THERMAL ORBITAL ENVIRONMENTAL PARAMETER STUDY ON THE PROPULSIVE SMALL EXPENDABLE DEPLOYER SYSTEM (PROSEDS) USING EARTH RADIATION BUDGET EXPERIMENT (ERBE) DATA

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ABSTRACT:

The natural thermal environmental parameters used on the Space Station Program (SSP 30425) were generated by the Space Environmental Effects Branch at NASA's Marshall Space Flight Center (MSFC) utilizing extensive data from the Earth Radiation Budget Experiment (ERBE), a series of satellites which measured low earth orbit (LEO) albedo and outgoing long-wave radiation. Later, this temporal data was presented as a function of averaging times and orbital inclination for use by thermal engineers in NASA Technical Memorandum TM 4527. The data was not presented in a fashion readily usable by thermal engineering modeling tools and required knowledge of the thermal time constants and infra-red versus solar spectrum sensitivity of the hardware being analyzed to be used properly. Another TM was recently issued as a guideline for utilizing these environments (NASA/TM-2001-211221) with more insight into the utilization by thermal analysts. This paper gives a top-level overview of the environmental parameters presented in the TM and a study of the effects of implementing these environments on an ongoing MSFC project, the Propulsive Small Expendable Deployer System (ProSEDS), compared to conventional orbital parameters that had been historically used.

INTRODUCTION:

The Earth Radiation Budget Experiment (ERBE) consisted of the Earth Radiation Budget Satellite (ERBS) launched in 1984 and instruments on two National Oceanic and Atmospheric Administration weather monitoring satellites, NOAA 9 and NOAA 10 launch in 1984 and 1986. The instruments on these platforms provided a total of 28 months of 16-second resolution wide-field data for solar radiation, albedo, and earth outgoing longwave radiation (OLR). This data, compiled by Langley Research Center, was statistically analyzed by the Space Environmental Effects Branch at NASA's Marshall Space Flight Center (MSFC) to provide temporal based environments data for the International Space Station (ISS) [Reference 1]. Of specific concern with using previous standard environmental parameters were the large area, low thermal capacitance thermal radiators on ISS.

This data was then compiled in a more general, but similar fashion in TM-4527 as a function of percentiles versus averaging time. An example of the tabular data from TM 4527 is shown in graphical form in Figure 1 [Reference 2] which illustrates the albedo and OLR for 0-30°

inclination low earth orbit as a function of "averaging time", which is intended to be analogous to thermal time constant. The averaging times ranged from the 16-second raw data interval to the full orbital period of the ERBE platforms of 5400-seconds. Additionally, this data revealed an significant dependence of solar zenith angle (e.g., angle between the Earth center-satellite vector and the Earth center-sun vector) on albedo, so this effect was normalized out of the data and treated as a "correction" term to be added to the value illustrated in Figure 1. The solar zenith angle correction in albedo is illustrated in Figure 2. The guideline also provided plots of albedo/OLR pairs to illustrate the relative magnitude of one parameter versus the other such as illustrated in Figure 3. The negative slope of the data in Figure 3 shows the general trend that as OLR increases, albedo decreases as many analysts have assumed, but since the plot is not a straight line, this plot also reveals that median values of OLR can accompany high albedo values and median albedo values can accompany high OLR values. All this new data proved to be of general interest to the thermal analyst but ambiguous for the thermal engineers attempting to implement these thermal environments in standard thermal analysis software.

A more recent NASA TM-2001-211221 entitled "Guidelines for the Selection of Near-Earth Thermal Environmental Parameters for Spacecraft Design" [Reference 3] has been published which provides updates to the previously published data as well as more guidance

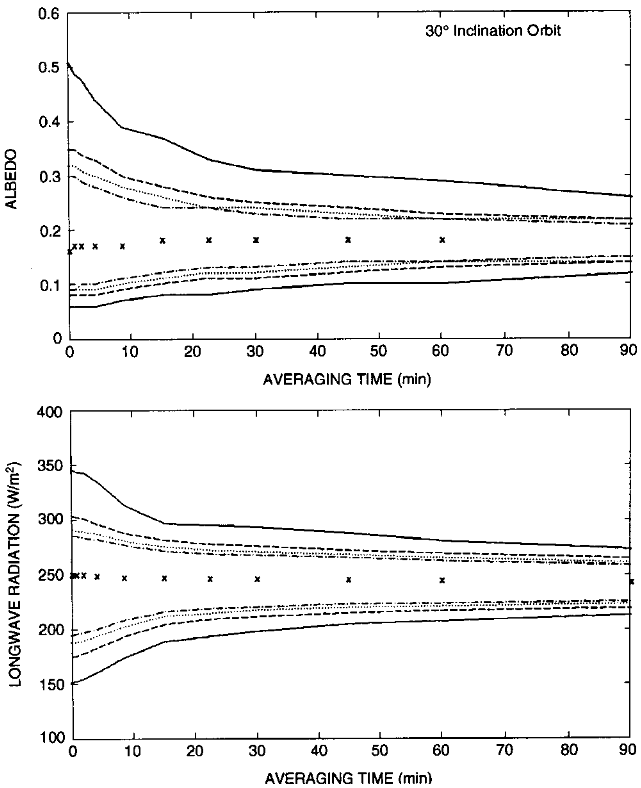


Figure 1: 30° Inclination TM 4527 Albedo and OLR Data

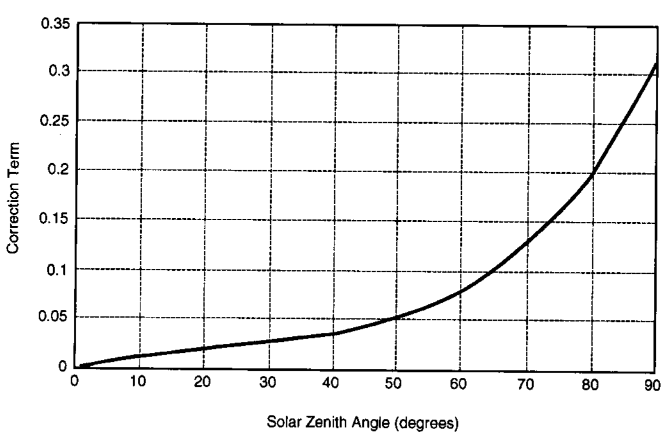


Figure 2: Solar Zenith Angle Albedo Correction Term

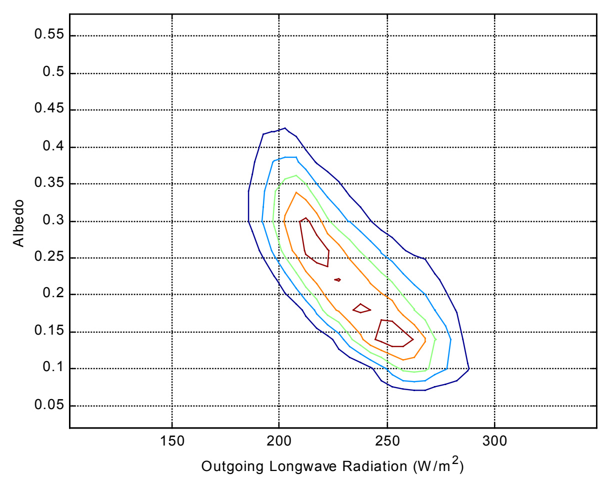


Figure 3: Albedo/OLR Pairing for 128-Second Averaging Time

for implementing these environments by the thermal analyst. For example, the solar zenith albedo correction term is provided as a function of "beta angle", which is more readily utilized by the analyst. A more rigorous analysis of the data for determining the interdependence of the albedo and OLR for a particular orbit is provided. The maximum averaging time is increased from one LEO period of 5400-seconds to 24 hours to accommodate longer thermal time constant systems. Lastly, more guidance is provided for determining "worst case" orbital parameters and addresses the risk of utilizing 5th and 95th percentile data that had been included in the previous publications.

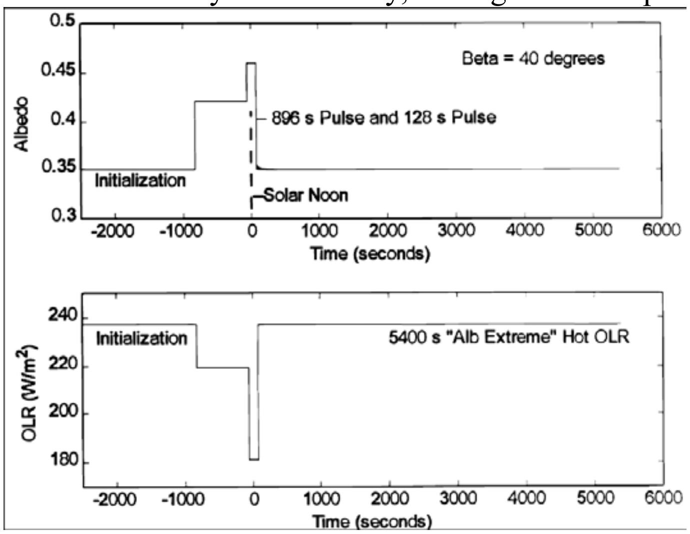


Figure 4: Example Hot Case Orbital Environment

The recommendation for implementation of this data is to impose a long averaging time thermal environment with "pulses" of shorter time constant environments based on the particular hardware being analyzed. An example, for a payload that is most sensitive to solar wavelength environmental heating to 896-second and 128-second spikes in the environment, a potential hot case albedo heating profile with albedo and corresponding OLR 896-second and 128-second "pulses" is illustrated in Figure 4 [Reference 3].

The addition of "pulses" to the analysts orbital calculations adds complexity, time and cost to the design/analysis phase. In cases where an intuitively sensitive component must be analyzed, the added complication of assessing short-duration "spikes" for environmental parameters is prudent (such as the case with the ISS thermal radiators). However, for many applications, it isn't immediately apparent whether implementing this data is worth the added effort and whether it will cause a hotter or colder extreme analysis predictions that would otherwise be unknown utilizing typical global averaged environmental constants as has been historically done in thermal orbital heating assessments.

This paper provides a comparison of orbital heating results utilizing this methodology compared to typical worst-case parameters utilized within NASA (hereafter referred to as the NASA "baseline" case). The case study utilizes thermal modeling of the ProSEDS instrument panel hardware. The ProSEDS is a secondary payload attached to the Boeing Delta II Second Stage as shown in Figure 5. ProSEDS is a MSFC space experiment intended to demonstrate the use of an electro-dynamic tether propulsion system to generate thrust in space by decreasing the orbital altitude of a Delta II Expendable Launch Vehicle second stage. ProSEDS, which is planned to fly in late 2002. ProSEDS will deploy a tether [5km (3.1mi) bare wire plus 10km (6.2mi) spectral wire] from a Delta II second stage to achieve ~0.4N (~0.09 lb_f) drag thrust. The instrument panel hardware (shown in Figure 6) consists of seven electronics boxes (two batteries, transmitter, power distribution, plasma contactor, and control electronics for two strut-mounted probes).

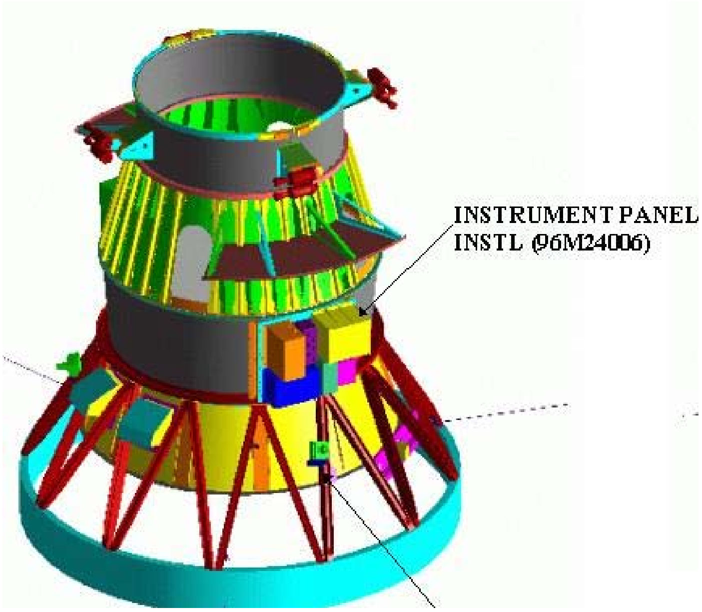


Figure 5: ProSEDS Mounted to Second Stage of Delta II.

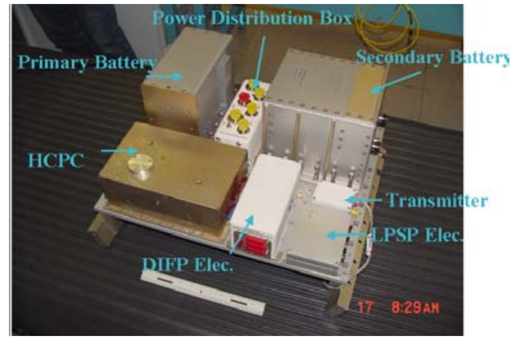


Figure 6: ProSEDS Instrument Panel Hardware.

The ProSEDS was chosen since the hardware is externally mounted and the thermal control system is entirely passive. This represents a more thermally sensitive payload than many spacecraft or payloads since no heater power or active thermal control measures were available. Typically, electronics are mounted internal to a bus cavity and mounted to externally viewing radiators or utilize active means, such as heat pipes or pumped cooling loops to maintain temperatures. Therefore, these more typical cases are less directly coupled to the orbital heating environment. This ProSEDS model will provide an example of the effects of implementing the NASA TM-2001-211221 environments that, although not as sensitive as large area to mass ratio components such as solar arrays or thermal radiators, represents a reasonably sensitive system.

THERMAL MODEL DESCRIPTION:

The thermal modeling of the ProSEDS instrument panel hardware was constructed in Thermal Desktop version 4.4. The Delta Second Stage is modeled in order to provide reasonable boundary conditions to the ProSEDS. The instrument panel hardware are coated with a variety of thermal control coatings that were either dictated by the electrical surface conductivity requirements (such as alodine for the plasma contactor) or were chosen to provide a reasonable hot to cold temperature swing for the components based on the design analyses results. The coatings are shown in Figure 7 and the corresponding as-measured thermo-optical properties are shown in Table 1.

In order to simplify this assessment of environments, only one power configuration was utilized for ProSEDs and an earth oriented orbital attitude was utilized. For the actual flight, the orbit and the power dissipation profile vary, but the intent of this study is only to analyze earth environment assumption effects on a realistic payload, but not to provide predictions for the actual ProSEDS payload.

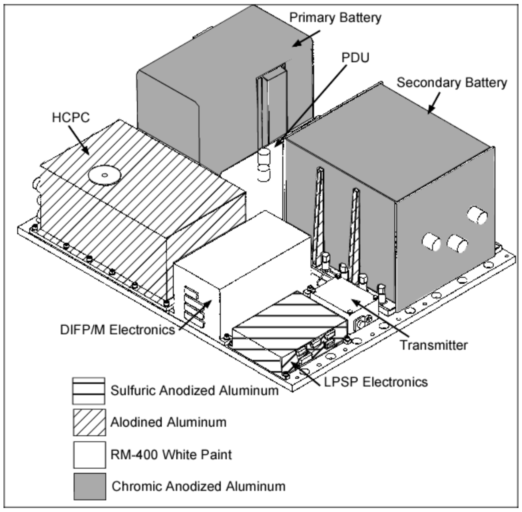


Figure 7: Instrument Panel Thermal Coatings

COMPONENT	EXTERIOR FINISH	SOLAR ABSORPTANCE	HEMISPHERICAL EMITTANCE
Delta Guidance Skin	White Paint	0.30	0.90
Delta Struts and Aft Skirts	Green Primer	0.80	0.887
Delta Longerons	Alodine Al.	.389	0.143
Delta Fairing	Per MDC 99H0013A	N/A	0.25
DIFP-M Electronics	RM-400 White Paint	0.317	0.892
HCPC	Alodine Al.	0.39	0.14
Shield Top		.439	.124
Shield Cathode Face		.454	.25
Shield Side toward DIPFM		.446	.19
Shield Side toward Primary Battery		.446	.148
LPSP Electronics	Anodized Al	0.377	.798
PDB	RM-400 White Paint	0.317	0.892
Primary Battery	Anodized Al	0.44	0.56
Cover		.39	.447
Ends		.345	.161
Stud Cover		.363	0.60
Secondary Battery	Anodized Al	0.32	0.70
Sides		.391	.704
Top Cover		.397	.422
Top Bracket	Alodine Al.	.391	.107
Transmitter	RM-400 White Paint	0.317	0.892
Instrument Panel	Anodized Al.	0.471	0.529
Cable Metal Braid Wrap		0.55	0.30
Permacel® 213XI Tape		0.37	0.90

Table 1: Instrument Panel Measured Thermo-Optical Properties

THERMAL ENVIRONMENTS:

The thermal environmental parameters that have been historically used at MSFC are derived from worst-case extreme parameters with the assumption that worst case albedo can simultaneously occur with worst case OLR. Many companies will couple worst case extreme albedo with minimum OLR and vice versa due to the assumption that high albedo environments in general occur due to highly reflective cloud cover, which causes the OLR to be attenuated and of lower magnitude (and vice versa for high OLR). For this assessment, the thermal environments more conservatively couple the worst-case albedo and OLR together for the hot and cold cases and represents an example case (NASA baseline) that can be compared to the NASA TM-2001-211221 environments (see table 2).

Environmental Parameter	NASA Typical Values	
	Hot	Cold
Solar Constant (W/m^2)	1419.1	1286.7
Albedo	0.35	0.25
Outgoing Longwave Radiation (OLR) - (W/m^2)	264.9	208.1

Table 2: Typical Global Orbital Environmental Parameters

Utilizing NASA TM-2001-211221, the solar constant ranges between 1419 W/m^2 and 1317 W/m^2. For the ProSEDS, given the orbital inclination of 39° falling into the 30-60° medium inclination orbit, the OLR and albedo environments would be determined from Table 4.2.3-2 of the TM, which is duplicated as Table 3 herein. Unlike previous publications of this data, the data includes a "Combined Minimum" and "Combined Maximum" intended to represent

an environment for a payload that may be more sensitive to a median albedo/OLR pair as opposed to an extreme albedo
or OLR case. The solar zenith albedo correction varies depending on the Beta angle case. Beta angles of 0°, 30°, and 60° were assessed in this study.

β Angle	Orbit Average Solar Zenith Albedo Correction	128-sec Max from Solar Noon SZA Correction	896-sec Max from Solar Noon SZA Correction
0°	0.04	0.01	0.03
30°	0.06	0.03	0.04
60°	0.12	0.08	0.10

Table 4: Albedo Correction Versus Beta Angle and Averaging Time

As shown in Table 4, the solar zenith angle (SZA) albedo correction increases with Beta Angle and for cases where smaller averaging time "pulses" are imposed near solar noon, the correction factor is smaller for that time slice since the highest SZA occurs near the orbital entry/exit.

The ProSEDS components which have a high solar-absorptance to hemispherical-emittance ratio (such as alodined aluminum) are likely influenced mainly by direct solar and albedo, whereas the white painted electronics are likely more OLR driven. In order to determine if albedo, OLR or a combined case is most extreme, all three possibilities are assessed for comparison.

ANALYTICAL APPROACH:

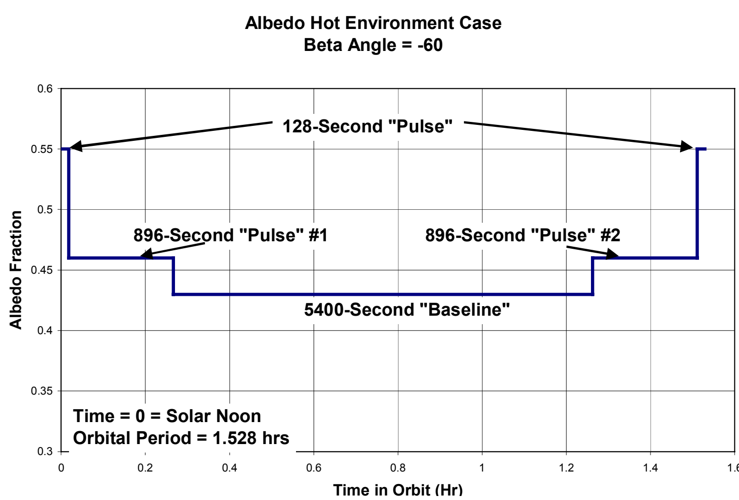


Figure 8: Example Orbital Profile for Hot Beta=-60 Albedo Case

The analytical approach is to assess an actual payload with the NASA TM-2001-211221 data and compare the results to a more historical environmental heating calculation approach. For brevity, only a hot case is compared in this assessment. Also, it is assumed that no ProSEDS component is susceptible to the very rapid 16-second pulse data, so the timeline utilized for the comparison assessment consists of a 128-second "pulse" centered at solar noon, preceded and followed by a 896-second "pulse" with the 5400-second data as the baseline or background orbital environment for the remainder of the orbit. An example of this is illustrated in Figure 8 for the hot case albedo extreme at β = -60. No real guidance is given in the TM concerning the proper number of pulses and the combination of pulse durations that are appropriate. The ERBE data reveals that these pulses occur randomly and can be repeated multiple times during an orbit [Reference 4], so the analyst has a lot of latitude in selecting the appropriate orbital profile to run. The profile chosen for this study is intended to be a representative case, but not an exhaustive assessment of the appropriate assumptions for the actual ProSEDS hardware.

In order to ensure these discrete transitions in orbital heating rates can be applied properly in Thermal Desktop, a flat plate model will be utilized to verify the incident flux calculations and the proper transition between the "pulses". The pulses are generated in a similar fashion to the method for handling eclipse transitions (i.e., orbital positions were defined immediately prior to and immediately after the pulse, so that the heat flux arrays included the abrupt step change in environments and did not "smear" the pulses). Once successfully implemented on the flat plate, these same orbital heating orbital positions (29 user-defined positions defining the pulses) and albedo/OLR versus time arrays were utilized in the ProSEDS instrument panel Thermal Desktop model.

The final comparison between the NASA baseline heating case and the TM-based cases is made between the maximum steady-state temperature results and the transient maximum temperature results for the various ProSEDS components. The steady-state compares the effect of the orbital averaged heating rates, while the transient results reveal whether the short term pulses induce larger discrepancies in the resulting temperatures.

ANALYSIS RESULTS:

Figure 9 illustrates the successful implementation of the discrete environmental "pulses" in Thermal Desktop for the β=-60º incident OLR energy to the earth oriented unity-area flat plate at the ProSEDS altitude. The orbital averaged incident flux from albedo and OLR for the three hot cases utilizing NASA TM-2001-211221 and the NASA baseline case at β=0º, -30º, and -60º are compared for the flat plate in Figure 10. This figure reveals that the OLR case gives the highest total incident flux. The NASA baseline hot case was not as severe a total incident flux compared to the high OLR case, but was very close to the "combined" albedo/OLR case. As expected, the albedo increases as β angle nears 0º. Also, the discrepancy in the total incident flux between the cases decreases as β angles decrease. At β =0º, the total incident albedo/OLR vary only 6% between highest/lowest case and only 1.8% between the highest case and the NASA "Baseline" case.

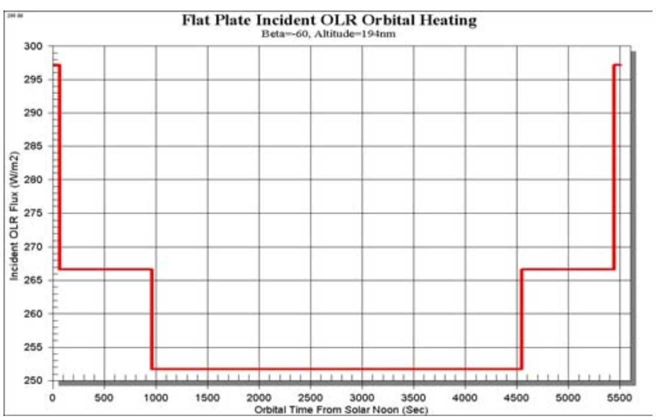
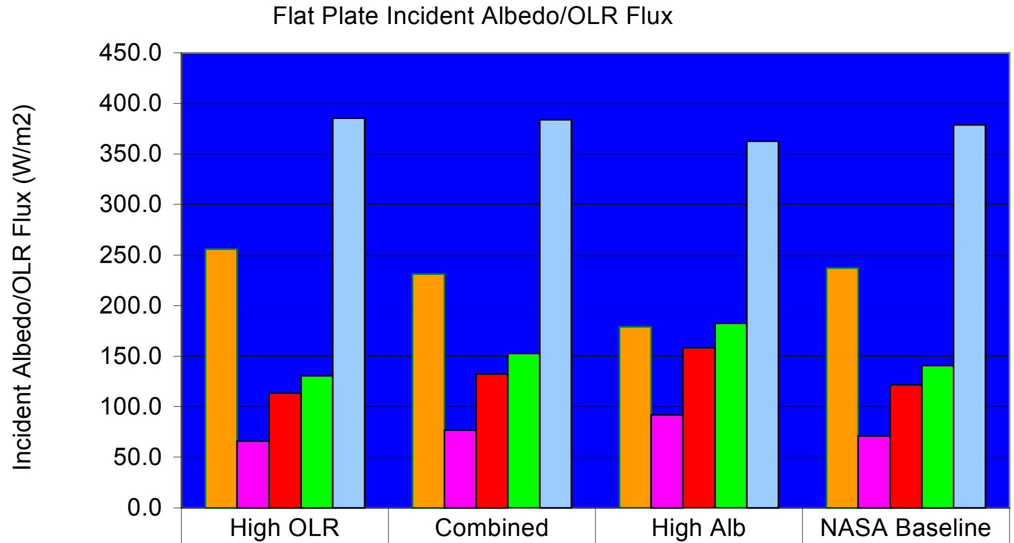


Figure 9: Flat Plate Incident OLR Flux Versus Orbit Time

Utilizing the ProSEDS instrument panel thermal mathematical models and the same orbital heating parameters as for the flat plate study, temperatures were generated for steady-state using orbital average heating rates followed by 8-hours of transient heating. The steady-state difference in results between the NASA baseline case and the three hot β=-60° cases, three hot β=-30° cases, and



	High OLR	Combined	High Alb	NASA Baseline
OLR (W/m2)	255.8	231.3	178.9	237.1
Beta=-60 Albedo (W/m2)	66.0	77.0	91.9	70.9
Beta=-30 Albedo	113.6	132.3	158.4	121.8
Beta=0 Albedo	130.7	152.9	182.6	140.7
Beta=0 Total Albedo/OLR	385.6	383.8	362.8	378.6

Figure 10: Flat Plate Incident Albedo/OLR for Each Environment Case

three hot β=0° cases for all the ProSEDS electronics are illustrated in Figure 11. The results reveal that all cases are hotter than the NASA baseline (by a minimum of 1°C) with a maximum difference of 10.1°C for the β=-30° high albedo case. For the β=-30° high albedo case, the smallest difference is 6.6°C, revealing that all the components (or more appropriately the instrument panel as a subsystem) are highly effected compared to the baseline case. The combined cases are, as a category, the closest to the NASA baseline (a maximum difference of 2.8°C for any β angle on any ProSEDS component).

Next, the transient results are compared in Figure 12. Most of the transient results have a smaller temperature differences than the steady-state cases and the difference is actually negative in the case of the β=-60° high albedo results. This reveals that the time constant of the components/system is larger than the duration of the environmental pulses, so the system doesn't fully react to the pulses during the transient simulation as, in effect, happens in the steady-state simulation.

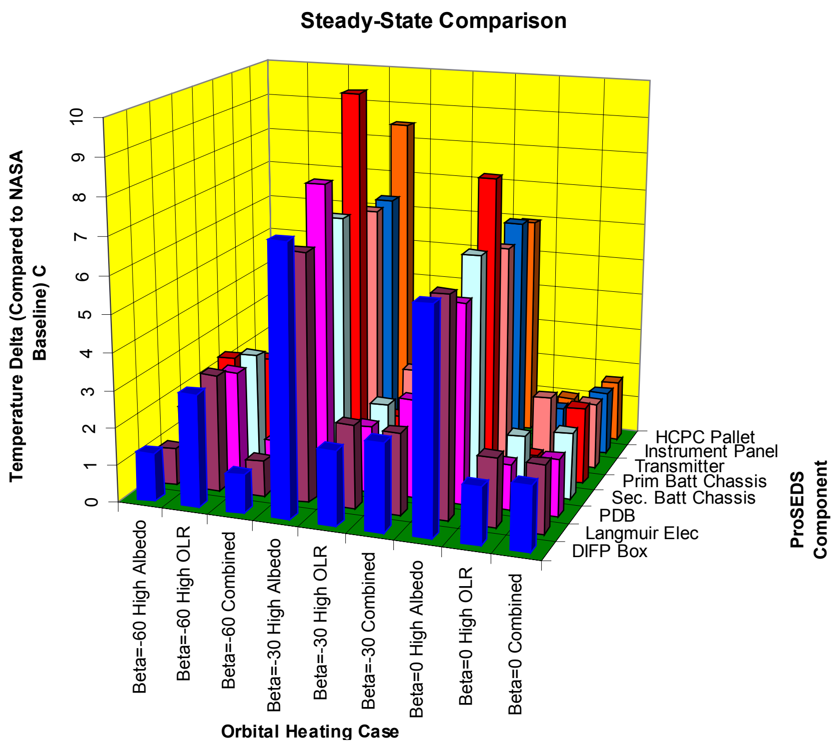


Figure 11: Steady-State Temperature Difference Between NASA Baseline and TM Cases

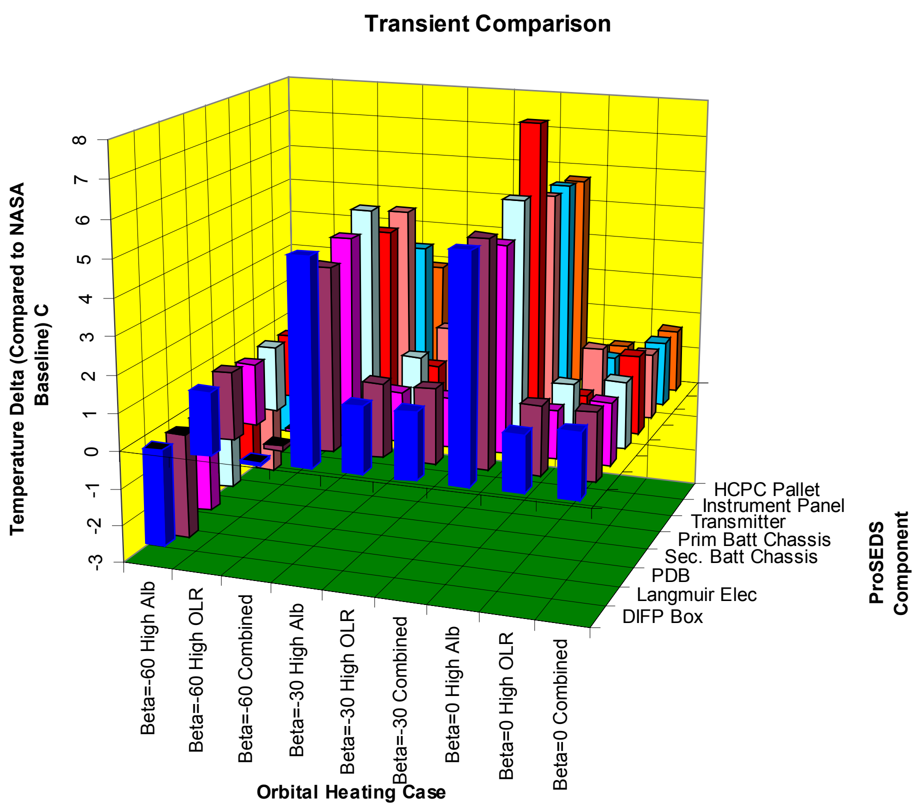


Figure 12: Transient Temperature Difference Between NASA Baseline and TM Cases

CONCLUSIONS:

The ERBE-based data published in various documents gives the thermal analyst much more insight into the thermal environmental parameters and the temporal nature of the albedo and OLR. For example, the data shows that the assumption that the highest OLR should be paired with the lowest albedo and vice versa is not necessarily conservative in that realistically, median values can be paired instead of minimums (as shown in Figure 3). Also the albedo increase at high solar zenith angles is illustrated and could be of particular significance in analyzing polar orbiting satellites. However, the implementation of the data into standard thermal analysis software is cumbersome and open to interpretation. Many potential additional analysis cases are involved and the determination of how many pulses and which averaging times to utilize is ambiguous.

Despite the added effort in assessing a satellite/payload with these orbital parameters, the ProSEDS example case reveals that the discrepancy could be significant for some hardware. ProSEDS is a fairly sensitive payload to the short term environmental variations, but is certainly not an extreme case. Even though the high albedo was paired with the high OLR for the NASA baseline, all but one of the nine TM-based cases resulted in higher temperature predictions. In fact, a difference of as much as 10.1°C was found, which would be as much or more than the thermal test margin for many programs.

It is recommended that the thermal analyst consult NASA TM-2001-211221, especially for intuitively sensitive hardware (e.g., high area-to-thermal capacitance ratio hardware or high solar absorptance-to-hemispherical emittance ratio hardware). For programs that impose previous publications of this ERBE-based data as an applicable document, caution should be taken to ensure appropriate implementation of the data. An example are the "percentiles" for the data in previous publications that lead the analyst to consider 95% hot albedo as having only a 5% chance of being exceeded and perhaps a reasonably conservative environment to utilize; however, as the newer guideline discusses, the percentile is relative to the averaging time. In other words, for a 90-minute averaging time, the 95% percentile data has a 5% frequency of occurrence of being exceeded, which would occur every 1.25 days on average. So for a full mission timeframe, such as a 14-day shuttle mission or a 5-year satellite mission, this value will very likely be exceeded many times according to the ERBE data.

ACRONYMS:

Alb	Albedo
DIFP	Differential Ion Flux Probe
ERBE	Earth Radiation Budget Experiment
HCPC	Hollow Cathode Plasma Contactor
ISS	International Space Station
LEO	Low Earth Orbit
LPSP	Langmuir Probe Spacecraft Potential
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
OLR	Outgoing Longwave Radiation
PDB	Power Distribution Box
Prim	Primary
ProSEDS	Propulsive Small Expendable Deployer System
Sec	Secondary
TM	Technical Memorandum
β	Beta Angle

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