GROUND OPERATIONS, LAUNCH AND ASCENT THERMAL ANALYSIS FOR THE UPCOMING LAUNCH OF THE LUNAR ATMOSPHERE AND DUST ENVIRONMENT EXPLORER MISSION

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ABSTRACT

The Lunar Atmosphere and Dust Environment Explorer (LADEE) mission is scheduled to launch in mid-to-late 2013 aboard the maiden flight of the Orbital Sciences Corporation Minotaur V Launch Vehicle to study the Moon's exosphere and impacts of the environment on lunar dust. To determine the pre-launch and launch and ascent environments and their impact on the spacecraft, thermal analysis was conducted to ensure that the existing design of the launch vehicle, gantry and storage facilities at Wallops Island, VA were sufficient to meet the thermal constraints of the space vehicle. In addition, a strict temperature and solar exposure requirement was imposed on the launch vehicle itself which necessitated thermal analysis of the Minotaur V motors during storage, gantry operations, and gantry roll-back. These thermal analyses required the creation of thermal models which accounted for convective effects as well as launch thermal loads, somewhat outside of the normal capacities of the conduction- and radiation-driven Thermal Desktop and SINDA/FLUINT programs primarily used by NASA Goddard Space Flight Center's Thermal Engineering Branch. This paper seeks to capture the crucial contributing factors to these analyses by discussing the numerous modeling considerations taken to capture such a complex thermal environment. The major environmental drivers for rapid temperature changes on the launch vehicle and space vehicle will be discussed. The largest contributors to the difficulty of this analysis included determining the appropriate convective coefficient for different thermal environments and the appropriate amount of model detail in various portions of the launch vehicle, such that it is enough to resolve thermal gradients without hindering runtime. The need to resolve these difficulties required the development of innovative approaches to reach logical, physically sound solutions. The important contributing factors learned throughout the thermal modeling process are presented in hopes that future missions with similar requirements can benefit from the challenges overcome for LADEE. However, it should be noted that the effectiveness of these factors have yet to be verified, and it is hoped that the launch of LADEE will confirm the accuracy of the thermal model.

LIST OF VARIABLES AND ACRONYMS

A_c, A_s	Cross sectional area of duct, surface area of duct
C_p	Specific heat
D	Characteristic dimension
h	Convection coefficient
k	Thermal conductivity
$\dot{m}$	Mass flow rate
μ	Dynamic viscosity of fluid

Nu	Nusselt Number
Pr	Prandtl Number
Re	Reynolds Number
ρ	Density
v	Velocity
$\dot{v}$	Volumetric flow rate
FMH	Free Molecular Heating
GSFC	Goddard Space Flight Center
HVAC	Heating, Ventilation, and Air Conditioning Unit
LADEE	Lunar Atmosphere Dust Environment Explorer
LV	Launch Vehicle
MLB	Motorized Lightband
PAF	Payload Attach Fitting
PK	Peacekeeper Motor
SV	Space Vehicle
WFF	Wallops Flight Facility

INTRODUCTION

The Lunar Atmosphere and Dust Environment Explorer (LADEE) mission is a NASA mission to study the Moon's atmosphere and enhance our nascent understanding of the surface boundary exospheres and dust processes throughout the solar system[1]. First observed during the Apollo missions as a faint "glow" around the lunar terminator[2], LADEE will determine the composition of the lunar atmosphere and determine factors that contribute to its distribution, variability, and volatility, with implications toward future exploration missions. To accomplish these objectives, LADEE will employ three instruments: the Lunar Dust Experiment (LDEX), the Neutral Mass Spectrometer (NMS), and the Ultraviolet Spectrometer (UVS). LADEE will also fly the Lunar Laser Communication Demonstration (LLCD) to test high-speed laser communications from the Earth to lunar orbit[3].

LADEE was fully integrated and tested at NASA Ames Research Center in Moffett Field, CA, and will launch aboard the maiden flight of the Orbital Sciences Corporation Minotaur V Launch Vehicle from NASA Wallops Flight Facility in Chincoteague, VA in the third quarter of 2013. Prior to launch, the spacecraft and launch vehicle will be integrated at Wallops and subsequent functional testing will be performed on the launch pad. However, as this work will be undertaken during the summer months, where temperatures can regularly exceed 38°C, there was significant concern as to the survivability of the spaceflight hardware during ground operations. Hence, thermal analysis was required to verify that the air conditioners available at the ground operations and processing facilities had sufficient capacity to cool both the LADEE Space Vehicle (SV) and Launch Vehicle (LV) to their respective required temperature limits. Post-launch, rapid changes in the environment around the SV also required thermal analysis to ensure that the spacecraft was within survival limits during all events in the ascent phase. The following discussion on the implementation of the thermal analysis serves to capture important factors learned throughout the process in hopes that similar future projects can benefit. However, as most of the crucial factors stated in this paper were only arrived at based on engineering judgment and previous experience, rather than empirical evidence, the true validation of the importance of these factors will be performed when LADEE launches.

OVERVIEW OF LADEE SPACECRAFT AND LAUNCH VEHICLE DESIGN

The LADEE spacecraft design is derived from the Modular Common Spacecraft Bus architecture: a small, low-cost spacecraft architecture which seeks to deliver scientific and technically useful payloads to a variety of orbits at lower programmatic costs and shorter development time. The instruments are mounted externally on the spacecraft bus with body-mounted, fixed solar arrays covering the bus in its entirety, save areas reserved for the thermal radiator and propulsion system. The LADEE orbiter and its component modules are shown in Figure 1.

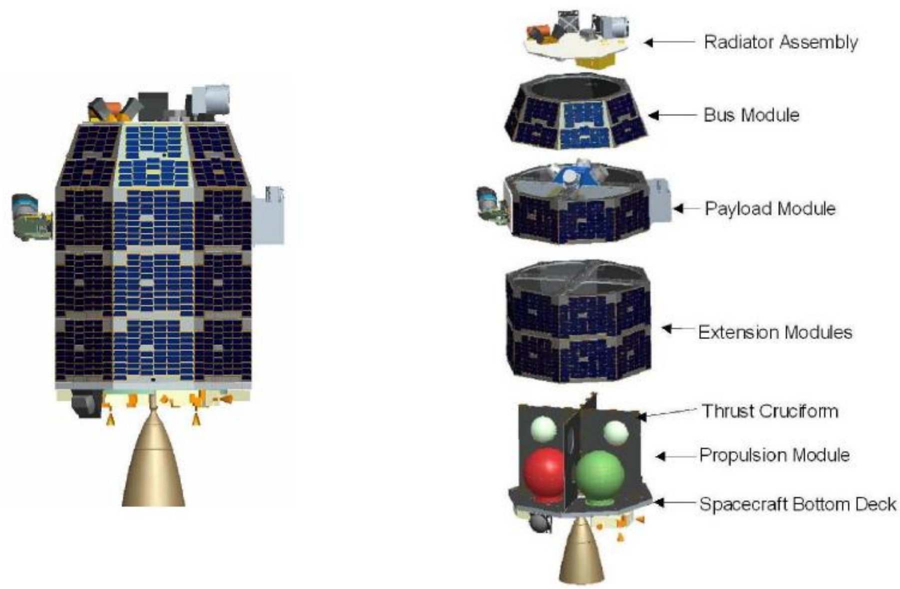


Figure 1. The LADEE Orbiter and Bus Modules[1].

The Minotaur V Launch Vehicle is a five-stage evolutionary version of the Minotaur IV which includes a fifth-stage Star 37 motor to launch small spacecraft to high-energy trajectories, including Lunar Transfer Orbit. The first four stages of the Minotaur V are Peacekeeper-based (PK) solid rocket boosters derived from heritage components shared with the Minotaur IV. The fourth stage is a commercial Star 48V motor. As shown in Figure 2, both LADEE and the fifth-stage motor are encased within the fairing, with the case for the Star 37 Stage 5 motor attached to LADEE via a Motorized Lightband (MLB) atop a composite latticed Payload Attach Fitting (PAF).

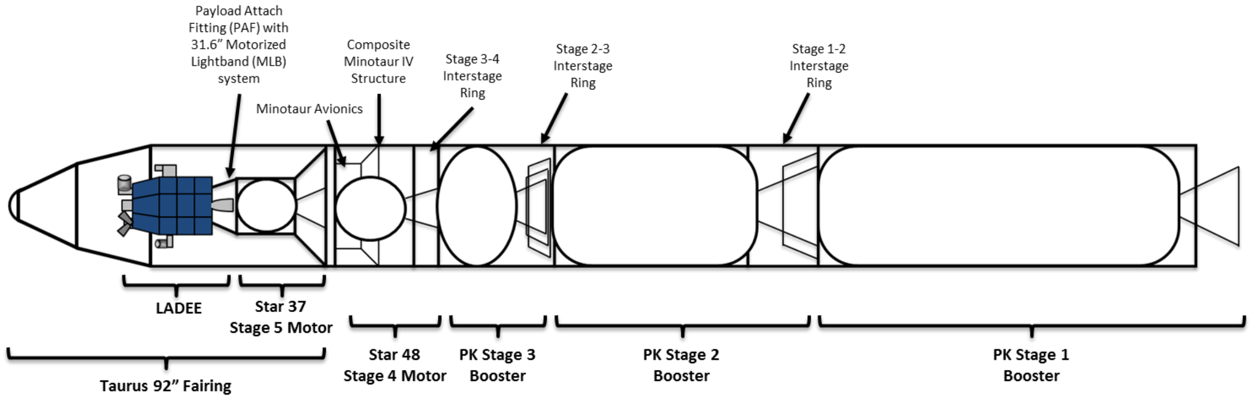


Figure 2. The Minotaur V Launch Vehicle[1].

OVERVIEW OF LADEE MISSION LAUNCH AND ASCENT PHASES

Though this is not the first launch of a Minotaur-series LV from Wallops Flight Facility, as previous Minuteman-derived Minotaur vehicles have successfully carried their payloads to orbit from WFF, LADEE will be the first launch of a Peacekeeper-derived vehicle. Hence, the relative novelty of this configuration necessitated thermal analysis of both the LV and SV in environmental conditions specific to WFF such that it could be ensured that both do not exceed their allowable temperature limits during ground operations.

Since LADEE will be launched in the mid-to-late summer season of Wallops Island, VA, both the gantry and storage facilities used for the PK boosters needed to be verified that they could keep the boosters within their stringent temperature limits during full summer environmental loading. For storage, the PK boosters are kept within air-conditioned high bays and other similar facilities on the Wallops premises. For pre-launch operations, the Minotaur LV is assembled on a concrete flame deflector and enclosed within a multi-level gantry. The gantry will have air ducted from a portable HVAC unit such the temperature inside the gantry is maintained within the LV limits. Thermal modeling was used to determine the transient responses of the LV/SV stacked configuration to changes in the environment, HVAC functionality, and gantry roll-back and testing operations with full environmental loading.

The LADEE SV in pre-launch ground operations will be unpowered with fairing air controlled and purged via the Ground Environmental Control Unit (ECU). Immediately before launch until before fairing separation, the fairing will be disconnected from the ECU and LADEE will be subject to air entering the fairing at prevailing environmental conditions. Launch operations of the Minotaur V will occur from the ignition of the Stage 1 Engine to burnout of the Stage 5 engine. During these operations, the SV will see rising temperatures on the fairing inner surface caused by aero-heating of the external fairing wall. As both LADEE and the Stage 5 motor are heated by these rising temperatures since both are embedded inside the fairing, the Stage 5 motor is covered by an MLI blanket to reduce heat flux from the fairing. In turn, this reduces soakback from Stage 5 to LADEE.

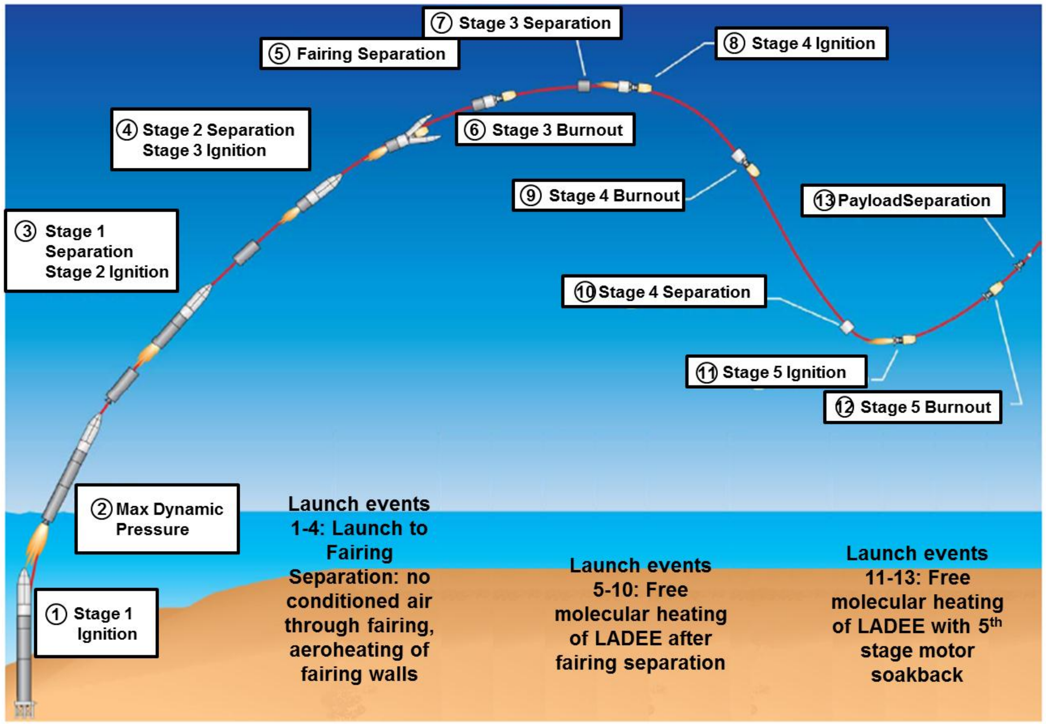


Figure 3. LADEE Launch and Ascent Events[5]

Figure 3. LADEE Launch and Ascent Eventsshows the events in the LADEE launch and ascent phase. The PK booster operations comprise the first through third stages of launch. After Stage 3 ignition, the LV fairing separates. The LADEE SV is subjected to a range of environmental factors, the most crucial of which is free molecular heating (FMH) in the ram direction of the spacecraft. FMH is at maximum right after separation and decreases almost logarithmically to zero after about six minutes. Stage 3 burnout is followed by Stage 4 ignition and burnout. Subsequently, the Stage 5 spin motor starts and spins the upper stage up to 1 rev/sec, after which Stage 5 is ignited and peaks in temperature at the time of payload separation. This will result in soakback to LADEE via the Motorized Lightband. Finally, after Stage 5 burnout, a Yo-Yo De-spin procedure occurs to reduce the angular velocity to 0°/sec, and payload separation ensues at about half an hour after launch[5].

IMPORTANT CONTRIBUTING FACTORS FOR THE GROUND OPERATIONS THERMAL ANALYSIS

Thermal analysis of ground operations comprised models of various scenarios during pre-launch processing of the LV and SV: (1) the PK boosters and transporters in storage at an air-conditioned Wallops facility; (2) the LV on the launch mount inside an air-conditioned gantry; (3) the LV on the launch mount after gantry roll-back, where it is exposed to full environmental loading during testing operations; and (4) the SV inside the fairing being subject to cooled purge air, while the external fairing is exposed to full environmental loading.

Facility Thermal Models in Ground Storage and Gantry Operations

Modeling of ground operations required the consideration of convective heat transfer effects to the conduction- and radiation-dominant Thermal Desktop program used at the Thermal Engineering Branch (TEB) of NASA Goddard Space Flight Center (GSFC). Convective heating and cooling effects were modeled as linear conductors from a boundary node held at HVAC exit air temperature to all of the external surfaces on the LV or SV. The conductance from the boundary node to each surface was calculated from the convection coefficient, *h*, per area of the surface. The value of *h* was obtained via the calculation of Nusselt Number based on volumetric flow rate from the HVAC system, via the following equations:

$$h = \frac{k\ Nu}{D} \qquad \text{Eq. 1}$$

Where:

$$Nu = 0.23Re^{0.8}Pr^{0.4} \text{(Dittus-Boetler Equation)} \qquad \text{Eq. 2}$$

And:

$$Re = \frac{\rho v D}{\mu} = \frac{\rho \dot{v} D}{A_c \mu} \qquad \text{Eq. 3}$$

$$Pr = \frac{C_p \mu}{k} \qquad \text{Eq. 4}$$

The temperature of the exit air was found via:

$$T_{exit} = T_{ambient} - (T_{ambient} - T_{inlet})e^{-\frac{hA_S}{\dot{m}C_p}} \qquad \text{Eq. 5}$$

The characteristic dimension, *D*, was not well-defined in the context of Equations 1 and 3. Therefore, characteristic dimensions were tested in the equation: the cross-sectional diameter of the air inlet duct, the cross-sectional diameter of the LV, the cross-sectional length of the gantry, the length of the LV per level of the gantry, and the length or cross-sectional diameter of the SV (for flow inside the LV fairing). However, for all characteristic diameters used, due to their magnitude as compared with the velocity of the incoming air, the resultant heat transfer coefficient calculated was only similar to or slightly larger than the lowest natural convection rate of 5 W/m^{2}K. Hence, for large-scale air flows surrounding the LV or SV, even though the air conditioner had a large volumetric flow rate at the inlet, the resultant forced air convection coefficient calculated did not vary much from the lowest natural convection rate due to the low Reynolds number from the scale of the objects inside the flow. ***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^{2}K).***

During analysis of the LV inside the air-conditioned storage facility and gantry, it was initially thought that air from the HVAC systems for each respective facility would contribute most to removing the internal heat from the LV components. Hence, more attention was paid to the calculation of the convection coefficient, *h*, as obtained from the volumetric flow rate from the HVAC system. The gantry and storage facility walls were modeled as a thin shell surfaces since it was initially thought that they would not provide much insulation from the external environment. However, through initial thermal analysis, it was found that the temperatures from analysis on the LV were much too high compared with the previously observed temperatures of objects with similar thermal masses in these facilities. Also, due to low convection coefficients, the HVAC air had minimal impact on cooling the LV, while the LV was being heated significantly by radiation from the facility walls. It was eventually found that these unrealistic results were the product of an incorrect assumption; the correct assumption should be that the HVAC air has a fairly low influence on the cooling of the LV, and merely replaces the air inside the facility such that a constant air temperature is maintained. However, the insulation on the outer walls of the facility play an enormous role in dampening the amount of environmental heat that reaches the LV. Therefore, the thin shell surfaces that previously represented the gantry and facility walls were not sufficient to capture the thermal gradient in these walls, and hence the LV experienced unrealistic amounts of heat from environmental loading. It was found that modeling the walls with solid geometries and at least two through-thickness nodal divisions between the outer and inner surfaces of the walls resulted in a much more realistic temperature on the LV. In modeling the wall, the wall substrate material was found to have minimal impact on the resulting temperature gradient, and the gradient was mostly dependent upon the insulation material used. Thus, the R-value for wall insulation is the most important factor in insulation of the LV from environmental heat. 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.***

Since the TEB at NASA GSFC focuses primarily on design, analysis, and integration of space flight hardware, the approach initially taken for modeling of the “hot case” was to stack the worst-case hot parameters with no diurnal variations in solar flux or ambient temperature, similar to the method taken for spacecraft on-orbit. It was initially thought that the enormous thermal mass of the launch vehicle would greatly dampen any diurnal responses of the system, and the stacked worst-case solar flux, ambient temperature, cold sky temperature, and natural convection rate would be a realistic worst-case ground operations scenario. However, analysis with these parameters at constant values and no diurnal variations resulted in extremely high, unrealistic temperatures on the LV. It was found through reiterations of the analysis that the daily changes in ambient air temperature, cold sky temperature, and solar flux were crucial to the resultant temperatures on the LV system and the accuracy of the solution. Though the bulk propellant responded very slowly to changes in temperature, other components such as the motor casing and the interstage rings have very significant transient responses, and the incorporation of daily temperature and flux variations allowed the launch vehicle to radiate most of its heat absorbed through the day, such that its temperature eventually converged to a sinusoidal variation around an average temperature. The worst-case flux variations and temperature variations for ambient air, diffuse sky, and HVAC conditioned air outlet temperature are shown in Figure 4 for record August conditions at Wallops Island, VA. In the plots, time starts at local midnight. Both the diffuse sky temperature and outlet air temperature vary as a function of the ambient air temperature. The diffuse sky temperature was calculated from the ambient air temperature via an equation from the vendor; the outlet air temperature was obtained from Eq. 5. As seen, the changes in both temperature and flux are quite dramatic in during the span of the day. Hence, it is crucial to incorporate these variations in flux and temperature such that the correct transient response of the system is achieved. The diffuse sky temperature is especially important as the LV radiates most of its heat absorbed from the environment to the diffuse sky. ***Important Contributing Factor: Daily Variations in Solar Flux and Temperature. 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.***

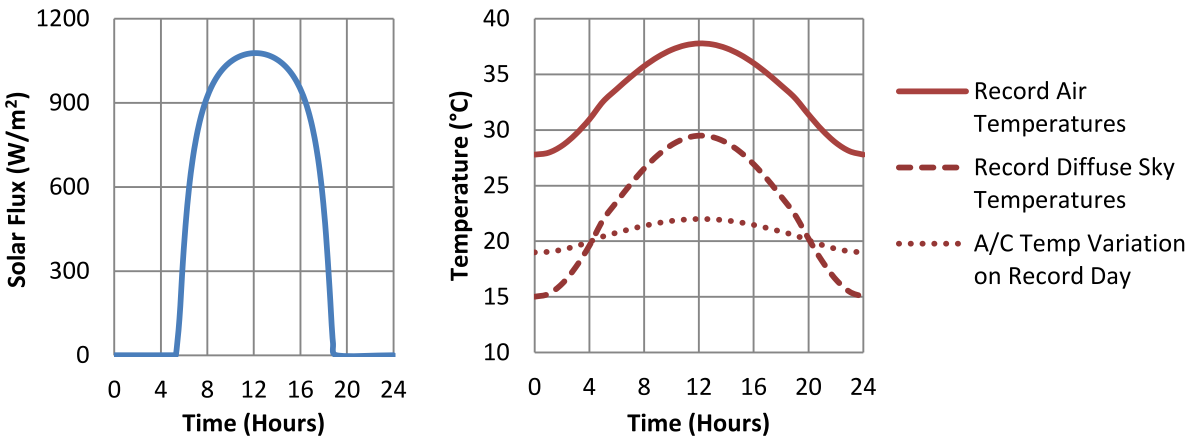


Figure 4. Diurnal variations in solar flux and record ambient air temperatures for Wallops Island, VA, during the month of August.

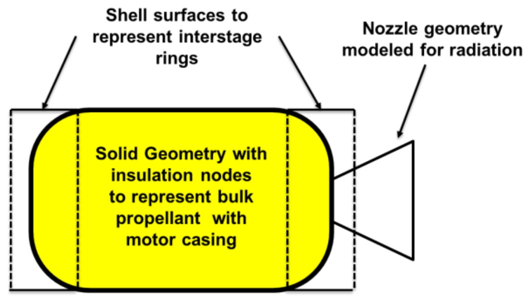
Launch Vehicle Thermal Model in Pre-Launch Operations

The Minotaur V LV is derived from the Peacekeeper ICBM. Its first through third stages are provided directly by the U.S. Air Force to Orbital Sciences Corporation, which then integrates them to the fourth and fifth stage motors and the fairing. Due to the missile-derived design and the sensitive nature of the LV data, it was difficult to obtain specific material and optical properties and design details in a timely manner. As such, scheduling constraints and the scarcity of information necessitated that the initial thermal models be developed solely based on launch vehicle user manuals provided by the vendor, with some parameters assumed where the user manuals did not provide details. However, many issues arose from the inaccuracy of these assumptions. Of these, the most prominent issues were the lack of coatings information and the lack of fairing properties.

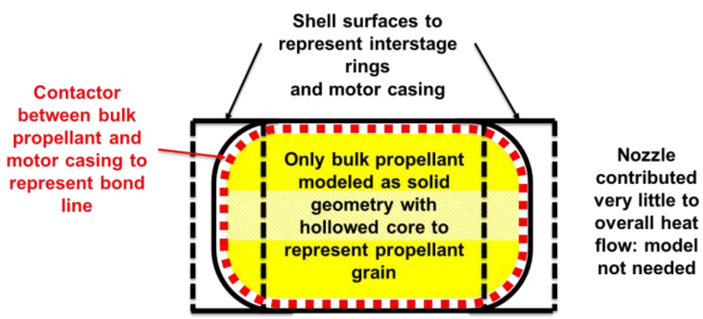
In initial model development, the user manual showed that the external insulation for the motor casing was a dark, black-paint-like proprietary material. Since there was no additional information from the supplier as to the external coatings of the LV, the external optical properties of the insulation were used. While no limits were violated with these assumptions, further discussions with the vendor regarding higher-than-expected temperature predictions revealed that the external coating of the LV was actually a proprietary white paint, though this was not explicitly mentioned in the user manual. Therefore, the model was updated with the new optical properties and new predictions were generated.

The requirement to keep the SV within its survival limits in the LV fairing during ground operations necessitated a separate thermal model to be developed for this purpose. The approach for the SV cooling model was similar to that of the LV inside the gantry: purge air conditioned by a ground environmental control unit was ducted to the nose of the Minotaur V fairing, where it proceeded to flow through the fairing around the spacecraft and eventually vent out of the stage 3 and 4 interstage ring. However, this case drew another parallel with that of the LV inside the gantry: the insulation material of the LV fairing played a pivotal role in shielding the SV from environmental effects. The user manuals did not provide any information on the fairing material or optical properties. Though this information was requested, the difficulty on the part of the vendor to find documentation on the exact insulation material and coatings used, coupled with possible export control issues related to the information, resulted in considerable delays to obtaining these properties for the thermal model. Due to scheduling constraints, the initial thermal analysis of the SV inside the fairing used the assumption that the fairing insulation was composed of 6.35 mm (1/4-inch) of fiberglass since the actual fairing properties were not available. However, when the real fairing properties were obtained much later, it was found that though the initial assumption of fiberglass was realistic with regards to thermal conductivity, the thickness was largely incorrect. The fairing structure was a composite sandwich structure, but the main insulation used a very thick (> 2 cm) acoustic blanket on the interior surface, which has very low thermal conductivity (on the magnitude of 10^{-2} W/m-K). Hence, the amount of environmental loading on the SV in the initial analysis was too large. Thankfully the results with the true properties did not impact overall the thermal design of the SV inside the fairing. However, erroneous results with incorrect properties could have had a huge impact on the cost and schedule of the SV by causing design changes due to false assumptions. ***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. Also, 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.***

In the initial models developed in Thermal Desktop from the LV user manuals, the sections of the motor case bonded to the propellant were just modeled as a solid cylinder with hemispherical domes on both ends, with insulation nodes covering the exterior surface to represent the motor casing. An effort was also made to capture the geometries of the nozzles correctly such that the correct radiative energy exchanges could be modeled. However, it was later found that the locations of greatest thermal sensitivity on the LV were the temperature of the bond line between the motor casing and propellant and the temperature of the bulk propellant itself. With the initial modeling arrangement of the motor casing and propellant being one solid geometry, the correct transient response of the bond between the motor casing and propellant could not be captured, nor could an appropriate average temperature of the propellant grain be calculated. Thus, the thermal model needed to be modified such that the bulk propellant and the motor casing were modeled as separate entities: the bulk propellant was kept as a hollowed solid cylinder with the density weighted to model the propellant grain, and the motor casing was changed into a shell surface. Conduction through the bond line was modeled as a contactor between the motor casing and solid propellant geometry. In addition, the effort to model the nozzle geometries was not needed since the nozzles were encased inside the respective interstage rings for each stage, have low conductivity to the motor casing and have little thermal mass. Therefore the heat exchanges between the nozzles and the surrounding structure was insignificant compared with the overall heat exchanges in the LV. Furthermore, it was found that due to the relatively low thermal capacitance of the interstage rings, these areas tend to respond faster to environmental loading than the motor casing and propellant. Hence, the interface between the interstage rings and the motor case for each LV stage needed to be modeled accurately and with sufficient detail, since a significant amount of heat is conducted through the interstage rings to heat the motor case. Schematics of the initial and final thermal models are shown in Figure 5. ***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.***



(a) Initial thermal model configuration



(b) Final thermal model configuration

Figure 5. Initial and final configurations for LV motor thermal models.

The initial ground operations temperature limits imposed for the LV required that it be maintained in a narrow 16-27°C band at all times, such that the flexseal, bulk propellant, and bond lines be kept safe. For a record hot day at Wallops, this already proved to be a demanding task within the gantry. Post-gantry-rollback, these limits severely constricted the amount of time allowable for the LV to undergo functional tests; in some cases, the sensitive LV components violated temperature limits after less than an hour of environmental exposure. The difficulty of maintaining LV components within such stringent limits resulted in an inquiry as to what motivated the requirements. It was later discovered that the strict limits were only imposed due to an OSEH requirement for personnel work around the LV within the gantry. The actual flight hardware, especially the flexseals (which were extremely difficult to maintain within the previously imposed limits), could withstand much higher temperatures during launch. Even during ground operations or storage, most launch vehicle components can at least withstand temperatures between 0°C and 35°C. Hence, the requirements were relaxed and this 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.***

IMPORTANT CONTRIBUTING FACTORS FOR LAUNCH AND ASCENT THERMAL ANALYSIS

Thermal analysis for the launch and ascent phases of the LADEE mission comprised three main segments: from the moment of launch to fairing separation; free molecular heating (FMH) after fairing separation; and simultaneous FMH and soakback heating after Stage 5 ignition. The launch thermal model required integration of the detailed LADEE observatory model and a simple Motorized Lightband, Payload Attach Fitting, 5th stage motor, and fairing model which correctly captures the interfaces and the geometries of each. The other LV stages are fairly isolated from the fairing and therefore do not thermally impact the environment seen by LADEE. For these phases, the thermal analysis is only focused on the heat flux into LADEE and the resultant temperatures from this environmental loading. As such, the LV components will not be discussed to great length.

Thermal Analysis during Initial Launch and Ascent

First-cut thermal analysis results of LADEE in launch showed that temperatures in the spacecraft drastically and unrealistically skyrocketed immediately after launch; temperatures close to the propulsion deck exceeded 1000°C on some nodes. Closer investigation showed that many propulsion nodes in the observatory model were conductively tied to boundary nodes which represented thruster and combustion chamber temperatures during thruster firings. Since the propulsion thermal model was provided by the commercial vendor of the propulsion subsystem, these boundary nodes could not be easily deleted as they were referenced in the various SINDA/FLUINT INCLUDE files associated with the proprietary propulsion model. There was no simple toggle in the model to prevent thruster firing either. Hence, the conductors to these boundary nodes needed to be manually set to an unrealistically low conductance value, such that they did not impact the 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.***

Thermal Analysis after Fairing Separation

For the initial launch and ascent thermal model of LADEE, an assumption was made for the launch trajectory, since the detailed launch trajectory was not yet available from the ACS subsystem. The initial launch trajectory assumption was derived from a curve fit to the altitudes and distances traveled by the Minotaur V LV at various events in the launch process. The assumption did not take into account any roll maneuvers by the LV, nor the SV after fairing separation. It was initially thought that the launch phase and any transient roll profiles would be too brief to significantly impact the SV component temperatures. However, for the LADEE SV, which has body-mounted solar panels and instruments protruding from the spacecraft bus or mounted to the main SV radiator, the lack of roll profile associated with the assumed launch trajectory resulted in huge increases in the temperatures of the instruments angled towards the sun. Under this trajectory, some instruments exceeded their survival temperature limits despite the short duration of launch. During later analysis when a realistic trajectory and roll profile was input into the model, the temperature profiles of the instruments during launch changed drastically. The transient change in instrument temperature was a direct function of its solar exposure, which was determined by the roll profile; in some cases, even a brief exposure of the instruments to direct solar loading could raise its temperature by 20°C. Hence, roll profiles are an integral influence in component temperatures during launch. ***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.***

After fairing separation, Thermal Desktop allows modeling of FMH on the spacecraft with a specified orbit. The FMH phase of the launch was therefore modeled with this option with an FMH profile provided by the LV vendor and a user-specified launch trajectory. However, the results from the launch case consistently showed no heating on the temperature profiles of LADEE components after fairing separation, whereas an increase in temperature on the components was expected from FMH. It was later found through contact with the Thermal Desktop vendor that the FMH with orbit option did not allow for user-specified trajectories; there was no indication that this was the case within the Thermal Desktop program. The solution to this shortcoming within Thermal Desktop was to model this phase with two separate environmental heating cases: one from solar, albedo, and IR heating via the user-specified launch trajectory; the other from FMH applied with a vector list to the ram direction of the spacecraft. ***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.***

CONCLUSIONS

Of the important contributing factors learned from the thermal analysis of the ground operations, launch and ascent phases of the LADEE mission, a few overarching themes emerged. Firstly, it is crucial to get from the vendor as detailed thermal and optical properties of the LV as possible, and to determine which areas are most thermally sensitive on the spacecraft. This must be done before any modeling is initiated, and is especially applicable to cases where ITAR restrictions or other sensitivity issues prohibit information from being freely available. Secondly, small transient factors that initially may be assumed to not impact the LV or SV, such as diurnal temperature variations and roll profile, often are the greatest environmental influences, despite the large thermal capacitances of the vehicles. Therefore, all environmental details must be included in the launch vehicle analysis. Finally, the complexity of the ground operations and launch analysis cannot be underestimated. Even if all material and optical properties are specified correctly and all environmental factors are accounted for, the thermal analysis can still produce incorrect results due to lack of nodalization in certain regions of the model, or lack of detail in the heating profiles of certain environmental factors. Due to the transient nature of launch analysis, the results obtained from the thermal model must always be checked against common-sense principles and good engineering judgment to ensure that the solution is physically sound.

SUMMARY

The following is a complied list of all important contributing factors learned from ground operations, launch, and ascent analysis of the LADEE spacecraft:

1. 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).
2. 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.
3. Daily Variations in Solar Flux and Temperature: 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.
4. 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. Also, 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.
5. 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.
6. 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.
7. 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.
8. Roll profiles during launch: These have a large impact on the temperature profiles of SV components, especially for spacecraft with body-mounted solar panels.

9. 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.

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REFERENCES

1. 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.

2. Hollingham, Richard. “NASA Ladee Mission: Solving a Moon Mystery.” BBC News, 15 April, 2013. http://www.bbc.com/future/story/20130411-solving-a-moon-mystery

3. Delory, G. T. et al. “The Lunar Atmosphere and Dust Environment Explorer (LADEE),” 40th Lunar and Planetary Science Conference, March 23-27, 2009, The Woodlands, TX.

4. “Minotaur V Fact Sheet.” Orbital Sciences Corporation. 2013. http://www.orbital.com/NewsInfo/Publications/Minotaur_V_fact.pdf

5. Voss, Douglas. “LADEE – Lunar Atmosphere and Dust Environment Explorer.” Presented to the Eastern Shore Defense Alliance, 19 February 2013, NASA Wallops Flight Facility. http://easternshoredefensealliance.org/files/LADEEmoonmission.pptx