

Ground Plane and Near-Surface Thermal Analysis for NASA's Constellation Programs

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Most spacecraft thermal analysis tools assume that the spacecraft is in orbit around a planet and are designed to calculate solar and planetary fluxes, as well as radiation to space. On NASA Constellation projects, thermal analysts are also building models of vehicles in their pre-launch condition on the surface of a planet. This process entails making some modifications in the building and execution of a thermal model such that the radiation from the planet, both reflected albedo and infrared, is calculated correctly. Also important in the calculation of pre-launch vehicle temperatures are the natural environments at the vehicle site, including air and ground temperatures, sky radiative background temperature, solar flux, and optical properties of the ground around the vehicle. A group of Constellation projects have collaborated on developing a cohesive, integrated set of natural environments that accurately capture worst-case thermal scenarios for the pre-launch and launch phases of these vehicles. The paper will discuss the standardization of methods for local planet modeling across Constellation projects, as well as the collection and consolidation of natural environments for launch sites. Methods for Earth as well as lunar sites will be discussed.

Nomenclature

AGL	=	above ground level
CEV	=	Crew Exploration Vehicle
CM	=	Crew Module
IR	=	infrared
ISS	=	International Space Station
KSC	=	Kennedy Space Center
LAS	=	Launch Abort System
LST	=	local solar time
MLP	=	Mobile Launch Platform
NSRD	=	National Solar Radiation Database
POR	=	period of record
TD	=	Thermal Desktop [®]
WSMR	=	White Sands Missile Range

I. Introduction

NASA's Constellation Program aims to develop an integrated manned spaceflight capability to reach the International Space Station (ISS), the Earth's Moon, and beyond. The first two key components of this program include the manned spacecraft, called Orion, and the first launch vehicle, Ares I. Development of these vehicles is well underway and unmanned flight testing is to commence within the next year. In addition to these projects, NASA has begun studying lunar lander and habitat designs in preparation for the next set of moon landings sometime next decade. Each of these projects requires intense design and analysis of which thermal control system

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design and evaluation is an integral part. The mission phases for these vehicles must be carefully examined from preparation for launch to end of mission and landing. It is in the pre-launch and post-landing phases where an accurate thermal assessment of the vehicle with respect to the natural environment including the ground, the sky, and the Sun is vitally important. For these cases, a part of the thermal engineering community working on the Constellation Program has developed some guidelines and approaches on how to accurately model vehicles and account for the surrounding environment appropriately.

In the following pages, the problem of accurately modeling the near-surface environment will be explored and the shortcomings of standard analysis techniques in some of these cases will be explained. With this in mind, ground plane thermal analysis falls into two basic categories: cases where the effect of the vehicle on the ground plane is significant and cases where it is not. These two areas will be described in detail and compared in later sections. The other important factor to consider when performing near-surface thermal analysis is correctly identifying the surrounding natural environments. These include diurnal and yearly air temperature variation, solar flux, sky temperature, and winds. It is hoped that the ideas presented here will provide those attempting thermal control system design and evaluation for similar vehicles a good starting point for their detailed pre-launch and post-landing analyses.

II. The Importance of Near-Surface Thermal Modeling

For the Ares I and Ares I-X vehicles, the avionics and roll control systems are not actively controlled (thermally) during ascent. Instead, they are pre-conditioned during pre-launch using ground-supplied purge gas and then rely on thermal capacity of the units and mounting structure during ascent to maintain temperatures. Therefore, the pre-launch environment and potential ground effects on the vehicle environment are significant for determining the initial temperature conditions.

For lunar-based vehicles and habitats, the regolith temperatures can be greatly influenced by the vehicle and vice versa. Since the regolith has a very low thermal conductivity¹, large temperature gradients can form as a result of radiative interchange with a vehicle, which in turn can affect the vehicle temperature. An example comparing the difference between a fixed ground-plane temperature and an adiabatic ground plane that has radiative interchange with a lunar lander concept is shown in Figure 1. The temperature distribution in the regolith surface in proximity to the lander ranges over 200°C for the adiabatic ground plane and results in a difference in engine nozzle temperatures of almost 50°C compared to a fixed surface temperature, which illustrates that the ground plane modeling approach can have a significant effect on the thermal analysis results.

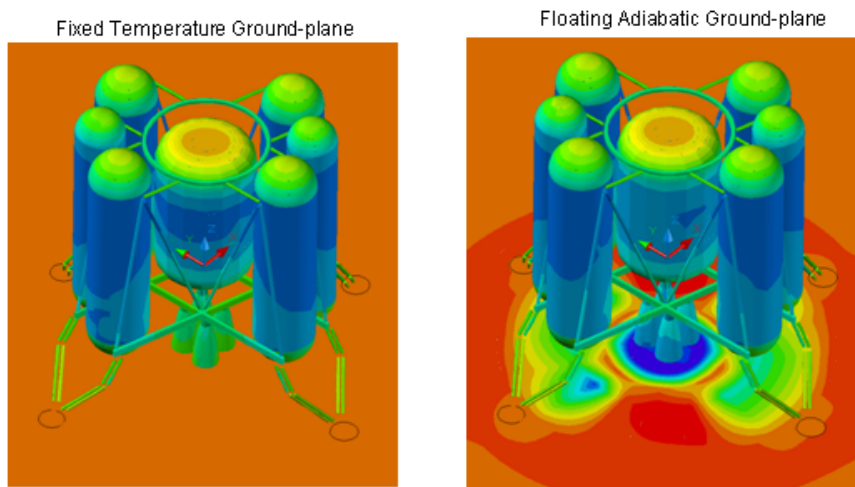


Figure 1: Example Lunar Lander and Regolith Temperature Contours

III. The Challenges of Near-Surface Thermal Modeling

Many thermal radiation analysis tools (including Thermal Desktop[®] (TD) software² containing a module called RadCAD) calculate the radiation interchange as well as the solar/planetary heating fluxes on an orbiting spacecraft. Most of these software tools were originally designed for simulating a spacecraft in orbit. However, for these

Constellation missions, the software also needs to be used for a vehicle on the surface of the planet. For the orbital spacecraft methodology, the computation of net radiation is done by calculating the incident and absorbed infrared (IR) heat fluxes from the planet, then the vehicle radiation conductors are tied to the deep space sink temperature. This method assumes the planet is unaffected by radiation from the vehicle and radiation interchange factors need not be calculated and included in the iterative temperature solution, which is normally a reasonable assumption for an orbiting spacecraft. However, for a vehicle on the surface, this radiation interchange with the ground cannot be neglected.

One way that this effect was traditionally handled for a vehicle on the planetary surface was to model a portion of the planet surface itself, by creating a planar or spherical surface with the planet radius that extended as far as necessary to encompass the vehicle field of view. However, this can lead to long run times, because rays are shot from every point of that planet surface, and many of them do not hit the vehicle at all, so a great number must be shot in order to get a reasonably accurate view factor calculation. Various adaptations of this method, for different scenarios, are discussed below. These methods are described specifically for implementation in Thermal Desktop, but similar methods can be used in any radiation analysis software.

The problem if Thermal Desktop is used in its standard way (in lieu of modeling a planet surface as discussed above) to calculate the planetary IR close to the surface of the planet is that it will basically double-count the planet IR load. Thermal Desktop radiatively couples the vehicle to the "Space" sink temperature, which is the radiation sky temperature for Earth surface analyses. So, the IR heat load calculation assumes that the vehicle is seeing a 360 spherical view to the sky. Then, the modeled planet surface is also adding an IR heat load, which double-counts the load over the view subtended by the planet.

IV. Cases Where Vehicle Effects on the Ground Plane are Significant

In all situations, a launch vehicle, habitat, or other facility will have a measurable effect on the temperatures of the ground plane surrounding it. These effects are caused by the facility casting shadows on the ground, creating local hot spots due to reflected solar energy, and exchanging radiative energy with the planet in the infrared (IR) spectrum. These temperature gradients on the ground plane generally do not have a significant effect on the facility creating them; however in some cases they cannot be ignored.

Determining whether ground plane temperature gradients are significant requires both geometric and environmental evaluation. Facilities having a low height to diameter ratio will be affected by ground plane temperature variations more than tall thin structures such as a launch vehicle stack. For example, a short, stout facility will cast a large shadow that has a significant view factor to the side of the facility facing it. In contrast, a tall thin facility will cast a long, thin shadow with a small view factor to the side of the facility facing it. Environmental considerations must include the thermal properties of the ground, the local convection environment, and all forms of solar loading at that location (direct, reflected, and diffuse). If the thermal conductivity of the ground material is very low, as in the case of sand or concrete, shadowed regions behind a facility and local hot spots in front of a facility can have a significant difference in temperature compared to the rest of the local ground plane. In cases where convection is poor, or non-existent, the vehicle will be more strongly coupled to the ground by radiation effects. Solar angles and time lengths can play a large role in how large shadowed regions can become, and how fast they move across the surface.

Lunar surface missions provide an excellent example of a situation requiring the ground plane to be included in thermal models. Lunar regolith has very low thermal conductivity; this fact combined with the 14 days of continuous sunlight and no atmosphere create slow moving shadows that can approach the nighttime regolith temperatures of approximately 100K. During Apollo lunar operations, rovers had to be parked so that tires would not be in a shadowed region and cause them to drop below their minimum temperatures³. In addition, the IR emissivity of lunar soil is extremely high at 0.92, which causes IR loading effects from the planet to be a significant mode of heat transfer. Solar absorptivity of the regolith is also very high at approximately 0.93 which causes hot spots on the surface due to solar energy reflected off the vehicle. These factors necessitate temperatures on the ground plane to be calculated along with facility temperatures in detailed thermal models.

Another example of a case where the ground plane-vehicle interaction is important is for the Orion Flight Test Program's series of pad abort tests. For these tests, the Orion vehicle's Crew Module (CM) and Launch Abort System (LAS) are placed on a mock separation ring which is itself placed upon a concrete launch pad at White Sands Missile Range (WSMR) in New Mexico. This configuration positions the CM approximately three feet above the pad surface and thus creates a situation where, as described above, the interaction of the vehicle, its shadow, and the surrounding ground can vary significantly depending on whether the aforementioned interaction is considered. Figure 2 below shows the Orion CM arranged on the WSMR launch pad at different times of the day. This progression demonstrates the resulting temperature gradients that develop between the shadowed portion of the ground surrounding the spacecraft and the unshadowed portion and how the shadow moves with respect to the sun. In this figure, the 1500 (in local solar time, LST) afternoon results show temperatures on the unshadowed concrete approaching 145°F but within the shadow, the temperature drops to near 85°F. The shadow progression also demonstrates the path of the sun over the vehicle (nearly over the top, but slightly off to the left side). This is a parameter that can be modified when calculating heat rates for different times of the year in Thermal Desktop and other radiation analysis codes.

The method for modeling the ground plane in these situations can vary. In general, thermal properties of the ground including thermal conductivity, heat capacity and density are required as inputs. Also required is the depth under the ground surface where the temperature remains constant over the course of the day. The ground plane can be modeled either as a solid with this thickness, or a surface connected to a boundary node with an appropriate conductance value to simulate the surface thickness. All environmental conditions must be considered and applied to the ground plane. The goal is to have the calculated ground temperatures match closely with measured data for the particular location being studied.

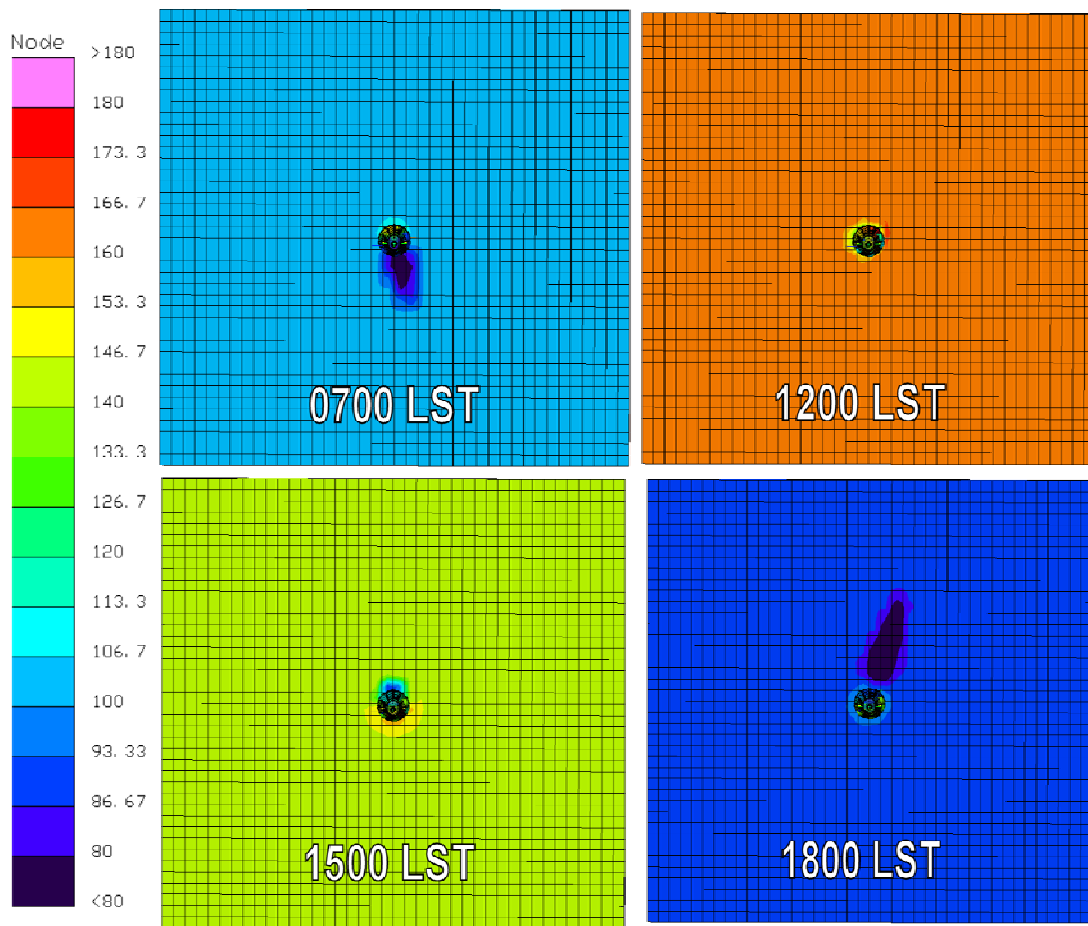


Figure 2: Orion Pad Abort 1 Flight Test showing movement of diurnal shadow and ground temperatures (°F).

V. Cases Where Vehicle Effects on Ground Plane Are Negligible

For scenarios where the ground temperature is not influenced by the vehicle, inclusion of the modeled planet surface in an analysis run is to be avoided where possible. One reason is that, with the planet surface included, the bounding box defined for the radiation calculation will be huge, and the associated oct cells will also be large, with the vehicle usually falling entirely in just one oct cell, which to a great extent invalidates their usefulness in speeding up the calculations. An advantage to the methods described here is that the bounding box for any radiation case that does not include the modeled planet surface will be much smaller, leading to much more reasonable-sized oct cells and thus faster solutions and better results. In general, shooting rays from the modeled planet surface should be avoided, because it would take an extreme number of rays from the planet to yield any reasonable result, since so few rays from the planet will hit the vehicle.

For the Constellation launch vehicles (Ares I and Ares V) and the demonstration flights (Ares I-X, etc.), the vehicle form is tall and thin, and will be located on the Mobile Launch Platform (MLP), which blocks much of the direct view of the vehicle to the nearby planet surface. For these reasons, the ground temperature is considered not to be substantially affected by the vehicle presence. The vehicle shadow on the ground is very thin, and its effect on vehicle temperature is negligible. This effect is shown in Figure 3, with a closeup of the vehicle and ground structures thermal model, as well as of a view of the vehicle on the modeled ground plane. Thus, in the Ares thermal analyses, the ground temperatures are not calculated explicitly in the run, but are instead taken from historical data. For Ares, the methodology is a hybrid of the standard Thermal Desktop planetary heating method and the ground plane surface modeling method. The incident heat to the vehicle is separated into three calculations that are all performed with the Case Set Manager: direct solar flux and albedo, diffuse solar flux, and planetary IR. This methodology is discussed in detail in the following paragraphs.

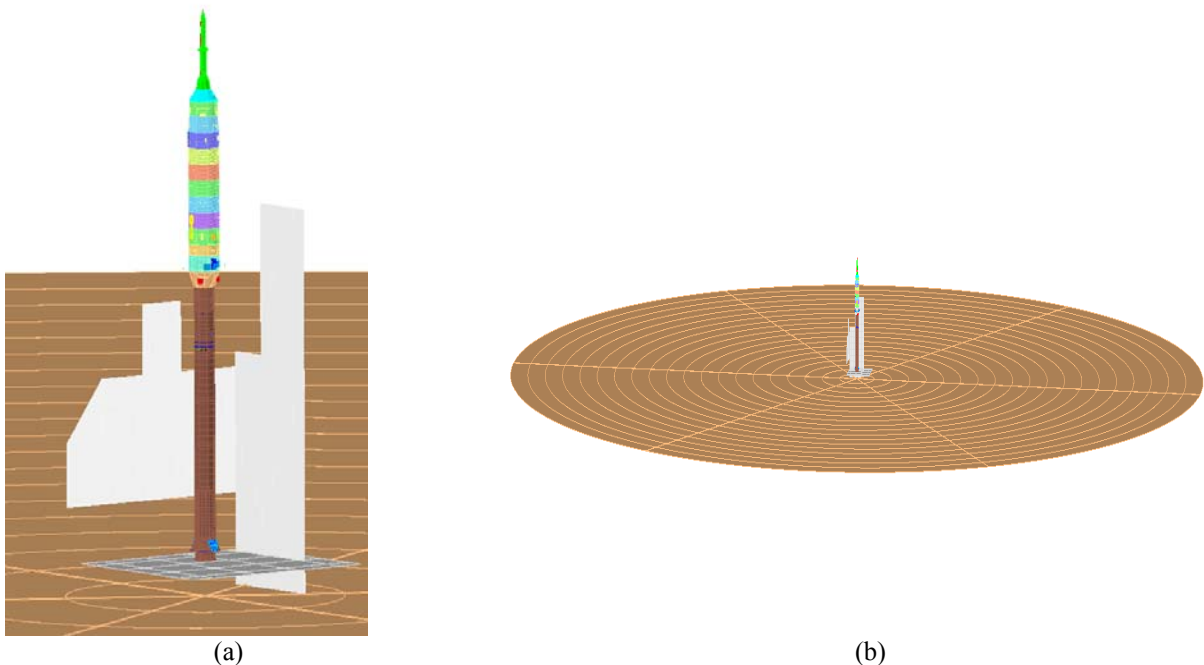


Figure 3: Ares I-X vehicle model with ground structures: (a) detail of vehicle, (b) with entire ground plane.

For direct solar flux and albedo calculations, the Thermal Desktop / RadCAD module is used to make those calculations with the Thermal Desktop planet (not the surface built in the model to simulate the planet). Thus, an orbit is defined in the Case Set Manager, using the Geo Lat/Long orbit type. This approach allows the user to input the vehicle position on the planet surface (moving or stationary), using latitude, longitude altitude and rotation. The right angle of the sun and prime meridian can be calculated in the form from the date. The entries should give the

vehicle position versus time, and the last time point must correspond to the solar period (i.e., 24 hours for Earth). The planet albedo should be correct for launch site local region, but the planet temperature will not be used, since the IR transfer is calculated via a different method. The table of solar flux versus time should be correct for the local region, and should include direct incident flux only; diffuse solar flux will be handled separately.

A radiation group should be defined that includes all the external surfaces on the vehicle that will be subjected to solar flux and ground albedo. This group should not include the modeled simulated planet surface. In the Case Set Manager, a radiation heat rate task is defined to calculate the heat rates using this radiation group and orbit. This radiation task is only to calculate solar flux and albedo, so those two are the only outputs that should be requested in the task, and the calculation is done in only the solar waveband.

Diffuse solar flux is the solar flux received on a cloudy day, which comes from the entire sky hemisphere rather than along the direct line to the sun. This flux cannot in general be handled in the same radiation task as direct incident solar flux. For calculation of this flux, a second radiation group is defined, which includes the same surfaces as above as well as the modeled planet surface. This radiation group should have a unique name from any other to allow it to be placed in a separate directory when the run is performed. The reason to include the planet surface in this model is to ensure that the ground reflections of diffuse flux are included. In the Case Set Manager, another radiation task is defined using this diffuse radiation group. Since the planetary surface is part of this radiation group, normally RadCAD would shoot rays from it. If rays are allowed to be shot from the ground surface, a very large number of rays will be needed to get an accurate calculation; a sample of how few rays hit the vehicle is illustrated in a ray plot in Figure 4. as discussed previously. However, since the ground temperature will be externally defined, the diffuse solar absorbed by the ground is not important and does not need to be calculated. Thus, this calculation can be done without shooting rays from the ground surface and still be completely accurate. To accomplish this, simply define the list of nodes in the Control tab to exclude the submodel that contains the ground surface. Assuming the ground-surface submodel starts with a unique letter (for Ares models it is the only submodel starting with 'E'), this is simple to accomplish with wildcards (e.g., listing [A-D]*.* and [F-Z]*.* captures every node in every submodel that does not start with E). The solar waveband is used for the calculation, since this calculation deals with diffuse solar. Under Radk Output, output filenames are defined that should differ between hot case and cold case. The user will select 'Output as Heating Rates' and under Edit, input the time dependent array of diffuse solar flux versus time. This array input must be done separately for hot cases and cold cases.

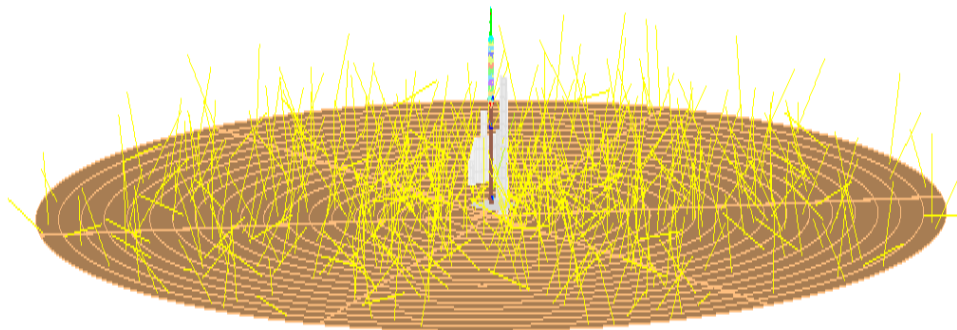


Figure 4: Ray plot with rays shot from planet surface.

For planetary IR calculations, a radiation group is defined with the same surfaces as above (vehicle exterior and planet modeled surface). This group will be used to model the radiation exchange with the planet in the infrared waveband. In the Case Set Manager, a radiation task to calculate the radiation conductors in the IR waveband is defined. Similar to the case above, in the controls for this task, the planet will be excluded from the nodes used to shoot rays from. In general, when a radiation conductor is determined, it is done by shooting rays from surface i to surface j and then averaging the two form factors obtained. However, if no rays are shot from the planet, the form factor from the vehicle surfaces to the planet will be calculated only based on the rays shot from the vehicle. This will be much more accurate than including the reverse form factor, since in general a ray shot from the planet will not hit the vehicle. When this calculation was done with rays shot from the modeled planet surface, it was found that a few very small surfaces would get random high fluxes. This was due to one ray from the planet hitting that

surface, and causing an artificially high form factor to that surface. Removing the planet from the nodes that emit rays not only cut the calculation time down by orders of magnitude, it also made the calculation much more accurate and repeatable. In this form, the space node should be set to whatever node used to define the radiative sky temperature. Both ground and sky node temperatures can be set in the model logic itself to constant values, or diurnal arrays, depending on the case. There is currently no flight or test data to support this method, but result checks look reasonable against hand-calculations as well as previous modeling methods.

VI. Near-Surface Natural Environment

Definition of the surrounding natural environment is an important factor to consider when performing near-surface thermal analysis. These environments include diurnal and yearly variation of air temperature, solar flux, and sky temperature. Currently, these data have been obtained for the primary launch site (Kennedy Space Center, FL) and the testing site for the launch abort system (White Sands Missile Range, NM). Once primary landing sites, as well as other testing sites, are determined, similar data can be obtained.

Air temperature data for both Kennedy Space Center (KSC) and White Sands Missile Range (WSMR) consist of hourly values, typically measured at a height of 10 m above ground level (AGL). The period of record (POR) for the KSC data is 1957 through 2002, while WSMR is 1947 through 1998. Diurnal profiles of air temperature were constructed by calculating the desired percentile level for each hour of each month. For hot cases, the 99th or 95th percentile diurnal profile for a hot month (June, July, etc.) can be chosen. Cold cases can be represented by either the 1st or 5th percentile profile from a cold month (December, January, etc). Figure 5 compares the 95th and 99th percentile diurnal profiles from July to the 50 hottest days in the KSC POR, and the 1st and 5th percentile diurnal profiles from January to the 50 coldest days in the KSC POR.

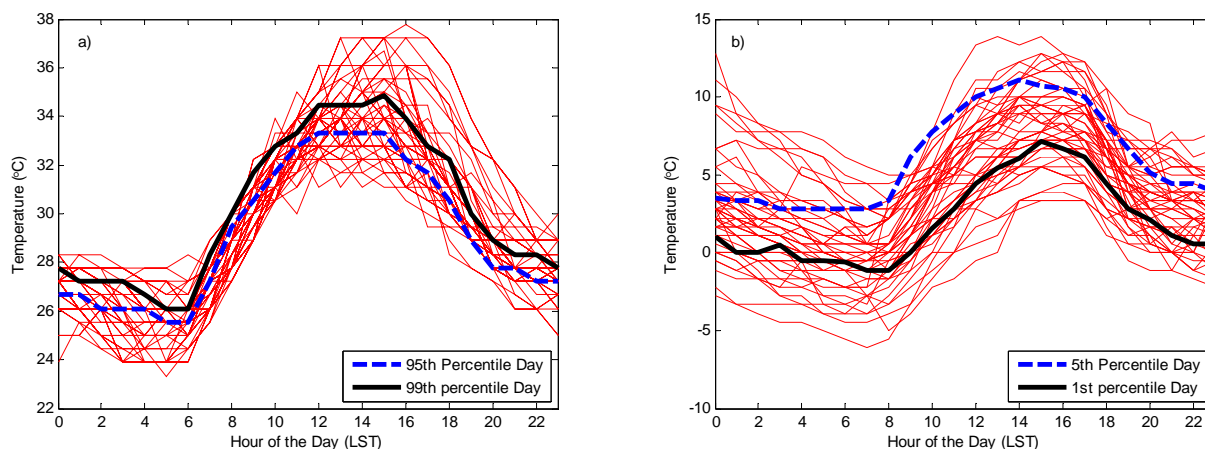


Figure 5: Comparison of a) the July KSC 95th and 99th percentile diurnal profiles to the 50 hottest days (in red) and b) the January KSC 1st and 5th percentile diurnal profiles to the 50 coldest days (in red).

The total solar radiation flux density, or solar insolation, to a horizontal surface is the combination of direct beam, which comes directly from the sun's disk, and diffuse, which comes from the whole sky, not including the sun's disk. Measuring devices usually detect the direct beam incident insolation and the total sky insolation (total horizontal). The direct beam incident insolation is to a surface normal to the sun vector. Diffuse insolation is determined by subtracting the vertical component of direct beam incident insolation from the total horizontal insolation. In the absence of measuring devices, solar insolation can be modeled through use of surface observations and/or satellite data. Solar insolation data for KSC and WSMR were obtained from the National Solar Radiation Database (NSRD), which provides modeled hourly values of direct beam incident, diffuse horizontal, and total horizontal insolation (NSRD data provided by the National Renewable Energy Laboratory, Golden, Colorado, USA, from their web site at http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/)⁴. The POR for the NSRD is 1991 through 2005. As with temperature, diurnal profiles of solar insolation were generated by calculating the desired percentile level for each hour of each month. To keep the direct incident, diffuse, and total horizontal insolutions correlated, the desired percentile level for the direct incident was first determined, and the corresponding values for diffuse and total horizontal for that particular direct incident value were recorded and then given the same percentile

level. This method allowed a consistency in the concept that days with high direct incident insolation will occur on clear days, and hence have little to no diffuse insolation. Likewise, days with cloudy conditions would have low direct incident, but high diffuse. Direct incident insolation was the anchor for this analysis since it is the most important component in the thermal models. Hot and cold cases can be represented by high and low percentile diurnal profiles, respectively. The highest 50 days of direct incident for July at KSC is shown in Figure 6, along with the July 95th percentile diurnal profile. The associated diffuse profile is also given.

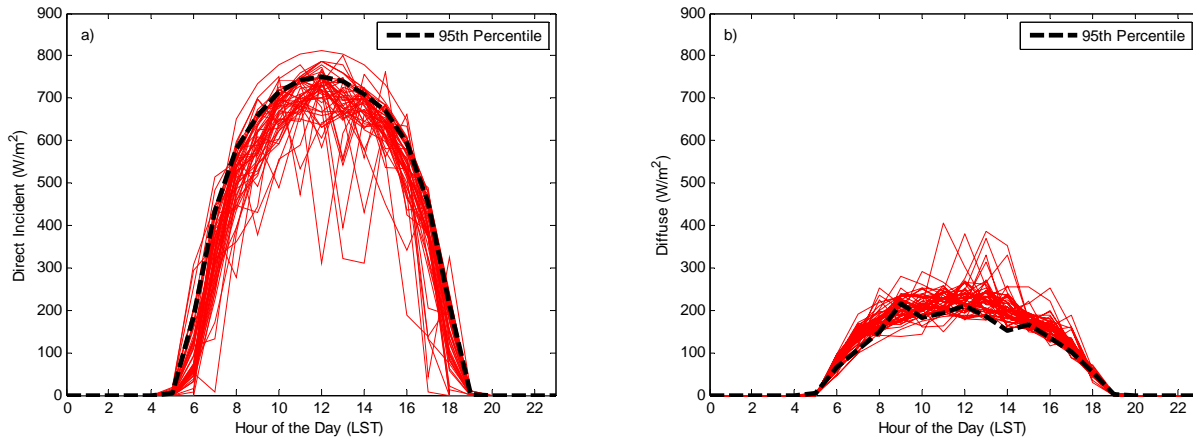


Figure 6: Comparison of a) the July highest 50 days of direct incident insolation at KSC (in red) to the July 95th percentile diurnal profile and b) the associated diffuse profiles.

Sky temperature is defined as the temperature the infinite sky would have if it radiated as a blackbody. When evaluated at the earth's surface, sky temperature includes emitted longwave radiation from the earth's atmosphere. Since clouds hold heat better than the clear sky, the sky temperature will be colder in clear sky conditions than in cloudy skies. Sky temperature data for KSC and WSMR were obtained from the North American Regional Re-analysis (NARR) database (POR 1979-2006), which contains 8 times a day values of downward longwave radiation at the earth's surface on an approximately 32 km grid surrounding the North American continent (NARR data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their web site at <http://www.cdc.noaa.gov/>)⁵. The longwave radiation was converted to temperature by use of the Stephan-Boltzmann law. Diurnal profiles of sky temperature were computed for each of the 8 daily values, per month, for a selected percentile level. Hot and cold cases are represented by high and low percentile profiles, respectively. The 95th and 99th percentile diurnal profiles from July are compared in Figure 7 to the 50 highest sky temperature days in the KSC POR, and the 1st and 5th percentile diurnal profiles from January are compared to the 50 lowest sky temperature days.

The analyses for air temperature, solar insolation, and sky temperature were done separately and there was no attempt to correlate them. Therefore, there may be some discrepancy in using case profiles for each of the environments. For example, the hot case air temperature profile may not correspond to the hot case solar insolation and sky temperature profiles. For Ares I-X, the hot case was considered a clear day and cloudy night. The hot case air temperature and solar insolation were used together, but the daytime values for the sky temperature hot case were reduced to better represent clear skies. Future work will include analyses to better define and illustrate the correlation between air temperature, solar insolation, and sky temperature for certain environments.

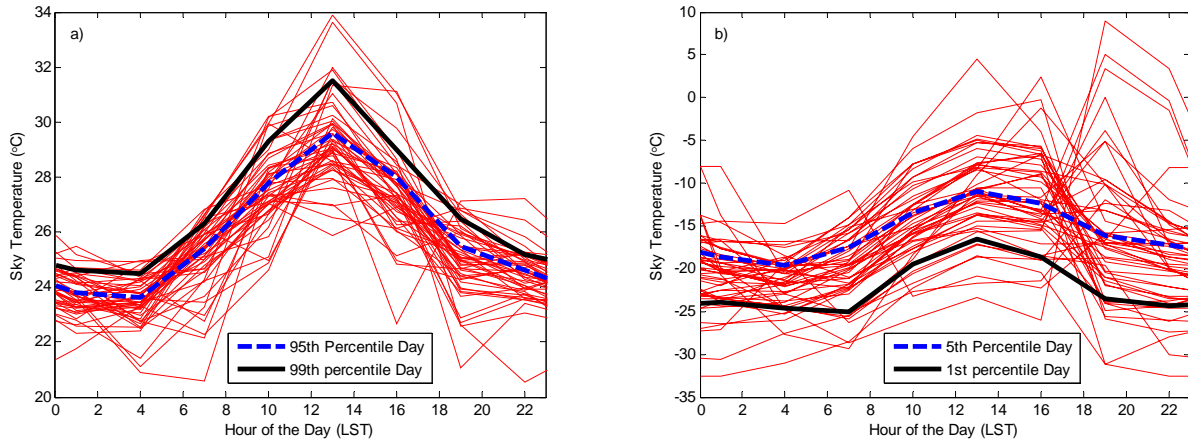


Figure 7: Comparison of a) the KSC July 95th and 99th percentile diurnal profiles to the 50 highest sky temperature days (in red) and b) the January 1st and 5th percentile diurnal profiles to the 50 lowest sky temperature days (in red).

VII. Parametric Study Results

When conducting an analysis, it is useful to understand how the size of the planet will affect the temperatures of the vehicle or facility being modeled. Performing detailed trade studies on planet size with a detailed vehicle model can be time consuming due to long solution times and the need to check multiple components or vehicle segment temperatures for each case. This task becomes even more time consuming in cases where the vehicle or facility has a measurable effect on planet surface temperatures, which in turn affects temperatures on the vehicle. In order to make this process more efficient, a simple tool was developed which assists the analyst in determining up front the minimum planet size required in the analysis, and perhaps more importantly, the relative effects of all environmental loading on the vehicle. This information immediately shows the analyst which boundary conditions require the most attention in the detailed model.

The extent that the planet surface will affect the temperature of the vehicle (or facility) being modeled depends on the local environment, the profile of the vehicle, and the size of the planet. It is important to note that view factor alone should not be used to determine the size of the planet, since other environmental or artificial loads such as external convection or internal air conditioning may be the dominant modes of heat transfer. For situations where it is obvious that vehicle effects on the planet are negligible, a very simple model (< 5 thermal nodes) can provide relative environmental effects versus planet size that will closely match trades performed in a detailed model.

A graphical description of the ground-plane sizing tool is provided in Figure 8. Thermal Desktop was used to create a model consisting of a cylinder with two caps (discs) to represent the outer surface profile of the vehicle, and a circular disk to represent the planet. The geometric model of the vehicle contains three nodes for radiation calculations; however correspondence data is used to assign these to a single node in the thermal math model (SINDA). This approach effectively provides only one node that needs to be considered while performing trades. This single node is defined as arithmetic so that steady state analyses can be performed without requiring information on vehicle mass or materials. The planet surface contains only one node for both radiation and thermal calculations. Two separate boundary nodes also exist to model the air temperature and the surrounding radiation sink temperature (not shown).

All environmental loading and boundary conditions that will be applied to the detailed model should be applied to the simple vehicle model, and they should be applied and calculated in the same manner. In general, the loads and boundary conditions that should be considered include direct solar, diffuse solar, albedo, planet IR, external convection, planet surface temperature, air temperature, and radiation sink temperature. Depending on the situation, other considerations may include internal environmental control or total internal heat load, both of which could be simulated using a heat load applied to the vehicle with either a negative or positive value. Once these considerations have been included in the model, the relative steady state transfer of heat from the vehicle to the surroundings can be plotted versus planet diameter.

A simple steady state analysis was performed using the model described above. Environmental loads were similar to 99% worst case hot conditions for Kennedy Space Center. Solar angle information was calculated assuming the local time is 11:00 am during the month of April. Optical properties for the ground were typical of a Kennedy launch site, and optical properties of the vehicle were typical of common white paints. Descriptions of all model parameters and the values used for this study are provided in Table 1.

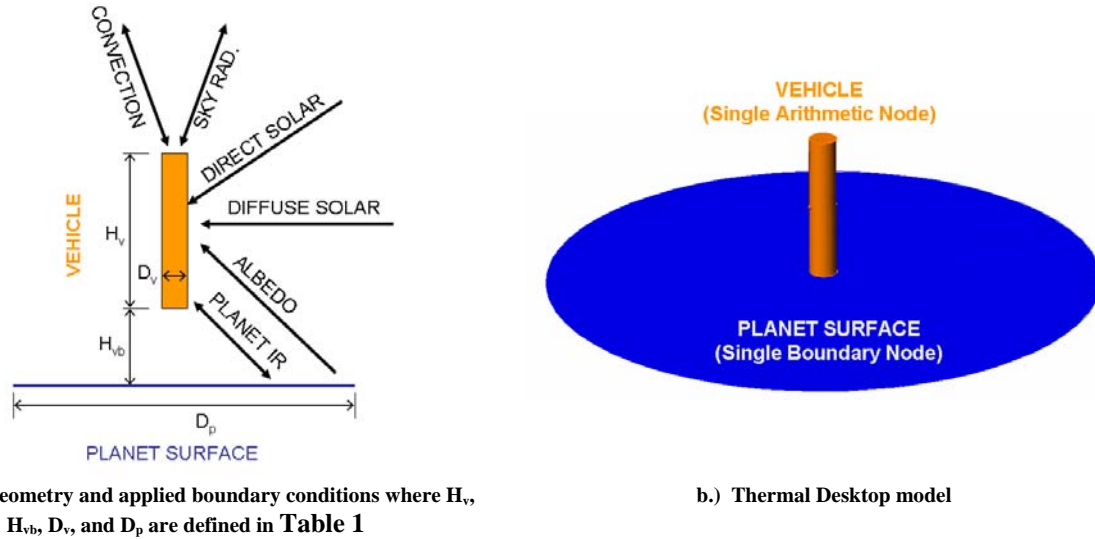


Figure 8: Description of ground-plane-sizing tool for the case when vehicle effects on the planet are negligible.

Table 1: Parameters Used in Ground-plane Sizing Tool

Parameter [Units]	Description	Test Case Value
D_v [m]	Diameter of the vehicle	5
D_p [m]	Diameter of the planet	Independent Variable (10-5000)
H_v [m]	Height of the vehicle	100
H_{vb} [m]	Height of the vehicle base above the planet surface	5
T_v [°C]	Temperature of the vehicle	Calculated by analysis
T_p [°C]	Temperature of the planet	34
T_{air} [°C]	External air temperature	34
T_{sky} [°C]	Radiation sink temperature	15
h_{air} [W/m ² K]	Convection Coefficient	Free vertical cylinder correlation
ϵ_v	IR emissivity of the vehicle	0.85
α_v	Solar absorptivity of the vehicle	0.3
ϵ_p	IR emissivity of the planet	0.88
α_p	Solar absorptivity of the planet	0.7
Q_{solar} [W/m ²]	Direct solar heat rate	840
Q_{albedo} [W/m ²]	Albedo heat rate	244 (or 0.29)
$Q_{diffuse}$ [W/m ²]	Diffuse solar heating	132

The results of the study described above are shown in Figure 9. The results in this plot show the relative heat transfer for each mode versus the ratio of planet diameter to vehicle diameter (D_p/D_v). Heat transfer absorbed by the vehicle is defined as being positive; relative heat transfer is defined as the heat transfer by each environmental mode divided by the total heat absorbed by the vehicle, which for steady state is equal to the total heat leaving the vehicle. Also provided is the calculated steady state temperature of the vehicle for each planet/vehicle diameter ratio (T_v). With increasing planet diameter, view to the space node is blocked which decreases heat transfer to space, and increases IR exchange with the planet. Although the absolute amount of direct solar and albedo heating remain constant, the diffuse value changes since it is calculated as a heating rate based on the vehicle's view factor to space (section V). This effect causes the relative solar loading to adjust as the planet size is increased. Interestingly for this case, the calculated vehicle temperature remains basically unchanged for diameter ratios of 2 through 1000,

although the relative effects of each heat transfer mode change considerably. A diameter of 100 or greater would likely be sufficient for this scenario.

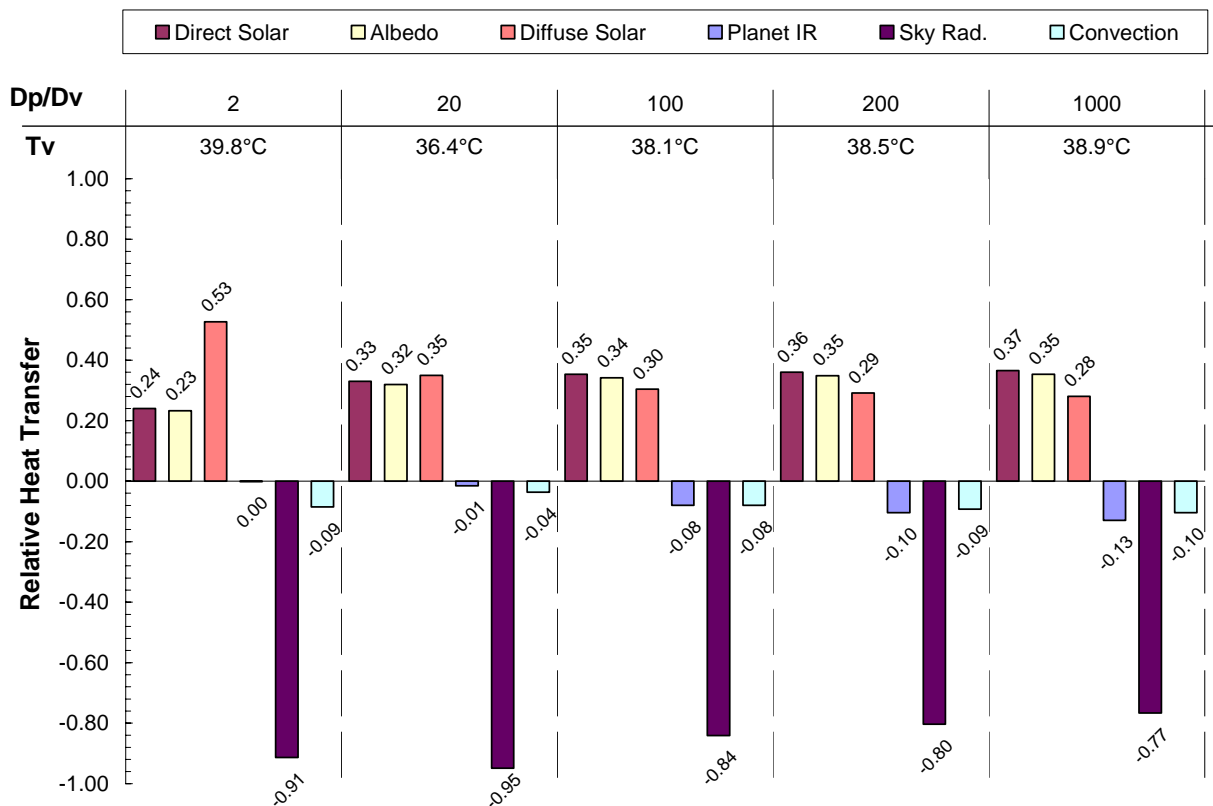


Figure 9: Relative heat transfer versus planet/vehicle diameter ratio for the inputs described in Table 1.

Some items of interest that might be unexpected can be observed in Figure 9. In this scenario, diffuse solar has nearly the same impact as direct solar even though its absolute flux value is much lower. Radiation to the sky temperature has much more impact than convection or radiation to the planet. These effective values will be different for hot cases versus cold cases, and at various time points in the day, but these plots can be a very useful tool to show the analyst which inputs have the most impact and thus are most worthwhile to estimate correctly.

This simple tool, which assumes the ground-plane temperature is fixed, can be used to determine the required ground-plane size for situations where the vehicle's effects on the ground are deemed significant. Since the tool only contains one node to represent the vehicle, the average vehicle temperature is calculated in the analysis. Ground-plane temperature gradients have the most noticeable effects on smaller vehicle sub-components that may be shaded from direct solar, as can be seen with the thruster nozzles shown in Figure 1. Average vehicle temperatures are not significantly affected by variations in temperature on the ground plane. For this reason the full effects of the vehicle-ground plane interaction are not apparent using such a simplified vehicle representation. However, the simple model can help with determining the minimum amount of nodalization and area around the vehicle where the ground plane effects are most important. Outside of this area, the rest of the ground plane can be modeled with surfaces with much less nodalization to help keep run times down.

A description of the tool developed to capture the minimum ground plane area requiring detailed nodalization is shown in Figure 10. In this model, the ground plane is rectangular, and broken into two sections; the inner section is sized to capture the shadowing and solar reflection effects on the surface, and the outer section is sized in the same manner as in the previous tool. The solution procedure for these cases is to first determine the size of the inner surface diameter (D_s) and the level of nodalization required to capture the ground plane temperature gradients to the desired resolution. The second step is to then size the remainder of the planet (D_p) and produce a chart like the one shown in Figure 9. It is important to note that for transient cases, the size of the inner section required will depend on time of day. A detailed study of the variation of the solar vector during the course of a day needs to be done before choosing D_s for cases that will be run transiently.

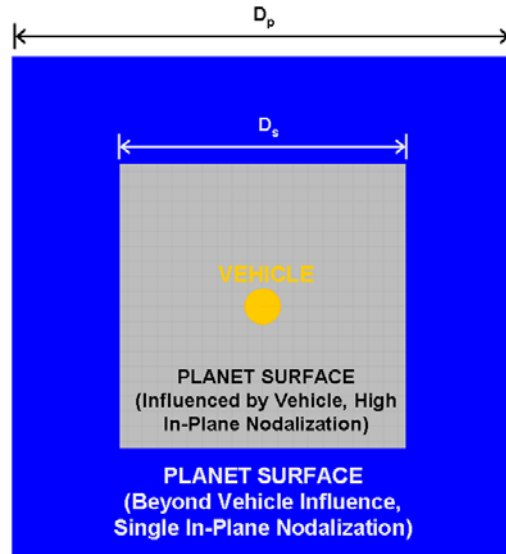


Figure 10: Ground-sizing tool for cases where vehicle-ground interaction is important

An example sizing study assuming a lunar environment is shown in Figure 11. Note that this is only applicable for this particular time of the lunar day, and will change depending on solar angle. As the nodalization is increased, the shadow and re-radiation areas become more defined, and the effective area of the inner region can be reduced. If there are small, lightweight vehicle components near the ground-plane temperature gradients, the shadows should be highly resolved. Average vehicle temperatures are not significantly affected between cases a.) and c.) shown in Figure 11 since the average temperature in the gradient regions are balanced by the relative sizes of the regions. In the detailed model however, small structures and components will be affected differently by the different shadow regions shown.

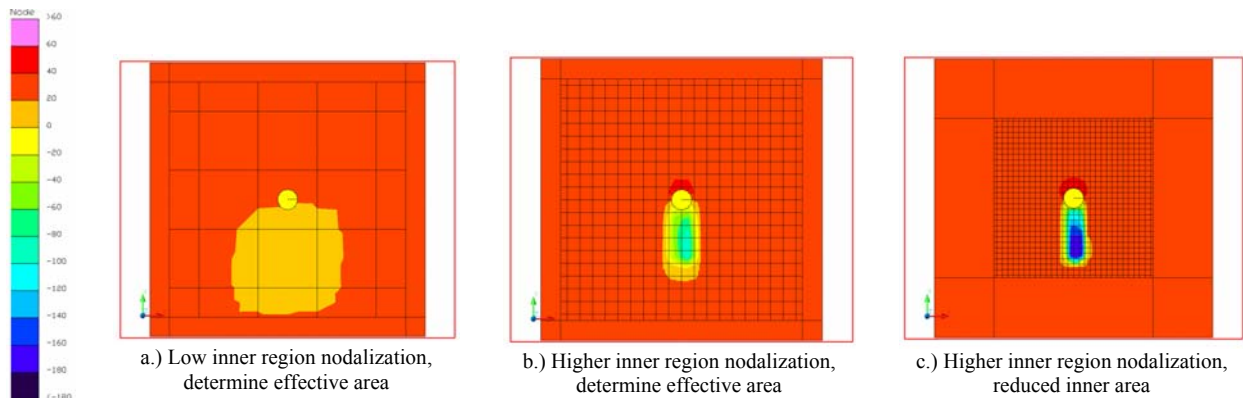


Figure 11: Resolving the shadowing/re-radiation area for the case where vehicle temperatures have an effect on the ground-plane surface. Temperatures in °C.

VIII. Conclusion

The information provided here describes the techniques that are being employed for the thermal modeling of near-surface environmental effects on the Constellation projects. There is currently no flight or test data to support these methods, but the results seem reasonable when compared to hand-calculations and previous modeling methods. The capabilities of modern thermal software tools and the availability of extensive natural environment data allow for techniques that may be well beyond the ground environmental modeling done for previous programs. The approaches described here are intended to improve the ground-modeling capability, but without causing undue computational burden to unnecessarily slow down the analysis process. The desire of the Constellation project

thermal engineers is to compare measured ground data to predicted results as the opportunities arise in the future (e.g., Pad Abort testing at White Sands, Ares I-X demonstration flight from KSC, etc.). As this ground data becomes available and as future refinement on the correlation between the environmental parameters is completed, these modeling techniques will continually be evaluated and improved as necessary.

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