Ground Operations, Launch and Ascent Thermal Analysis for the Upcoming Launch of the LADEE Mission

Presented By
Kan Yang, NASA Goddard Space Flight Center

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Overview

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- Overview of LADEE Mission
  - LADEE Space Vehicle Design
  - Minotaur V Launch Vehicle Design
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- Important Contributing Factors to Thermal Analysis
  - Ground Ops
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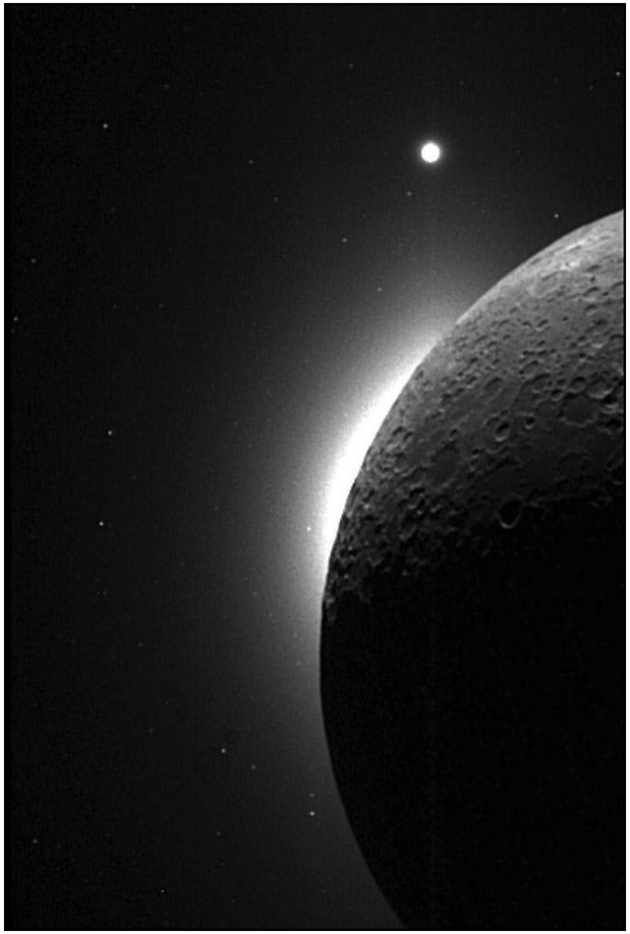
Lunar **A**tmosphere and **D**ust **E**nvironment **E**xplorer

To explain the motivation for the LADEE mission, we must first start with Apollo…

… when the Apollo 8 astronauts first went around the moon, they were surprised to find a bright crescent of light glowing on the horizon at lunar sunset and sunrise

The astronauts called this phenomenon

Lunar Horizon Glow (LHG)



Source: NASA, www.nasa.gov

Introduction to the LADEE Mission

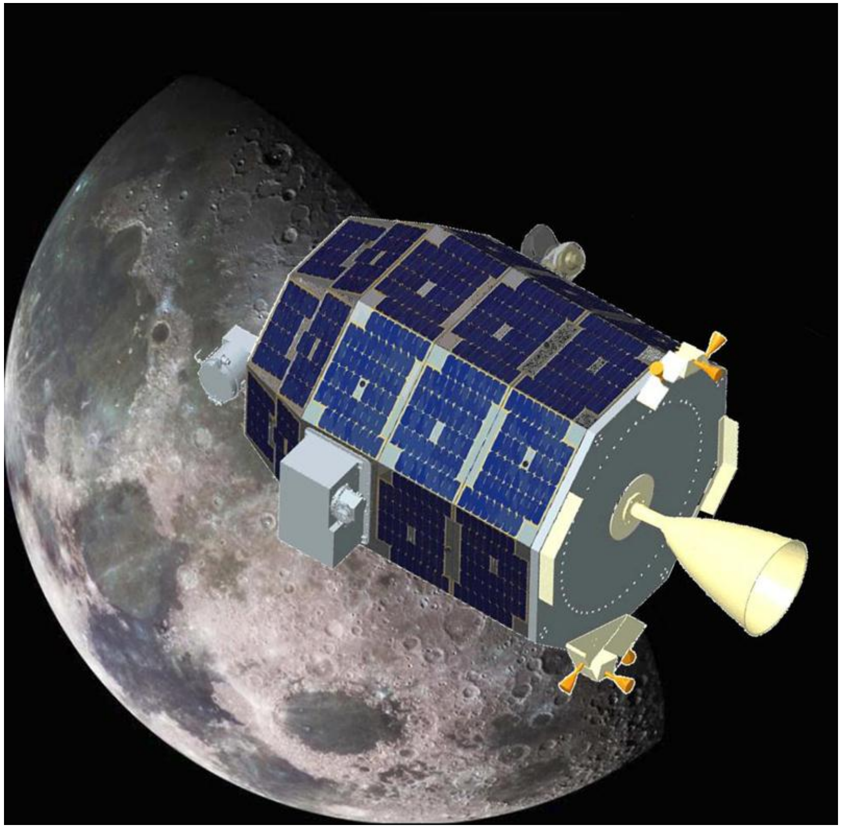
- On Earth, this phenomenon is called **Zodiacal Light** and occurs when sunlight scatters off dust particles and moisture in the Earth's atmosphere. It is usually visible slightly before sunrise and after sunset

Source: Kwan O. Chul, TWAN

- **But what causes it to occur on the moon?**
  - The moon has no atmosphere, and therefore no air to suspend the particles
  - Could it be caused by strong electric fields around the moon causing electrostatic repulsion? Or plasma from the sun? Or another yet unexplained phenomenon?

LADEE Mission Goals

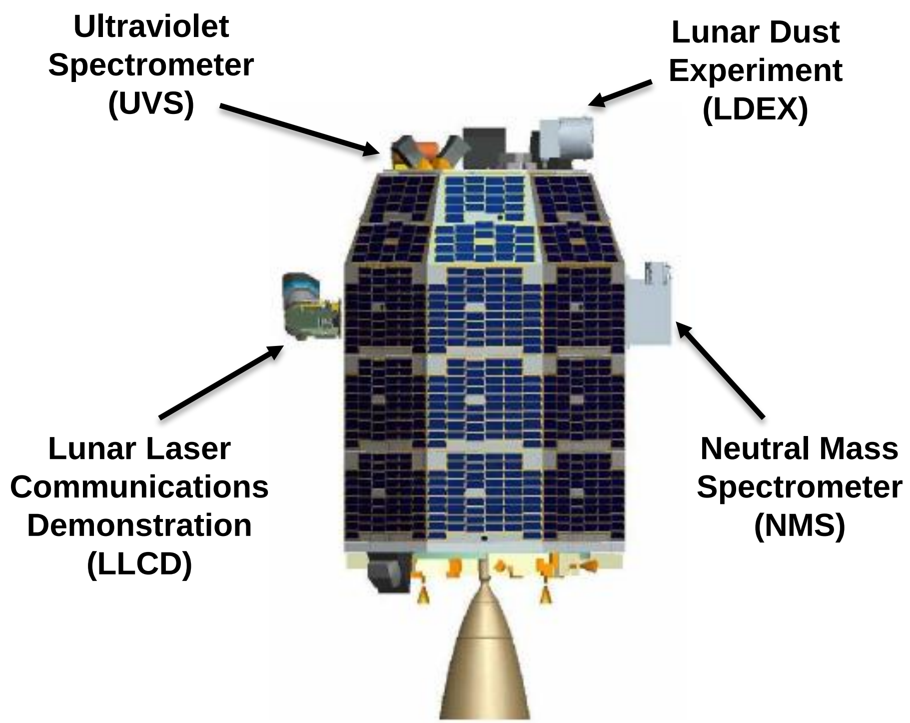
- The LADEE Mission seeks to study the moon's exosphere and dust processes to explain this phenomenon, by:
  - Determining the composition of the lunar atmosphere
  - Determining the factors that contribute to the atmosphere's dust distribution, variability, and volatility
  - Applying the information learned to enhance our understanding of dust processes throughout the solar system, with implications towards future exploration missions



Source: Space Systems/Loral

LADEE Space Vehicle (SV) Overview

- The LADEE spacecraft design is derived from the Modular Common Spacecraft Bus Design, and incorporates three instruments and a technology demonstrator:



Source: Hine, Butler, et al. "The Lunar Atmosphere and Dust Environment Explorer Mission," Proceedings of the 2010 IEEE Aerospace Conference, Big Sky, MT, USA, March 6-13, 2010.

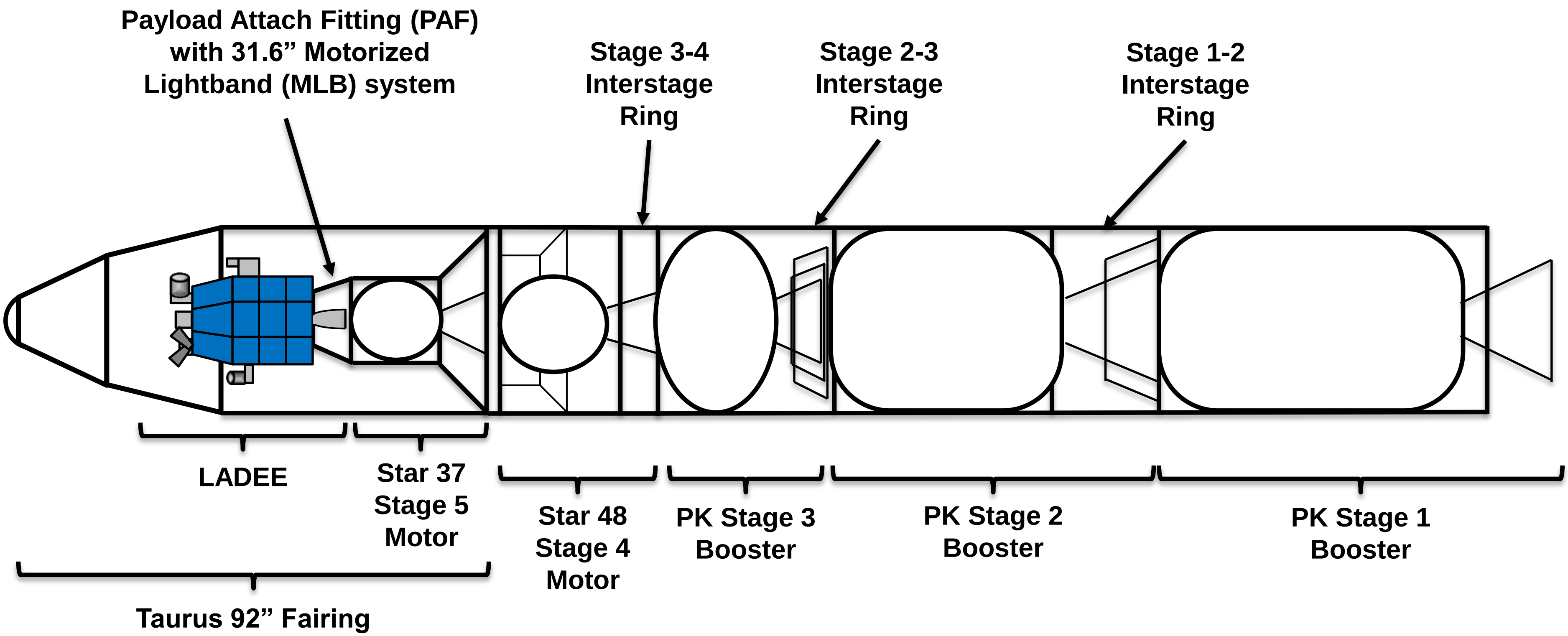
Minotaur V Launch Vehicle (LV) Overview

- LADEE will be launched in the 3rd quarter of 2013 from NASA Wallops Flight Facility aboard the maiden flight of the Orbital Sciences Corp. Minotaur V Launch Vehicle:

Source: http://easternshoredefensealliance.org/files/LADEEmoonmission.pptx

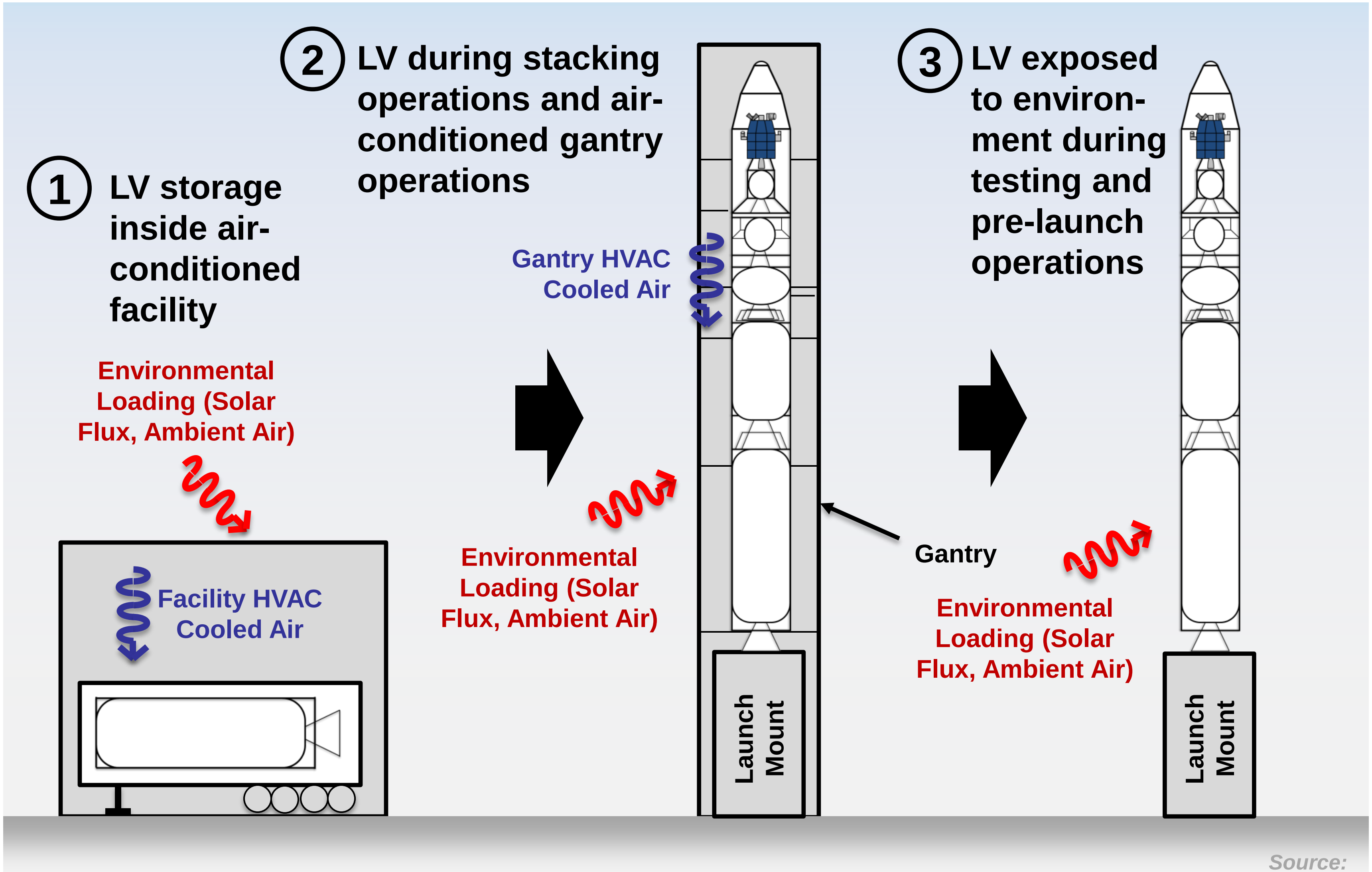
  - Minotaur V is a five-stage evolutionary version of Minotaur IV LV
  - Intended to launch small spacecraft to high-energy orbits including Lunar Transfer Orbit (LTO)
  - First three stages are Peacekeeper (PK) solid rocket boosters shared with Minotaur IV design
  - Fourth and fifth stages are commercial Star 48V and Star 37 motors, respectively

Minotaur V Launch Vehicle Design



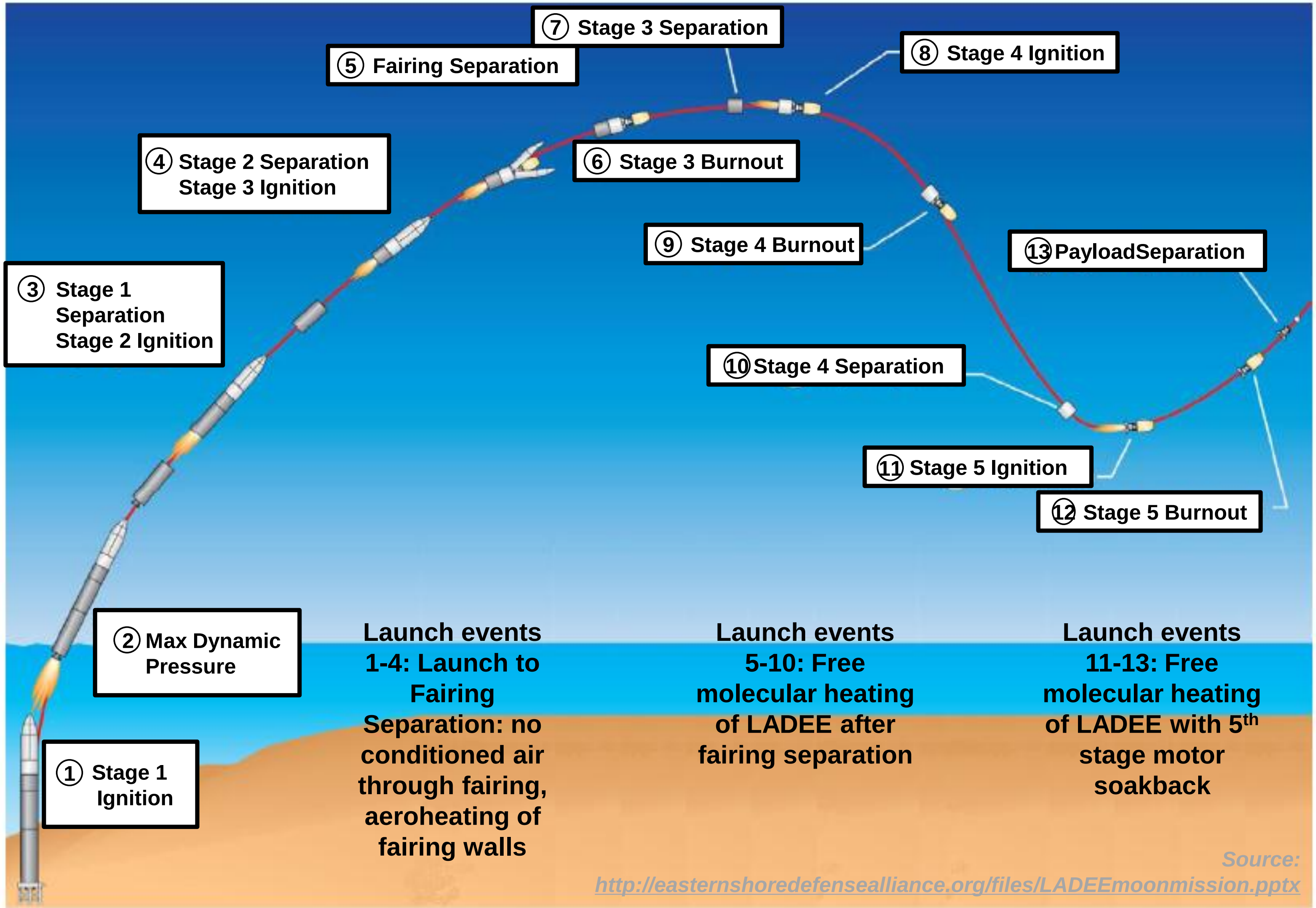
Source: Hine, Butler, et al. “The Lunar Atmosphere and Dust Environment Explorer Mission,” Proceedings of the 2010 IEEE Aerospace Conference, Big Sky, MT, USA, March 6-13, 2010.

Minotaur V Launch Vehicle Ground Ops



Source: http://easternshoredefensealliance.org/files/LADEEmoonmission.pptx

LADEE Launch Timeline



Important Contributing Factors learned from the Thermal Analysis of LADEE Ground Operations, Launch, and Ascent

Note: All thermal analysis performed with Thermal Desktop and SINDA/FLUINT

Factor 1: Convection Coefficient

- Modeling of ground operations required the convective heat transfer effects to be added to the conduction- and radiation-dominant Thermal Desktop analysis program
  - The value of convection coefficient, h, was calculated from:

$$h = \frac{k\,Nu}{D}$$

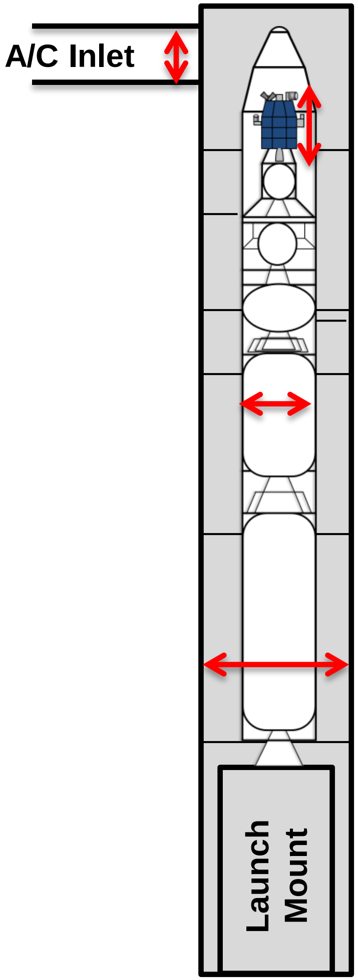
where:

where:	k	Thermal conductivity
	Nu	Nusselt Number, $Nu = f(Re, Pr)$
		$= f(\rho, \dot{v}, D, \mu, k, A_c, C_p)$
	D	Characteristic dimension

  - The effect of convection modeled as linear conductors from boundary node held at air temperature to all surfaces on LV/SV
  - However, the characteristic dimension, D, is fairly arbitrary, yet has an impact on the resultant convection coefficient

Factor 1: Convection Coefficient

- So, which characteristic dimension do you pick?



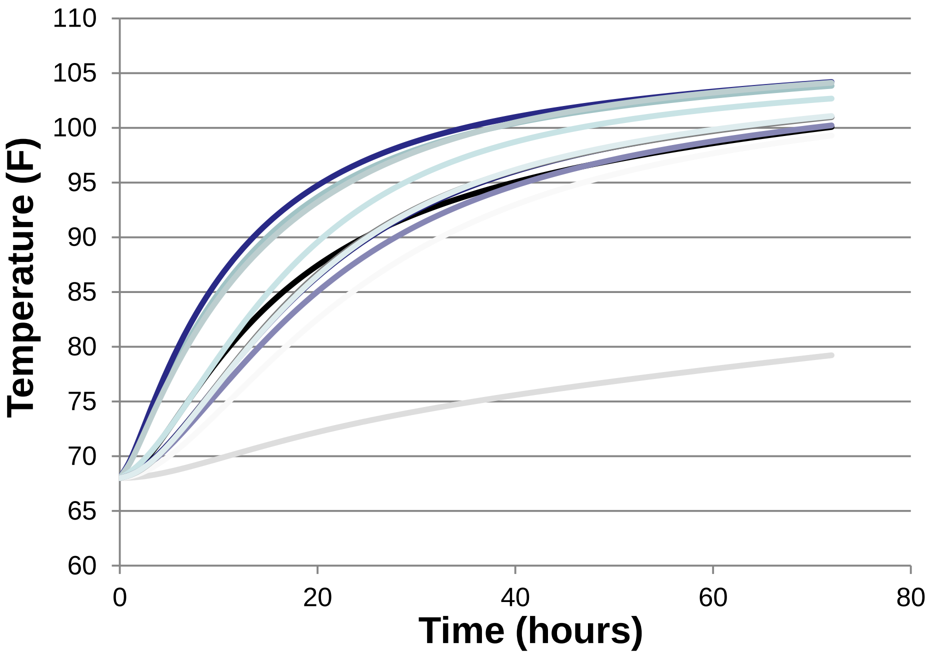
  - Many possible characteristic dimensions to pick from
  - However, due to the large scales of the LV or SV dimensions, the magnitude is much larger than the velocity of the incoming air and produces a low Re.
  - All of them produce a convection coefficient similar to or slightly larger than the lowest natural convection coefficient of 5 W/m^2K

Important Contributing Factor: Assumption of low convection rate. For forced convection coefficient from the HVAC system in a facility, gantry, or fairing flow, if the characteristic dimensions of the LV or SV overwhelm the size of the air inlet, and the incoming flow is laminar, then conductive heat transfer from the HVAC air can be approximated with a low natural convection coefficient (such as 5 W/m^2K).

Factor 2: Facility Insulation

- Initially, it was thought that the HVAC system during ground ops (facility and gantry) would contribute most to dampening out the heat loads from the environment
- Gantry walls modeled as thin shells, since it was thought that the insulation in the walls was less important

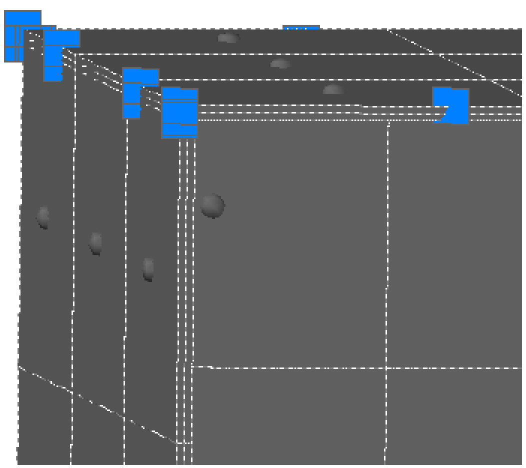
➔ Initial results showed **unrealistic increases** in temperature



Factor 2: Facility Insulation

- Eventually, it was found that this was an incorrect assumption
- Correct assumption:
  - HVAC Air has minimal effect on dampening the environmental loading
  - Facility insulation (R-value) has **enormous** effect in blocking out radiative and convective heating from the environment
  - For a typical facility, the thermal conductivity through the insulation is on the order of 10^{-2} W/m-K.

Important Contributing Factor: Facility Insulation. The dominant factor to isolate the LV from environmental loading within an air-conditioned facility is not the cooled air, but rather insulation of the facility walls. Therefore, the facility walls must be solid geometries with enough through-thickness nodalization such that the appropriate temperature gradients can be captured.



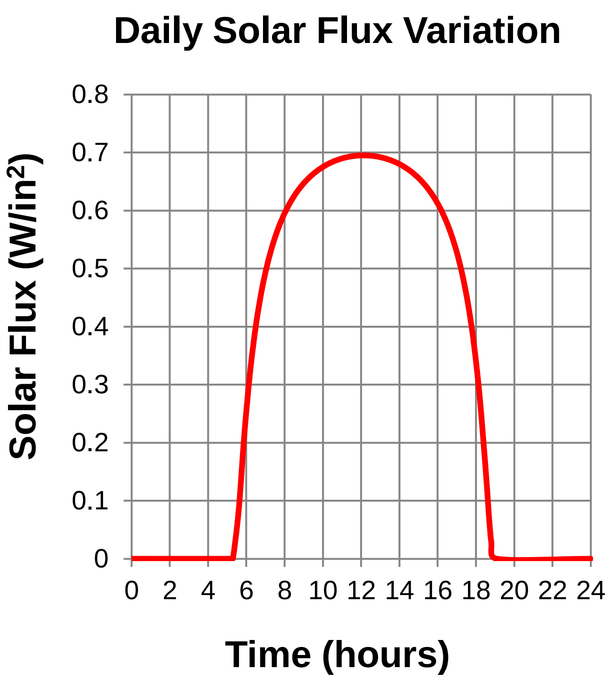
Factor 3: Diurnal Variations

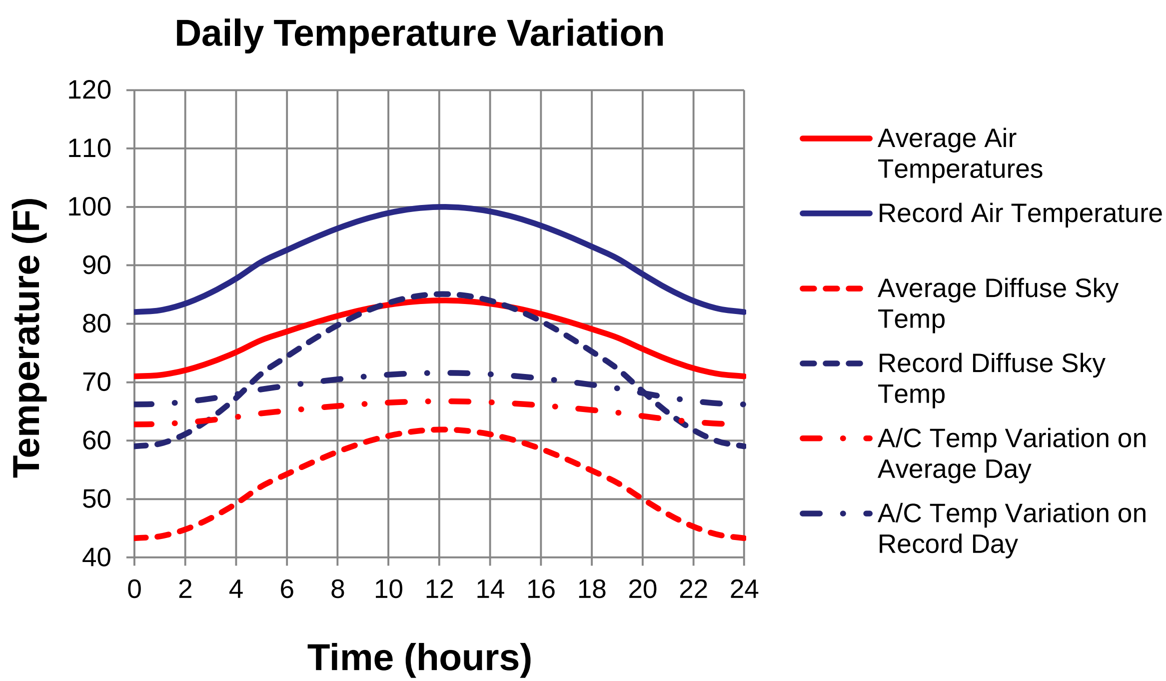
- Initial approach taken to modeling “hot case” during ground ops was to stack worst-case solar flux, ambient temperature, cold sky temperature, and natural convection rate with no diurnal variations
  - Initial thought was the enormous thermal mass of the LV would dampen any diurnal responses

➔ However, the lack of diurnal variations resulted in continually increasing temperatures on the LV over time, due to its large thermal capacitance and inability to dissipate heat

Factor 3: Diurnal Variations

- It was found that the large daily variations were crucial to the temperatures on the LV system (esp. the lower thermal mass components such as the motor casing)
  - Variations in environmental conditions allow the LV to radiate most of the heat it absorbs throughout the day



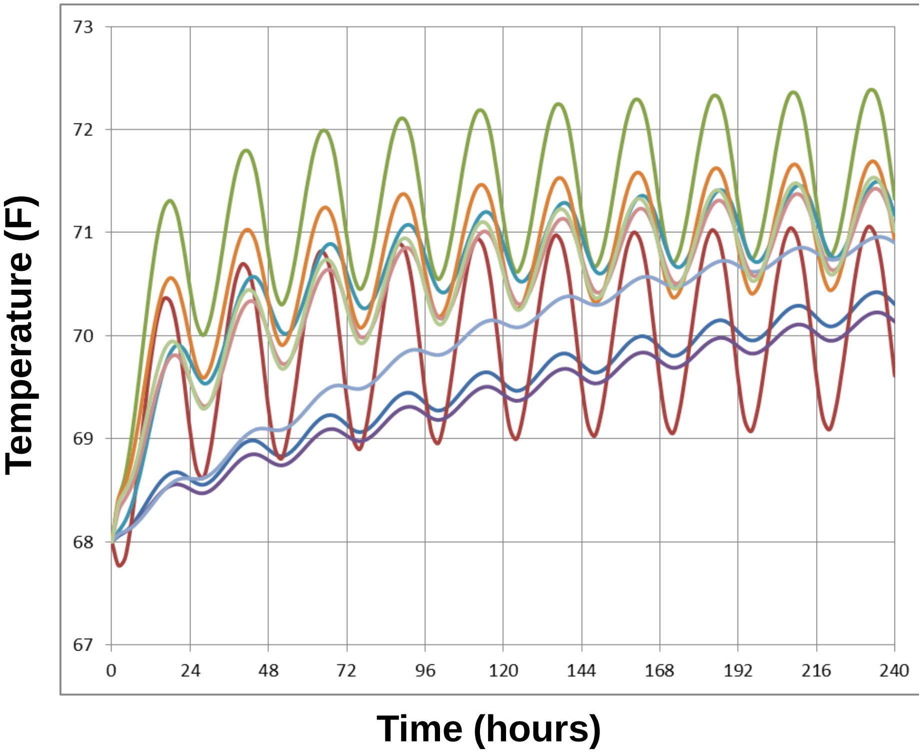


Source: Accuweather.com, Orbital Sciences Corporation

Factor 3: Diurnal Variations

- Due to variations, the LV solution can converge to a realistic solution: sinusoidal variation around a fixed average temperature

Important Contributing Factor: Daily variations in Solar Flux and Temperatures. In LV ground operations, though the transient responses of the LV components are fairly slow, they are still greatly impacted by diurnal air temperature and solar flux variations. Therefore, these daily variations must be incorporated into the model to ensure the accuracy of the thermal analysis.



Factor 4: Obtain Information Early

- Since Minotaur V is derived from Peacekeeper ICBM, material/optical data and design details are ITAR controlled and difficult (or time-intensive) to obtain
  - Development of thermal model required density, specific heat, thermal conductivity, and absorptivity/emissivity for all materials to be available
  - The LV User Manuals provided by the vendor gave very little detail on many of LV components
  - Schedule constraints for thermal analysis led to assumptions being made for properties that the User Manuals did not provide
- Analysis issues arose from inaccuracy of assumptions
  - Most prominent issues were lack of coatings information and lack of fairing properties

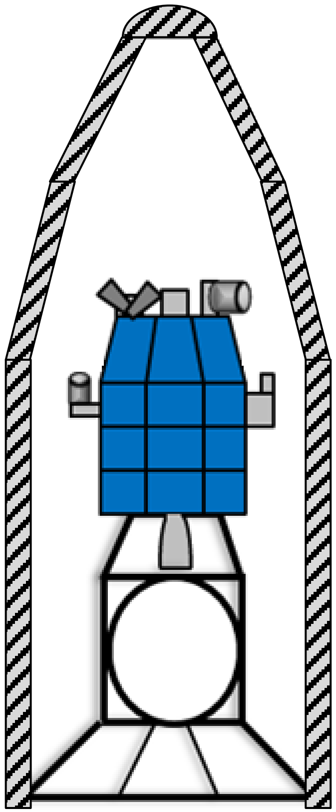
Source: Wikipedia

Factor 4: Obtain Information Early- Coatings

- The LV User Manual provided external insulation material and optical properties for the motor casing
  - Since there were no other coatings specified, it was assumed that the external insulation optical property (a black-paint-like material) was the LV external coating
- Later, it was found out from the vendor that the external paint used on the LV is not the same as the external coating
  - Runs with incorrect external insulation optical property did not result in glaring temperature errors (results were in same order of magnitude), therefore incorrect coating was kept through various iterations of model
  - Thermal models re-run when vendor indicated that the correct coating should be a proprietary white paint

Factor 4: Obtain Information Early- Fairing

- Separate thermal model developed for SV inside LV fairing based on requirement to keep SV within survival limits during ground operations
  - Fairing thermal control managed through ducting purge air from a Ground Environmental Control Unit (ECU) to the nose of the LV fairing. Air then flowed through the inside of the fairing and vented through the Stage 3-4 interstage ring.
  - As learned earlier through the gantry ground ops analysis, the fairing insulation is crucial in shielding the SV from environmental effects
  - Information on fairing properties was requested from the vendor since user manuals did not provide any information



Factor 4: Obtain Information Early- Fairing

- Difficulties with finding documentation on the insulation material and coatings used and possible ITAR issues prevented the information from being provided in a timely manner
  - Scheduling constraints required analysis to be completed before actual fairing properties could be obtained ➔ assumed fairing was ¼" fiberglass insulation for thermal model runs
  - When fairing information finally available, it was shown that the initial assumption of thickness was too conservative ➔ assumed environmental loading on SV was too large in analysis
  - Acoustic blanket on fairing interior provides huge amounts of thermal isolation from environment
  - Thankfully, new results did not require change in thermal design of SV inside fairing. However, incorrect assumptions could have led to bad design changes and huge impact on cost/schedule

Factor 4: Obtain Information Early

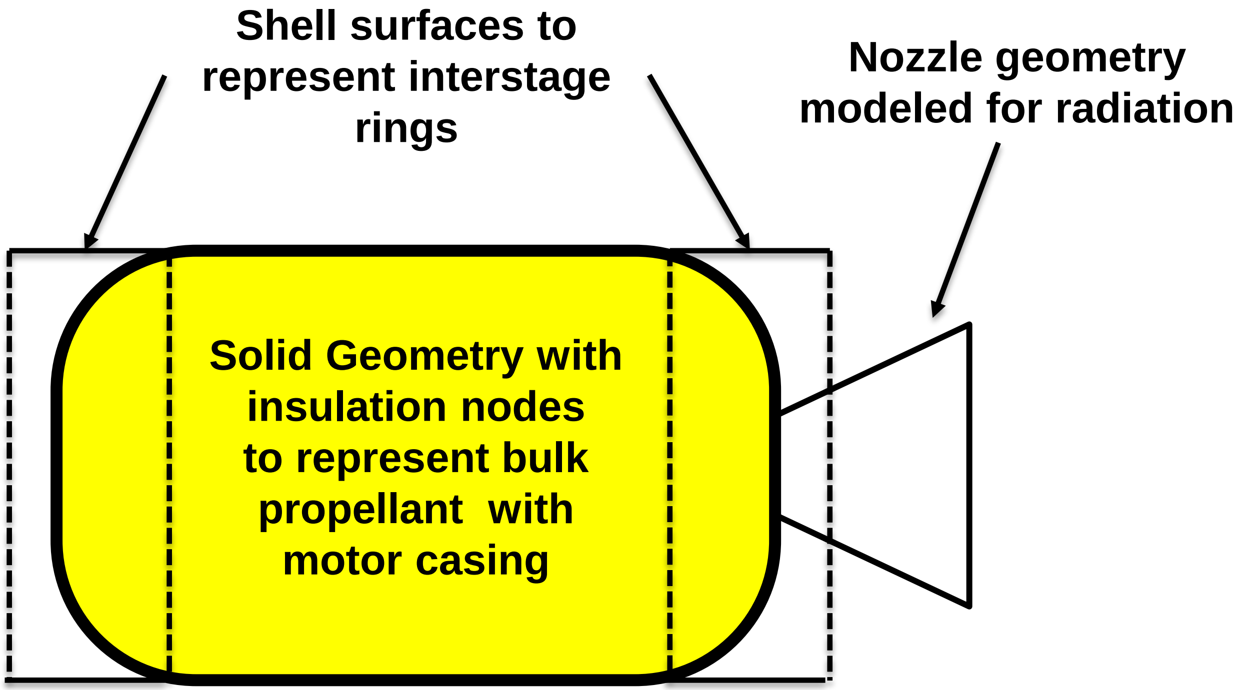
Important Contributing Factor: Detailed material and optical properties of all materials on the LV. Ask for these from the vendor very early in the analysis process, especially when such information may be of a sensitive nature. Specifically ask the vendor if any material or optical properties on the space flight hardware differ from that shown in the User Manual or other associated documentation.

For a first-cut analysis when detailed information is not readily available, it may be helpful to assume that the external coating is white paint, and the fairing is composed of thick, very low thermal conductivity material.

Source: Orbital Sciences Corporation
www.orbital.com

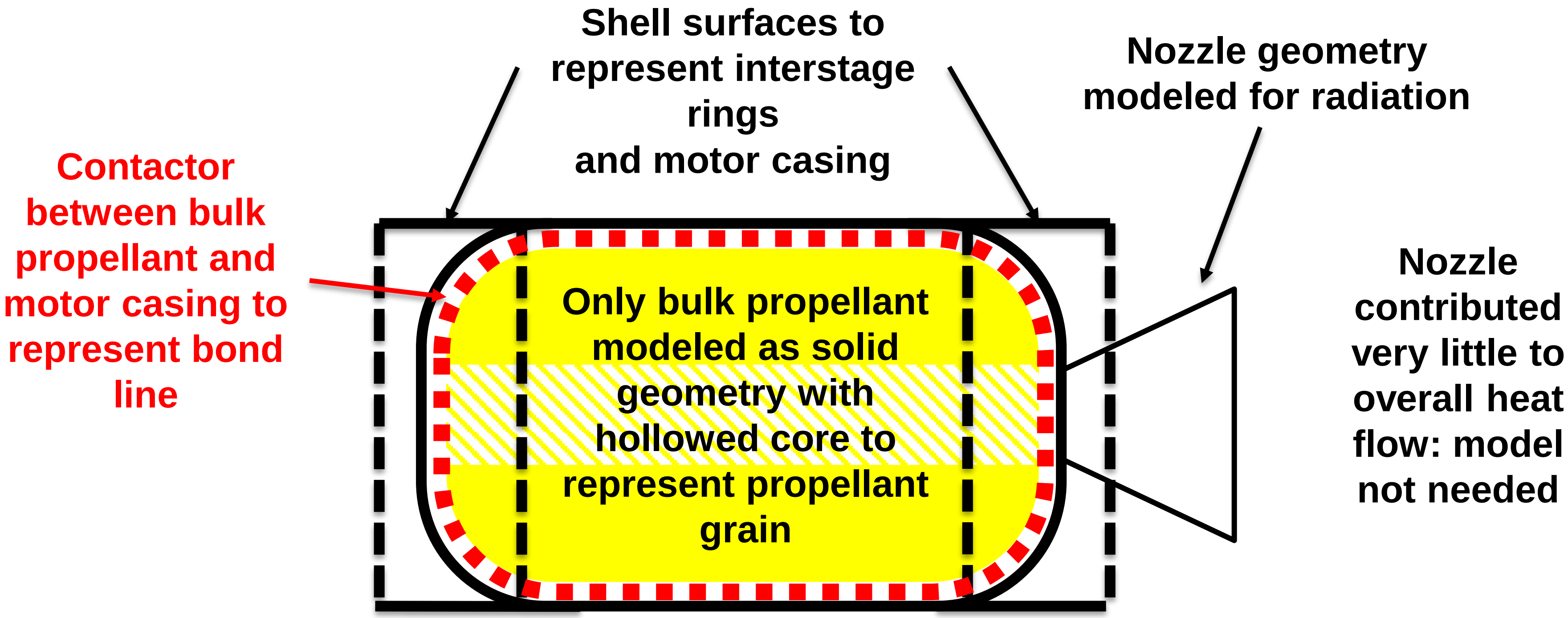
Factor 5: Model Details Correctly

- Thermal models first developed from the information provided in the user manuals of the motor stages: user manuals emphasized complexity of interstage rings and nozzles, so those were given more detail in thermal model



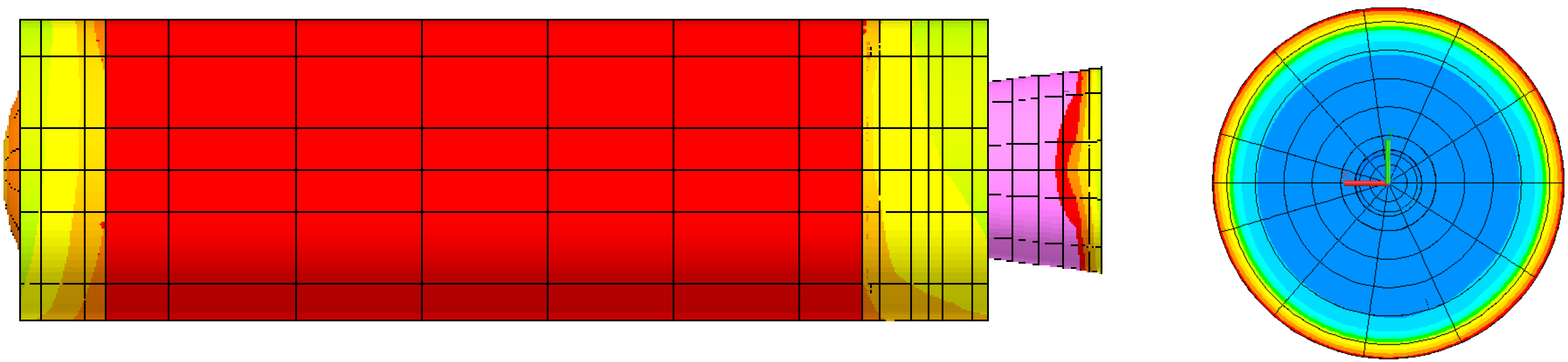
Factor 5: Model Details Correctly

- However, it was later found from the vendor that the locations of greatest thermal sensitivity on the LV were in the bond lines between casing and propellant, and bulk propellant itself ➔ original model needed to be changed to capture appropriate details



Factor 5: Model Details Correctly

Important Contributing Factor: Understanding the thermally sensitive areas of the LV. If possible, ask from the vendor which areas of the LV are most thermally sensitive before beginning the thermal model, such that those areas can be captured in appropriate detail.



Factor 6: Verify Temperature Requirements

- The original temperature limits for the LV during ground ops required all components to be maintained within a narrow 60-80ºF band during all times such that the thermally sensitive components (Bulk Propellants, Flexseals, Bondlines) were kept safe
  - For a record hot day, this is difficult to maintain inside the gantry for prolonged periods of time
  - For gantry pull-back to do functional tests, some of the components violated limits even after just one hour of environmental exposure

➔ The difficulty of maintaining LV components in strict temperature limits resulted in inquiry as to what motivated the requirements

Factor 6: Verify Temperature Requirements

- It was found that limits were imposed due to OSEH requirement for personnel work around the LV within the gantry
- Actual flight hardware can withstand much higher temperatures since they must survive launch
  - This is especially the case for the flexseals, which are very difficult to maintain in previously imposed limits due to their location/ thermal capacitance

➔ Relaxed, more realistic requirements consistent with what the hardware could withstand allowed for longer periods of testing after gantry rollback

Important Contributing Factor: Understanding temperature requirements. If any extremely stringent temperature requirements are imposed, especially for LV components which were designed to withstand the high temperatures of launch, it is valuable to understand what is motivating the requirements and under what conditions they apply.

Factor 7: Check Boundary Conditions

- Initial launch analysis indicated that the temperatures on the spacecraft increased dramatically after launch (up to 1000ºC on some propulsion subsystem nodes)
- Closer investigation revealed certain boundary nodes as the culprit
  - These boundary nodes represent thruster and combustion chamber temperatures during thruster firings
  - There was no simple toggle in the propulsion subsystem vendor's thermal model to shut off these nodes
  - These nodes could not be easily deleted in the model since the propulsion subsystem vendor's SINDA logic files referred to them

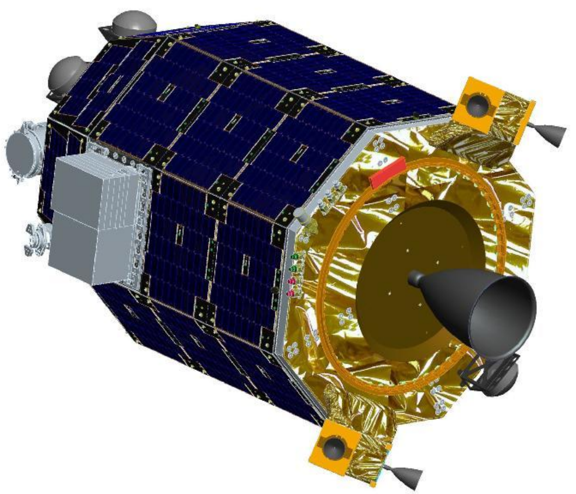
Factor 7: Check Boundary Conditions

- Solution: set any conductors to these boundary nodes to unrealistically low conductance values such that they do not impact final launch results

Important Contributing Factor: Boundary Conditions. Check boundary conditions imposed by vendors before integrating the LV model and SV Observatory model to ensure that there are no unrealistic boundaries being applied.

Factor 8: Launch Roll Profiles Important

- First launch analysis didn't have detailed launch trajectory available from ACS subsystem
  - Launch trajectory used from initial thermal analysis was based on curve fit of the altitudes and distances of Minotaur V LV at various launch events (stage burnout, fairing separation, etc.)
  - It was thought that any transient roll profiles would be too brief to significantly impact the SV temperatures
- Later analysis revealed roll profile had enormous impact on SV component temperature
  - Due to LADEE having body-mounted solar panels and instruments protruding from SV bus and main radiator



Source: NASA, www.nasa.gov

Factor 8: Launch Roll Profiles Important

- With realistic roll profile in later analysis, it was found that transient change in SV component temperatures was directly impacted by roll profile and solar exposure
  - Some components had temperature fluctuations of up to 20 C even with brief solar exposure.

Important Contributing Factor: Roll profiles during launch. These have a large impact on the temperature profiles of SV components, especially for spacecraft with body-mounted solar panels.

Factor 9: Free Molecular Heating

- Thermal Desktop allows modeling of FMH on the spacecraft with a specified orbit
  - This option was used for modeling FMH on SV after fairing separation, using the FMH profile provided by vendor and launch trajectory provided by the ACS subsystem

- However, analysis results didn’t show any increase in SV component temperatures from FMH after fairing separation

Source: NASA, www.nasa.gov

Factor 9: Free Molecular Heating

- Contact with Cullimore & Ring (Thermal Desktop vendor) revealed that FMH with orbit option did not allow for user-specified trajectories
  - However, there was no indication of this shortcoming within the Thermal Desktop program itself
- Solution was to model this phase of the launch with two separate environmental heating cases:
  - Albedo, Earth IR, and solar heating from launch trajectory
  - FMH heating provided with vector list to ram direction of SV

Important Contributing Factor: Model method validation. Do not underestimate the complexity of simulating FMH and radiative environmental loads during launch modeling with commercial thermal analysis software packages. Use results to verify that all of the environmental heating factors are accounted for in the analysis.

Summary of Important Contributing Factors

1. Due to the large characteristic dimensions of the LV/SV, the effects of convection from conditioned air from HVAC system in ground ops can be approximated with low natural convection coefficient
2. The dominant factor to isolate the LV from environmental loading inside a facility is not the conditioned air, but the insulation of the facility walls → nodalize through-thickness properly in thermal model
3. Daily variations in solar flux, ambient temperature, and diffuse sky temperature **must** be included in ground operations thermal model
4. Ask for detailed material/optical properties from vendor very early in design process, especially if information is ITAR sensitive

Summary of Important Contributing Factors

5. Before modeling, find out first from vendor which areas of LV are most sensitive to temperature changes, then add more detail in those regions
6. Question what is motivating any stringent temperature requirements
7. Check boundary conditions imposed by vendor models before starting any launch thermal analysis
8. Launch roll profiles have huge impact on overall SV component temperatures
9. Do not underestimate complexity of simulating FMH

Conclusions

- Three major themes explored in this presentation:
  1. It is crucial to get as detailed information as possible on material/optical properties of LV, and determine where on LV is thermally sensitive
  2. Transient environmental factors (Diurnal variations, roll profiles) can have the greatest impacts on your LV analysis: do not omit any factors from the environment
  3. Do not underestimate complexity of ground operations/ launch analysis. Use common sense and good engineering judgment when looking at results to ensure that all factors accounted for in analysis and solutions are physically sound

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Thank You

Questions?