

USING THERMAL DESKTOP TO DETERMINE EQUIVALENT SOLAR HOURS ON SPACECRAFT SURFACES

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ABSTRACT

Equivalent solar hours (ESH) are the duration of exposure of a surface to solar radiation, particularly ultraviolet (UV) radiation. Since UV light causes degradation to optical properties of thermal control surfaces, the determination of ESH is important to calculate end of life (EOL) optical properties for spacecraft external surfaces. A higher ESH value generally correlates to greater UV degradation experienced by the surface, resulting in an increase in solar absorptivity. This paper details a novel approach for calculating ESH using Thermal Desktop. Since the ESH value is useful for thermal analysts, this technique is beneficial to quickly perform the analysis internally with tools readily available without relying on external support and funding. The example presented in this paper shows how this method was developed and used for NASA's lunar Gateway spacecraft.

This method of analysis is used to calculate ESH for the transit, assembly in orbit, and operational phases for Gateway, utilizing each of the program's planned configurations throughout its 15-year lifetime. ESH values were calculated using the Monte-Carlo ray tracing capability of Thermal Desktop using both direct solar heating and indirect solar heating due to reflections from other surfaces. The output of this analysis includes an ESH gradient map across the spacecraft. Post-processing of these results enabled identification of the average and maximum ESH on critical surfaces such as radiators. The final ESH values for each surface are then used for determination of EOL optical properties.

INTRODUCTION

Spacecraft surface optical properties degrade in the space environment due to ultraviolet (UV) radiation. The degree to which degradation occurs is affected by the duration of sunlight exposure, known as equivalent solar hours (ESH). Optical properties, specifically solar absorptivity and IR emissivity, are important for thermal control of the spacecraft. Figure 1 below shows an example of how increases in solar absorptivity decrease the heat rejection capability of a one square meter radiator exposed to sunlight.

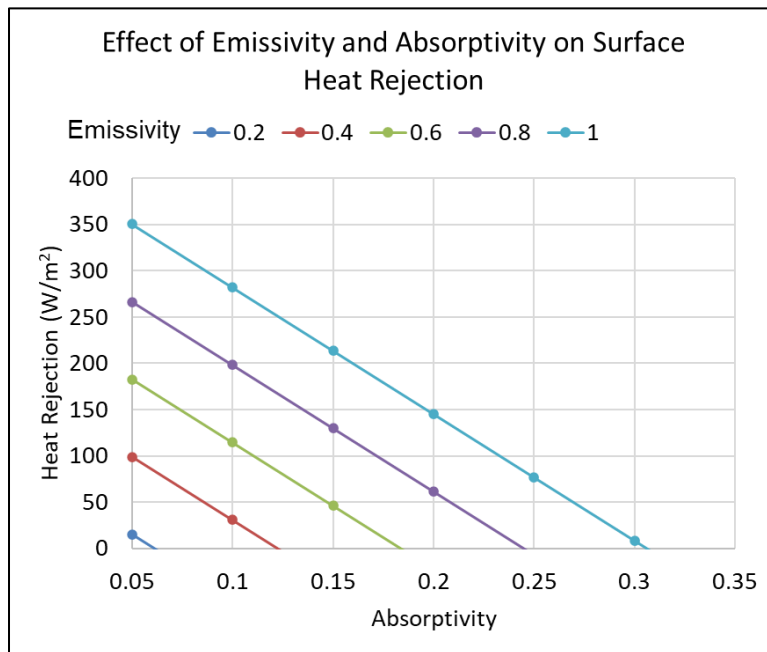


Figure 1. Impact of Emissivity and Absorptivity on Heat Rejection Capability of Radiator at 20°C

While IR emissivity generally doesn't change significantly with increased ESH, solar absorptivity will often increase, leading to higher temperatures. Absorptivity at the end of life (EOL) is needed to estimate the worst-case heating that a spacecraft will experience during its mission.

Thermal analysts don't usually determine ESH on their own and instead would be required to outsource the work to other groups. ESH analysis is a component of contamination analysis which is often outsourced to third-party companies by the Induced Environments group, increasing cost and schedule of the program. This paper details how ESH can be calculated with Thermal Desktop to allow thermal analysts to perform this analysis independently without the need for support from the Induced Environments group and third-party contractors. This technique was developed for the Gateway program to help determine the EOL optical properties for its 15-year mission lifetime.

BACKGROUND

Degradation to optical properties can be caused by a combination of multiple sources such as UV radiation, solar wind and charged particles, molecular contamination, atomic oxygen, plume

impingement, dust coverage, and more. UV radiation, one of the forms of degradation impacted by ESH, tends to darken surfaces over time, increasing their solar absorptivity. This means that larger ESH values cause larger increases in solar absorptivity, however, this effect is nonlinear and levels off after a certain threshold which is dependent on material. This is particularly relevant to radiator materials because if they are positioned in view of the sun, they will absorb more solar energy as they degrade causing a decrease in thermal performance over the lifetime of the mission. Figure 2 below shows an example of how the solar absorptivity of several thermal coatings changes with ESH. This data was collected at the U.S. Air Force's Space Combined Effects Primary Test Research Equipment Facility (SCEPTRE) in an effort to evaluate UV degradation on certain candidate radiator materials for a lunar surface power¹.

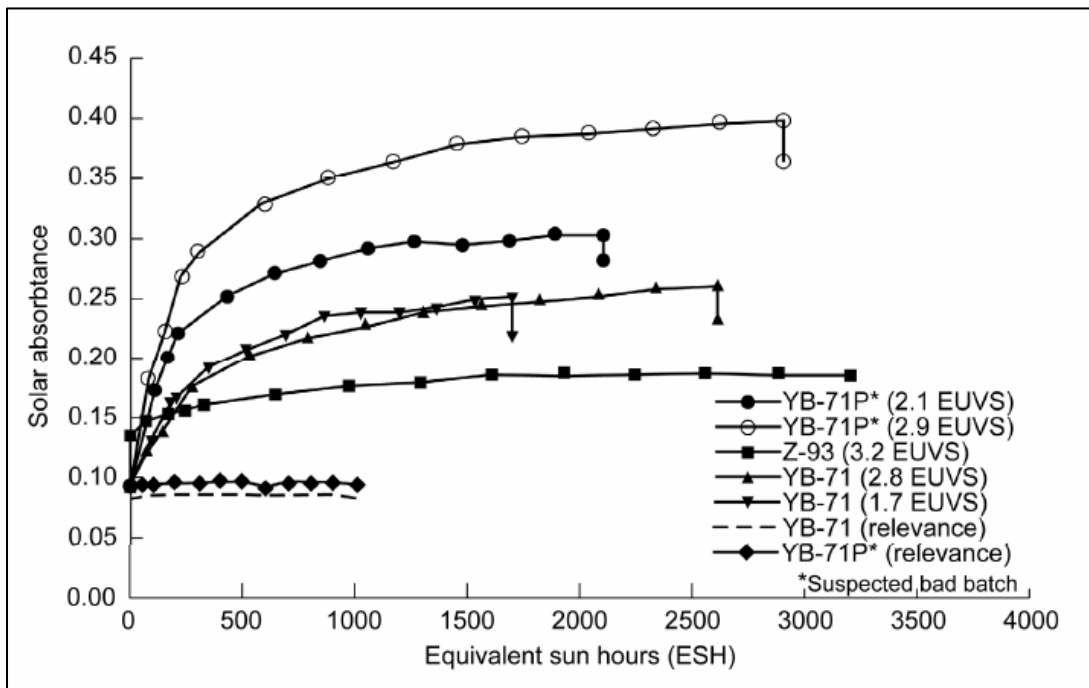


Figure 2. ESH Effect on Solar Absorbance from SCEPTRE Data¹

For the Gateway program which has a 15-year mission life, an overly conservative estimate for EOL property determination was to assume a total 15-year ESH on all surfaces. This can be considered a bounding value, however a much more accurate estimation for EOL properties can be made by calculating the ESH seen by each surface. By doing such an analysis, the EOL properties on surfaces which are space-facing or shadowed will show significantly less degradation than the overly conservative assumption of 15 years of solar exposure. These more accurate ESH values will help to provide a better understanding of EOL properties.

In addition to UV degradation, ESH also affects the level of contamination and solar wind degradation. The more solar exposure a surface sees, the more contaminants it may outgas, leading to an overall higher molecular contaminant level on nearby surfaces. Higher solar wind degradation is correlated to higher ESH in that an increased view to the sun leads to increased exposure to solar wind.

Knowing the ESH value is important for bounding UV testing duration and identifying locations where the highest degradation is expected. UV testing may take place after the analysis is complete. Generally, the duration of UV testing is limited by about 1/3 of the ESH value for accuracy, meaning that if 3000 ESH is expected, the test will take a minimum of 1000 hours to complete. It is essential to calculate an ESH value before testing to get the required testing exposure times.

METHODS

The Monte-Carlo ray tracing capability of Thermal Desktop was used to calculate the amount of solar radiation incident to every exterior surface of the Gateway vehicle. This was done by setting up a radiation analysis task in the case set manager where heating rates were calculated only for solar radiation, excluding other sources of heat (such as albedo and Lunar IR). Albedo could be ignored in this specific use-case for Gateway due to Gateway’s high-altitude orbit and the Moon’s very low albedo, which leads to Gateway receiving negligible albedo compared to other forms of radiation. Duration in eclipse was also not accounted for since Gateway spends less than 0.1% of its time in this position. Cases were created for each configuration of Gateway, and the attitude was set to solar pressure equilibrium attitude (SPEA) based on the configuration being analyzed. The different configurations analyzed accounted for assembly of Gateway and visiting vehicle arrivals/departures throughout Gateway’s lifetime in Near Rectilinear Halo Orbit (NRHO), however attitude was only run for SPEA and did not account for attitude deviations for docking events or orbit maintenance. Configurations were run and ESH results were scaled for the duration of each configuration. Because Gateway’s orbit is solar inertial, heating rates from only one orbit position needed to be analyzed when in NRHO. When calculating ESH during transit however, many orbit positions needed to be calculated as the vehicle’s attitude relative to the sun changed continuously throughout transit.

In addition to running the model for each configuration during NRHO, transit was run for the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO), also referred to as the co-manifested vehicle (CMV). The CMV transit to NRHO is over 1 year in duration due to its low thrust solar electric propulsion, therefore many surfaces on the CMV will experience significant ESH before ever reaching NRHO. The CMV was run using the Environment Bounding Mission (EBM) orbit, which is the estimated longest flight path for the CMV to NRHO. The CMV’s attitude was modeled to minimize solar exposure on zenith and nadir surfaces per current design assumptions. Solar arrays articulate such that they face the sun throughout the mission.

Equation 1 below was developed to transform heating rates into ESH:

$$ESH = \frac{Duration}{Solar\ Constant} [Q''_{Sol\ Direct} + Q''_{Sol\ Indirect}] \quad [Eq. 1]$$

where “Duration” refers to the time over which the heat flux from the sun is applied, “Solar Constant” refers to the heat rate per unit area that a blackbody facing perpendicular to the sun would absorb at the Earth’s mean distance from the sun, and $Q''_{Sol\ Direct}$ and $Q''_{Sol\ Indirect}$ refer to

the direct and indirect solar flux incident to each surface. Note that these values of $Q''_{Sol\ Direct}$ and $Q''_{Sol\ Indirect}$ are the total incident solar flux to the surface, and not just the portion which is absorbed by the surface. Indirect solar heating is the amount of solar radiation incident to a surface due to reflections off of other surfaces, rather than from direct line-of-sight to the sun. This includes both diffuse and specular reflections. Only the specular reflections in the UV spectrum were included since wavelengths longer than UV do not cause significant degradation.

Thermal Desktop directly outputs values for $Q''_{Sol\ Direct}$, but $Q''_{Sol\ Indirect}$ must be calculated using the following equation:

$$Q''_{Sol\ Indirect} = \frac{(Q''_{Total\ Absorbed} - Q''_{Direct\ Absorbed})}{\alpha} \quad [\text{Eq. 2}]$$

Here, $Q''_{Total\ Absorbed}$ is the amount of solar radiation absorbed by a surface from both direct and indirect solar heating. This means that the difference between $Q''_{Total\ Absorbed}$ and $Q''_{Direct\ Absorbed}$ yields the amount of radiation that was absorbed indirectly. By using the surface's solar absorptivity, α , the total incident indirect solar heating on a surface can be calculated.

A post-processing script was written in Python to compile ESH for every surface using nodal heat fluxes and the equations above. The script did this for each configuration and then summed the total. The script output a CSV-type file that can be read by Thermal Desktop to display the ESH on each surface with a color bar.

RESULTS

Figure 3 below depicts the total ESH for Gateway surfaces including both transit and 15 years in NRHO.

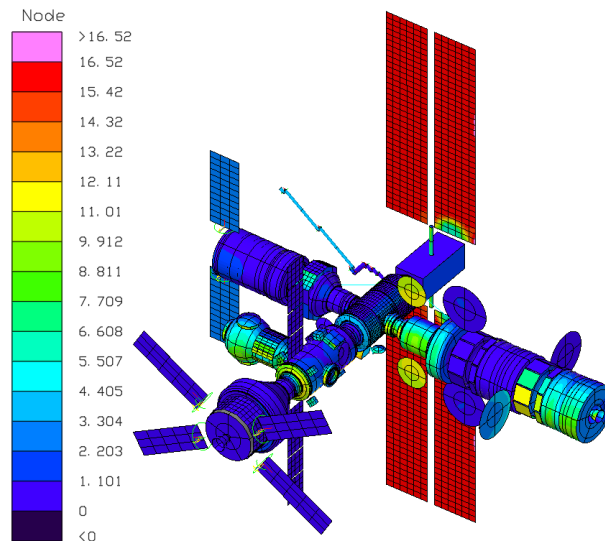


Figure 3. Gateway ESH Thermal Desktop results over 15-year mission (scale is in years)

As seen in Figure 3, the solar arrays on PPE receive about 16.5 years of ESH. This is equal to the duration of time spent in transit plus the 15 years in NRHO as well as any reflections from other modules. Other surfaces see significantly less ESH over their lifespan, especially modules which arrive at Gateway later into the mission life such as IHAB or visiting vehicles. Additionally, intermodular shadowing causes some areas to see reduced ESH, such as the area on PPE's solar arrays which were shadowed by the Ascent Element's solar arrays. Certain locations between modules and concave surfaces however will experience solar entrapment, resulting in a higher ESH than their surrounding surfaces. For example, solar entrapment occurs at the docking interface between HALO and HLS in the figure above whenever the Gateway vehicle is yawed by -45° .

The most critical surfaces to examine are the radiators of each module. The ESH values calculated in this analysis will be used to determine the impacts on EOL optical properties. The ESH values from this analysis will also be used to bound solar wind and UV testing. While PPE radiators experienced very little ESH, radiators of most other modules experienced significant ESH and will likely reach the maximum possible degradation that can be caused by UV exposure. HALO in particular experienced substantial ESH on its radiators during its transit phase prior to reaching NRHO, therefore there will be a significant increase to its solar absorptivity prior to any crewed missions to Gateway. According to the SCEPTRE data seen in Figure 2, if HALO radiators utilized Z93P white paint, they would experience a 0.04 increase in absorptivity whereas if they used YB-71P (2.9 EUVs) they would experience a increase of 0.31.

CONCLUSIONS

This novel approach for calculating ESH on external surfaces is a convenient way for thermal analysts to compare data from UV testing to estimate EOL properties. It is especially useful if UV is the only or major source of degradation. ESH is also a critical input for contamination analysis, which further helps define EOL properties if contamination is a concern. In regards to Gateway, critical surfaces were identified and their ESH was estimated. Updated EOL properties for Gateway can now be used for future thermal analysis.

REFERENCES

1. Jaworske, Donald, and Kline, Sara. “*Review of End-of-Life Thermal Control Coating Performance.*” 2008.