How are launch vehicle risk categories defined?

- ***Category 1: Low complexity and/or low cost payloads; Class D payloads (NPR 8705.4) [Venture Class]***
- ***Category 2: Moderate complexity and/or moderate cost payloads; Class C, sometimes Class B payloads (NPR 8705.4) [Falcon 9, Taurus XL]***
- ***Category 3: Complexity and/or high cost payloads; Class A, sometimes Class B payloads (NPR 8705.4) [Atlas V, Delta IV, Delta II, Pegasus XL]***

The Current Fleet

Vehicle Class	Small		Medium	Intermediate / Heavy				
Launch Vehicle	Pegasus XL	Taurus-XL (Minotaur-C)	Antares 2XX	Falcon 9 Full Thrust	Atlas V 4XX	Atlas V 5XX	Delta IV Heavy	Falcon Heavy
Offeror	OSC	OSC	OSC	SpaceX	ULS	ULS	ULS	SpaceX
Launch Sites	CCAFS WFF KWAJ VAFB	CCAFS WFF VAFB	WFF	CCAFS VAFB	CCAFS VAFB	CCAFS VAFB	CCAFS VAFB	CCAFS

On the horizon: New Glenn (Blue Origin), Vulcan (United Launch Alliance), Antares (Northrop Grumman)

What We Do

Vehicle Certification
- Qualification Review
- Flight Margin Verification
- Independent Verification and Validation (IV&V) Analyses

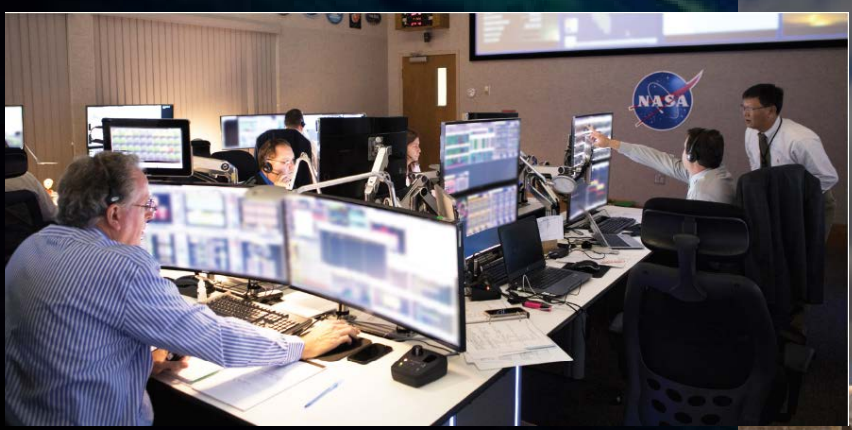
Fleet Insight
- Vehicle Enhancements
- Qualification Review
- Post Flight Data Review
- Anomaly Resolution

Mission Integration
- ICD Formulation & Verification
- Mission Unique Modifications
- Aeroheating/FMH Analysis
- Venting Analysis
- Integrated Thermal Analysis
- Hardware Acceptance
- Launch Ops Support
- Post Flight Data Review

Development
- Analytical Methods
- Technology Advancement
- Enhanced mission architecture

Launch Operations

- Thermal and Fluids personnel are part of the NASA Chief Engineer’s day of launch team
- Monitor vehicle health via telemetered vehicle data
- Provide input to anomaly discussions between NASA LSP, launch vehicle, and payload teams.
- Provide go/no-go input to NASA Chief Engineer for launch day events: vehicle cryo load, launch readiness prior to final phase of count



How we do it…

Personnel:

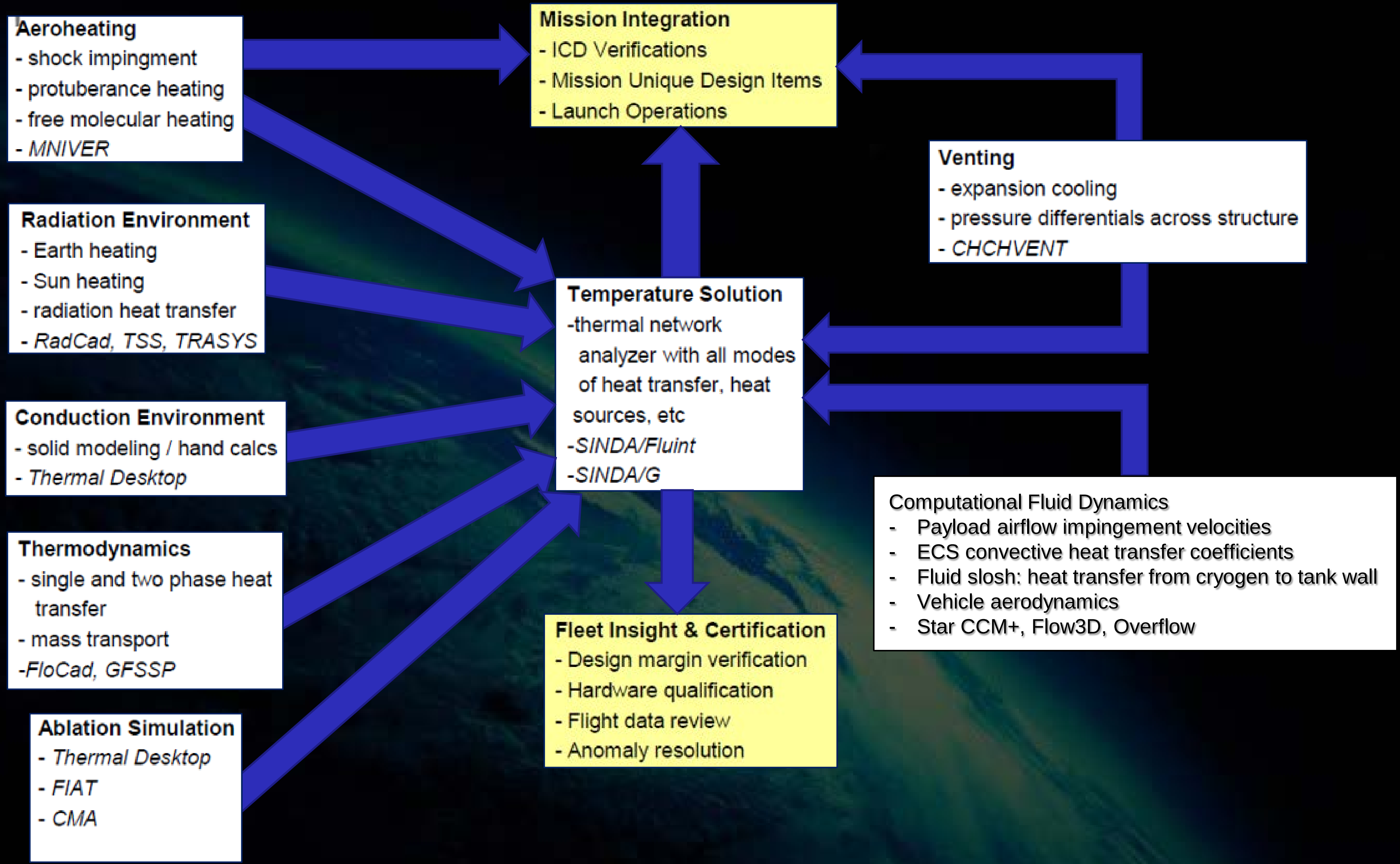
- Mix of Civil Servants and contractors via the Expendable Launch Vehicle Integration Services (ELVIS) contract
  - Expert areas:
    - Launch vehicle thermal control
    - Spacecraft thermal control
    - Aeroheating (thermal/fluids)
    - Aerodynamics (fluids)
    - Pressure/venting (fluids)
    - CFD (fluids)
    - solid rocket motors (thermal)
    - liquid rocket propulsion (thermal/fluids)

Software:

- Thermal Group:
  - Thermal Desktop (RadCad, FloCad)
  - Thermal Synthesizer System
  - TRASYS
  - SINDA/G
  - SINDA/Fluint
  - ESATAN-TMS
  - MINIVER
  - FIAT
  - CEA
- Fluids Group:
  - Flow 3D
  - Fluent
  - CHCHVENT
  - GridGen
  - GFSSP
  - OVERFLOW
  - FAST
  - Star CCM+
  - TetrUSS
  - Phantom
  - Tecplot

Large array of software driven by specialized environments and industry compatibility

Typical ELV Thermal/Fluids Analysis Landscape



Typical Analysis Methodology

- Fleet encompassing assumptions
  - "Design Reference Missions": hot and cold biasing assumptions to create an envelope that will bound a majority of possible mission profiles
    - » On-pad ECS set points assumed at max/min system capability
    - » Ascent hot biasing:
      - Maximum payload fairing inner wall from aeroheating
      - Maximum exposure to free molecular heating
      - Full solar exposure (no shadow)
      - Maximum solar constant, Earth heating
      - Maximum engine burn duration for items exposed to plume
    - » Ascent cold biasing:
      - No temperature increase to payload fairing inner wall from aeroheating
      - No free molecular heating
      - Maximum shadow periods
      - Minimum solar constant, Earth heating
      - Long mission duration (6-8 hours) and associated long coasts

Typical Analysis Methodology

- Mission Specific assumptions
  - The conservative tactics employed in the "design reference mission" fleet bounding analyses are dialed back:
    - » On-pad ECS set points refined to provide desired payload condition
    - » Mission specific trajectory sets provided by LSP Flight Design in the form of sun/earth vectors formatted for Thermal Desktop®
      - This can consist of only a handful of possible trajectories to many hundreds
    - » A multi-faceted geometric entity is used to generate sun/earth heating across all trajectories provided by LSP Flight Design
    - » The resulting heating is then screened to select a subset of worst case thermal cases
      - The facets of the geometric entity are used to better screen trajectories for specific areas of the payload or upper stage
    - » Ascent hot biasing:
      - Maximum payload fairing inner wall from aeroheating
      - Mission specific exposure to free molecular heating
      - Maximum solar constant, Earth heating
        - Time of year solar value used if launch window is definitively set
    - » Ascent cold biasing:
      - No temperature increase to payload fairing inner wall from aeroheating
      - No free molecular heating
      - Minimum solar constant, Earth heating
        - Time of year solar value used if launch window is definitively set

Thermal/Fluids Model Inventory

System Level Upper Stage Thermal Models

- Atlas V Centaur (Single and Dual Engine)
- Delta II 2nd Stage
- Delta IV Cryogenic Upper Stage
- Falcon 9 2nd Stage
  - Detailed Composite Overwrapped Pressure Vessel
- Pegasus XL 3rd Stage
- Star 48BV 3rd Stage (Parker Solar Probe)

Booster (1st Stage) Thermal Models

- Atlas V Booster Avionics Pod
- Falcon 9 entire booster
- Solid Motors: detailed modeling of joints, nozzles

Thermal Qualification Standard

- NASA LSP generally follows the guidelines of MIL-STD-1540 and/or SMC-S-016 to evaluate launch vehicle qualification and acceptance thermal test levels
- Qualification:
  - 24 thermal cycles
  - Worst case thermal prediction +/-21C (11C uncertainty, 10C qualification margin)
    - » Thermal predictions provided by launch service provider and often independently validated with NASA LSP analysis
  - Dwell at plateaus sufficient for equilibrium
  - Operation and functional testing at plateaus and during temperature transitions
  - All test anomalies are independently reviewed and dispositioned by NASA LSP
- The first objective is to qualify to the Design Reference Mission worst case thermal ranges. If component cannot meet that robust level of qualification, the widest qualification is achieved and the qualification margin assessed on a mission by mission basis.
- Specialized requirements for batteries, ordnance
- "Test like you fly" is a critical standard of our assessment

What LSP Thermal can offer a payload

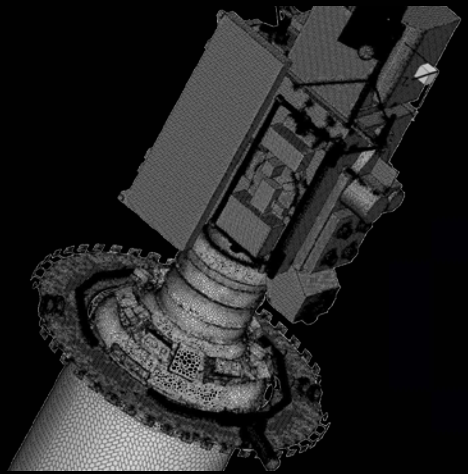
- Assistance with launch vehicle interface definitions and requirements
  - Analytical assistance to help define requirements (solar avoidance, for example)
  - Past experience with launch providers can minimize the iterations in converging upon acceptable requirements definition
- Higher fidelity simulations of the payload for special interest items
- Assistance with payload thermal model compatibility with launch services provider
  - Model format conversions
- Early or out of cycle integrated thermal analysis
  - E.g., prior to launch service award (see next chart)
  - E.g., solar array hinges, camera lenses

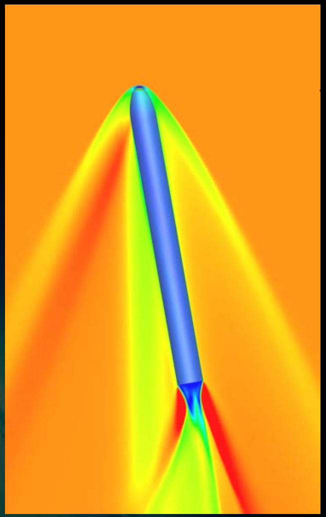
What LSP Thermal & Fluids can offer a launch provider

- Assistance with launch vehicle interface definitions and requirements
  - Analytical assistance to help define requirements (solar avoidance, for example)
  - Past experience with payload providers can minimize the iterations in converging upon acceptable requirements definition
- Focused high fidelity simulations of the launch vehicle areas for special interest items
- Assistance with payload thermal model compatibility
  - Model format conversions, appropriate fidelity for integration into launch provider modeling
- Out of cycle integrated thermal analysis
- Design enhancement, technology development for increased mission capability

Fluids Analyses

- Fluid modeling for internal and external fluid flows
  - Internal Environmental Conditioning System (ECS) flow
    - Flow Impingement
    - Cooling
  - Venting Analysis to verify ascent environment
    - Independent of contractor analysis
  - External Aerodynamics
    - Support Launch Vehicle Certification
    - Support for Commercial Crew
- Perform post flight analysis
  - Reconstruct vehicle aerodynamic flight parameters (Mach, Q, Aero Angles)
- Support other groups needing analytical work
  - Propulsion
    - POGO
    - Fluid line behavior
  - GSE
    - Purge line flow rate predictions
- Slosh
  - Predict the location of propellants in the tank during flight
- Contribute to failure investigations
  - COPV fluids analysis for SpaceX AMOS anlomaly
- Advisory mission
  - James Webb Space Telescope (JWST) pressure drop at fairing sep
  - Dual engine centaur base heating





ECS System Analysis

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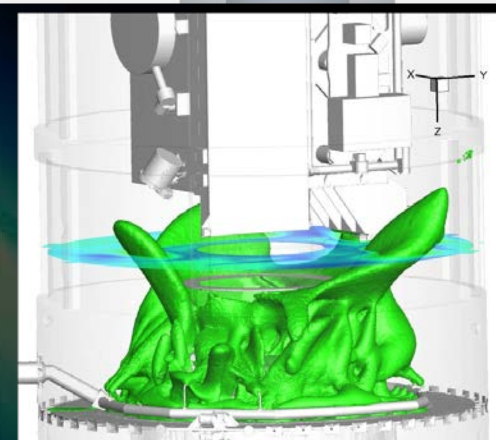
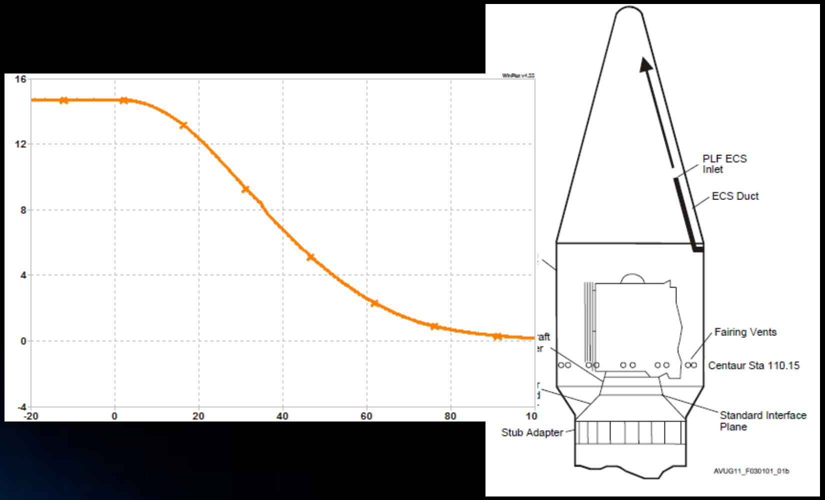
ECS Impingement

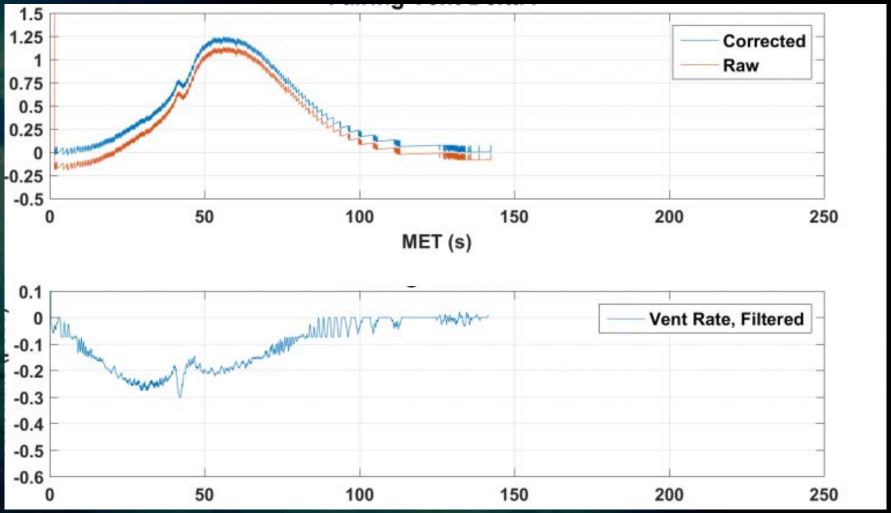
- Launch vehicle Environmental Control Systems (ECS) are required to move large quantities of air in order to maintain acceptable thermal conditions inside the fairing
- The ECS flow can become a problem if high velocity air impacts sensitive spacecraft components
- Some spacecraft also have temperature critical components that need to be kept at a certain temperature. Our Computational Fluid Dynamics (CFD) analyses help estimate heat transfer coefficients
- Some spacecraft are very sensitive to contamination so we use our CFD models to predict potential areas of concern



Venting

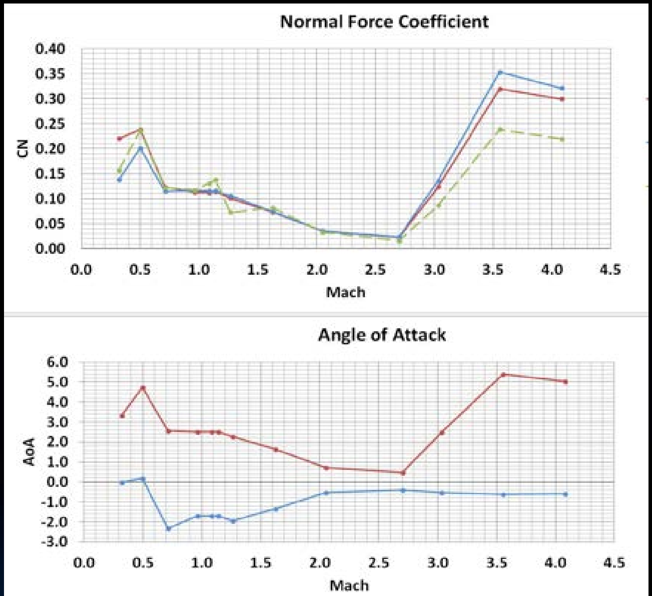
- Characterize the rate of depressurization of LV compartments during ascent to maintain acceptable pressure differentials across structures
- Some S/C are more sensitive than others
- Vent rate depends on
  - Fairing volume
  - S/C solid volume
  - Vent area
  - Trajectory
  - Number of vented S/C compartments

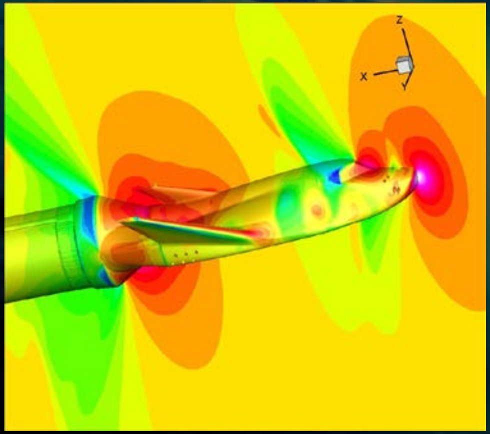


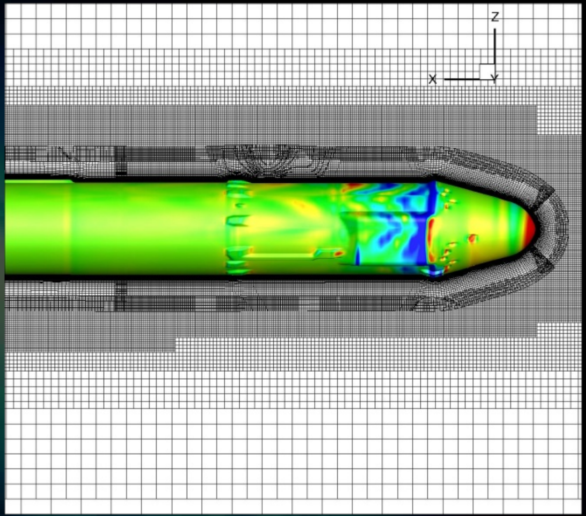


External Aerodynamics

- New configurations
  - Examine aerodynamic coefficients to support Flight Controls discipline
  - Examine Distributed aerodynamics to support Loads discipline
  - Independent validation of LV contractor aerodynamics coefficients
- Flight environment predictions
  - Plume Impingement
  - Anomaly investigation
- Review wind tunnel testing results

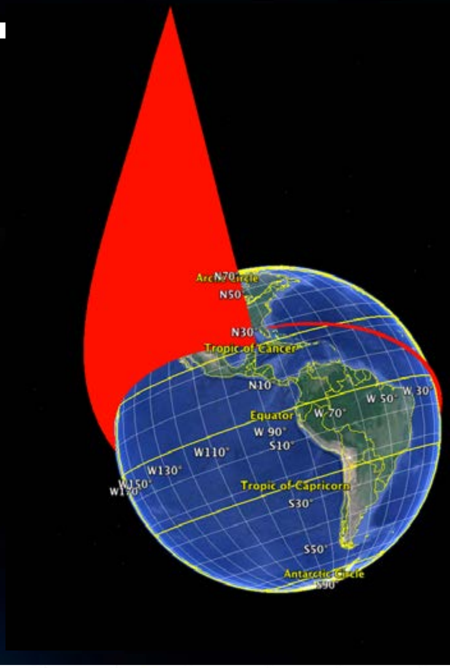


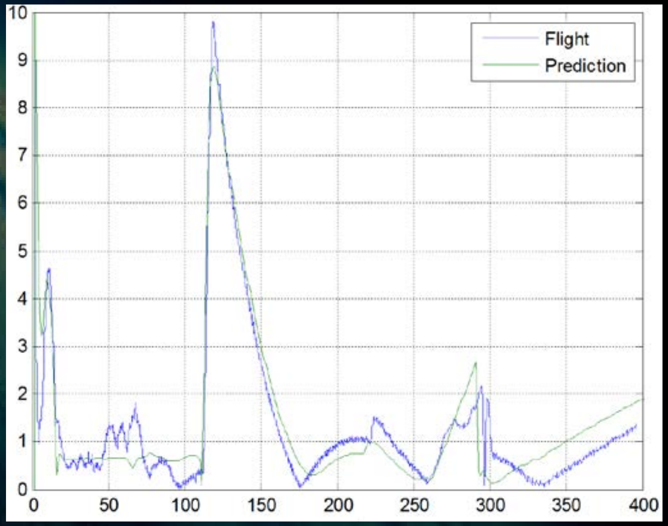




Post-Flight Analysis

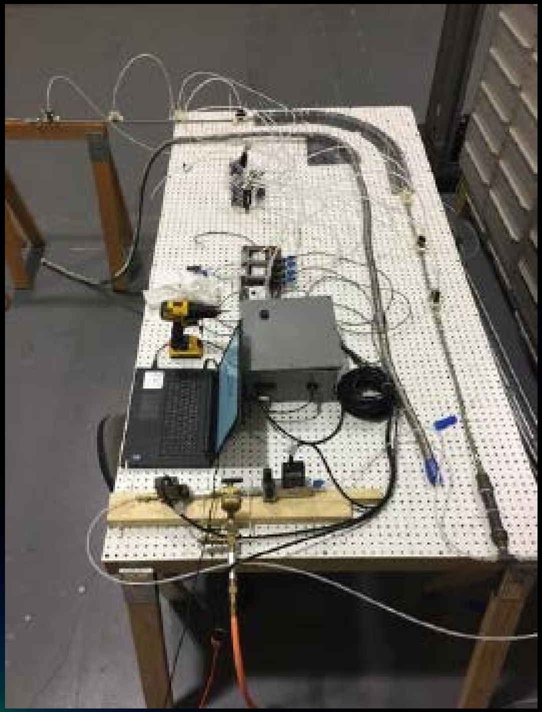
- Verify predicted environments agree with flight
- Generate as flown environments for other disciplines
- Post flight angle of attack reconstruction has been used during return to flight investigations – Delta II Heavy
- Post flight pneumatic system modeling has been used during accident investigations – Taurus Fairing

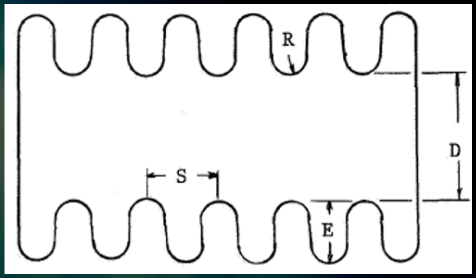




Supporting Other Groups

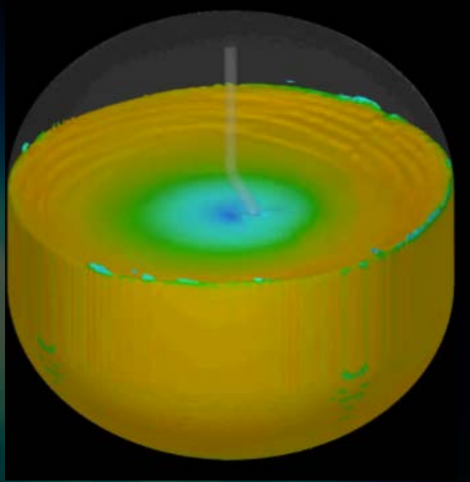
- Often get involved with one-off (mission unique) requirements that can benefit from analysis
  - Pogo issues
    - Look at past flight history
    - Try to predict pogo frequencies
  - Spacecraft purges
    - MMS had an issue with balancing the flow to 4 spacecraft
    - Spawned a special study
  - Heat transfer coefficient for thermal
    - produce convection HTC's for thermal group for use in thermal desktop models





Slosh

- Use CFD and analytical tools to predict the behavior of liquids inside the propellant tanks of rockets
  - During launch we look at slosh frequencies and damping
  - During coast we look at propellant location and droplet formation
- Slosh frequencies and damping rates are used by the controls group to study vehicle stability
- Propellant location is important to prevent from venting liquids and to locate the center of mass of the vehicle

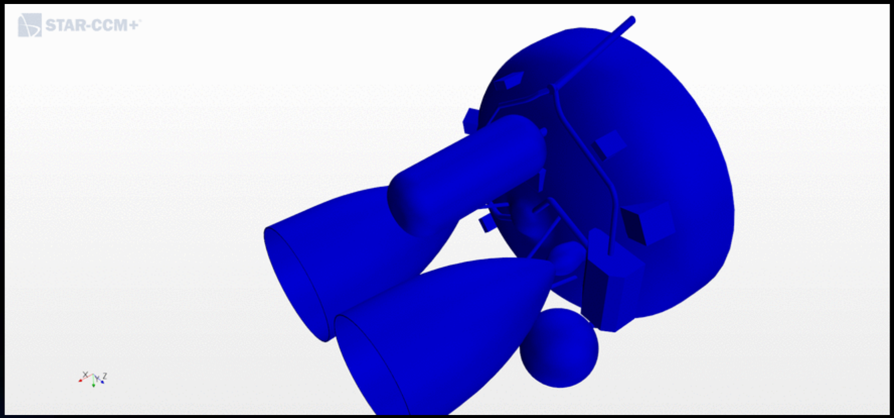


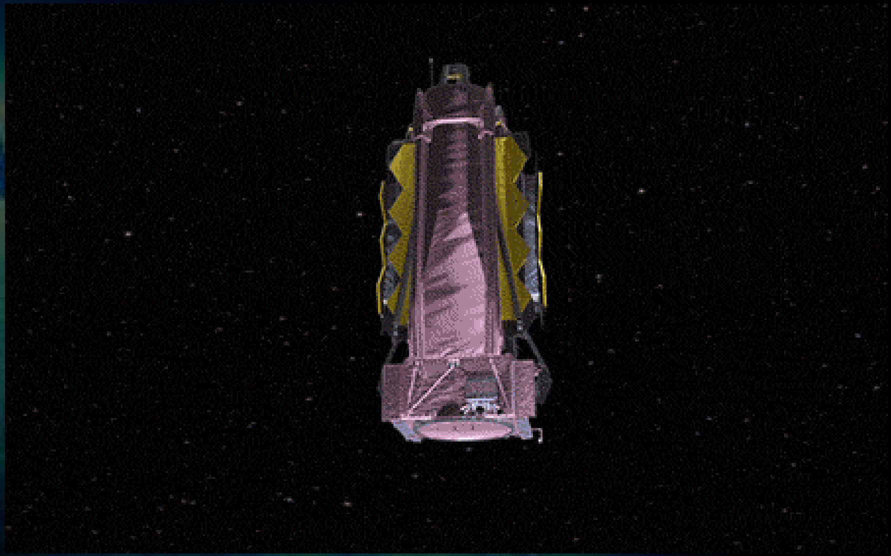
Failure Investigations

- Since most things are in contact with a gas or a liquid at any given time, we usually get involved in failure investigations
- Pressures
- Temperatures
- Aerodynamic forces
- Flight data reduction

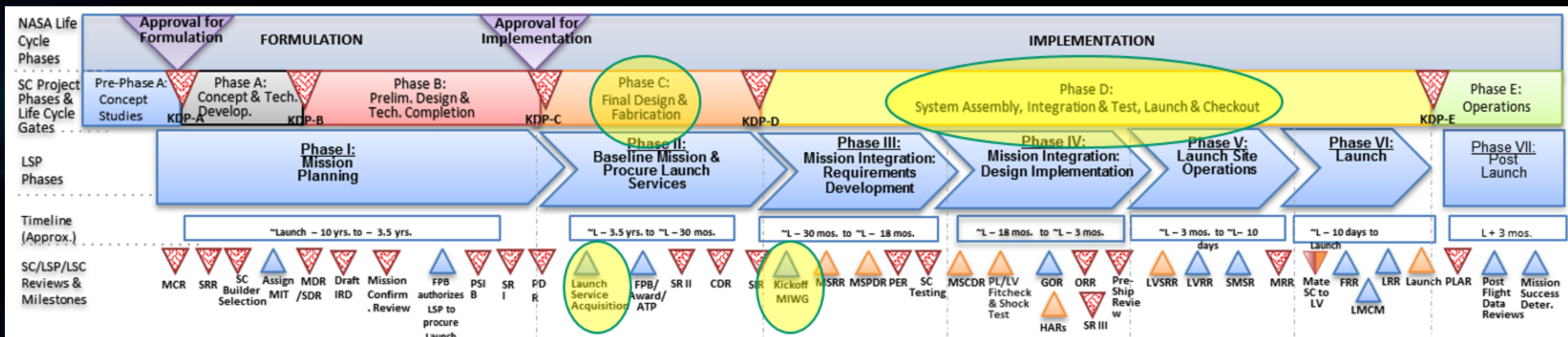
Advisory Missions

- The thermal/fluids group also helps with a wide variety of issues on advisory missions
  - James Webb Space Telescope JWST
  - Commercial Crew
  - Commercial Resupply to ISS
  - Air Force Missions





NASA LSP Mission Life Cycle



LSP Thermal and Fluids Analysis is available to help payloads *before* Launch Service Acquisition

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Optimized thermal design

Optimized interface requirements

Technology Development

Collaboration with industry & academia:

- SPHERES-Slosh
  - Improve understanding of fluid behavior in micro-gravity
  - Calibration of Computational Fluid Dynamics (CFD) models
  - Uses SPHERES units connected to clear test tanks of colored fluid on the International Space Station (ISS)
  - Massachusetts Institute of Technology
  - Florida Institute of Technology

Technology Development

Collaboration with industry & academia:

- Fiber Optic Sensor System (FOSS)
  - » Strain, temperature measurement at any location along a fiber optic cable
    - Up to 2,000 data points in each 40’ optical fiber with adjustable spatial resolution
  - » Currently funding development for flight demonstration on a fleet launch vehicle
  - » NASA Armstrong, commercial launch providers

- Cryogenic Orbital Testbed (CRYOTE)
  - » LH2, LO2 on-orbit transfer, handling, and storage
  - » Anchor analytical modeling
  - » United Launch Alliance

Thermal/Fluids Analysis Examples

Mars Science Laboratory (Curiosity)

Transient simulation of a failure of the on-pad payload fairing environmental control system to determine time to over pressurizing MSL tanks from heating due to the rover's MMRTG power source

- Fluids Team characterized the transient gas behavior via CFD from an operational ECS condition to a settled no flow condition
- Thermal Team converted that to a simplified fluid network to capture transient heat transfer between launch site and payload, including the vertical and radial gas stratification within the payload fairing

System Level Upper Stage Cryogenic Behavior

Several efforts from long coast fuel/oxidizer thermal characterization (boil-off, engine start box temperature) to on-pad transient tanking and pressurization interactions.

Similar Fluids and Thermal team interactions to characterize fluid/gas flow and surface interaction, and integrate that information into a system level thermal network

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