Engineering Notes

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Heat Loads Due to Space Particle Environment

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Introduction

THE total energy content of the energetic particles trapped in the Earth's geomagnetic field is small in comparison to other sources of potential spacecraft heating such as the sun. However, a recent study[1] has shown that advanced space systems that attempt to use cryogenic elements, such as long-wavelength IR optics, must consider the effects of the trapped particles to ensure that the thermal management requirements of these cold elements are met. Concepts for advanced systems that will be concerned with this heat source include thermal radiators that can reject waste heat at temperatures well below 100 K. Such a radiator designed to operate at 70 K in a circular, equatorial orbit at an altitude of 12,000 km will warm to an equilibrium temperature of approximately 75 K because of the heating effects of the trapped particles.[1] In the most intense part of the radiation belts, the peak instantaneous heat input is equivalent to that which would be radiated by a blackbody at a temperature in excess of 55 K. Obviously, for elements such as HgCdTe detectors, which are intended to be radiatively cooled either directly or through a secondary radiator, the trapped-particle heating mechanism must be included in thermal management subsystem designs.

Discussion

In this Note, we present a table of average and peak heat inputs for a number of orbits. The table was generated using the NASA environments AP8MIN and AE8MAX. We include a plot of the heat input as a function of time for a 24-h period to indicate the type of thermal profile one might expect in a particular orbit. We also discuss the accuracy of the heat calculations, the accuracy of the particle models, and the variability of the particle environment itself. The plots included in this report are intended only as a guide to the level of trapped particle heating that may occur in a particular orbit. The accuracy of the individual data points plotted or listed in Table 1 is limited by the accuracy of the trapped particle models that were used to determine the particle fluxes for the various orbits. In general, the particle models are good to a factor of 2 or 3 for long-term (>5 yr) averages. The calculations provide the total energy flux through a surface without regard to the depth in materials at which this energy will be deposited. However, the highest heating rate will occur at the surface. The heat due to the protons is deposited nearer the surface than that due to the electrons because the protons have a much higher linear energy transfer (LET) coefficient. In most orbits, 99% of the proton and 84% of the electron heat would be generated in a thin layer of aluminum 0.25 mm thick.[1]

Model Accuracies and Trapped Particle-Flux Variations

The calculations presented in this document used the NASA AP8 (Aerospace Proton #8) and AE8 (Aerospace Electron #8) models. These are the most recent updates to the models of the trapped radiation environments. The accuracy of the AP8 model is probably better than a factor of 2 in the inner zone (altitudes up to 3000 n.mi. at low inclination). In the outer zone, the accuracy is somewhat less certain, but is again probably good to a factor of two. Similarly, the AE8 model is probably accurate to a factor of two or better in the inner zone. In the outer zone, for long-term averages (averaged over a solar cycle), the AE8 model is probably low by about a factor of three for electrons with energies above 1.5 MeV. However, the major portion of the heat load for trapped electrons is due to the particles with energies between 100–500 keV. Furthermore, in some orbits examined, protons contribute more heat input (~75% of the total) than the electrons. For the purposes of analyzing heat input from trapped particles, electrons with energies above 500 keV can be ignored without affecting the accuracy of the estimates. Therefore, inaccuracies in the electron models are probably unimportant.

Although the inaccuracies in the particle models may not be important, the variations in the electron flux due to magnetic storms are. Immediately after a major magnetic storm, the entire outer-zone electron spectrum above about 100 keV is enhanced by a factor of 10 to several hundred. The lower energy electrons, below 100 keV, are more constant. It takes several weeks for this enhancement to subside.[2] For a satellite traversing this region of space, a significant increase in heating above normal would be observed.

Figure 1 is a plot of the 0.54-MeV electron flux at various L-values showing the response of the particle distribution to a number of magnetic storms over an 11-month period.[2] The term "L-value" used in this discussion refers to properties of the field lines. In a dipole field, the L-value corresponds to the distance from the center of the dipole to the equatorial crossing of the field line, in units of Earth radii. The field line retains its "L-value" designation all along its length, including the extension to low altitudes at higher latitudes. Note that for some parts of the magnetosphere, magnetic storms create an electron-flux enhancement of as much as four orders of magnitude. The models take these enhancements into consideration in determining average flux values. In general, for short times after major magnetic storms, the integral flux above 100 keV is enhanced by up to a factor of 10 over the average values. These enhancements will be particularly effective in increasing the transient heat load in orbits that traverse the outer zone between altitudes of 7000–12,000 n.mi., where the most intense outer-zone electron flux exists.

Figure 2 is a plot of the integral electron number flux (dashed lines) and the proton flux (solid lines) as a function of time during a 24-h orbit integration period in a low altitude, low inclination orbit. The peak fluxes observed here correspond to the peak heating levels listed in Table 1. Although a

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Table 1 Particle-induced satellite heating, W/m²

Inclination, deg	400-n.mi. circular		12-h elliptical		12-h circular		24-h circular	
	Ave	Peak	Ave	Peak	Ave	Peak	Ave	Peak
0	9.0×10^{-6}	1.2×10^{-4}	8.7×10^{-2}	5.5×10^{-1}	1.4×10^{-1}	1.6×10^{-1}	1.3×10^{-2}	1.6×10^{-2}
30	2.1×10^{-4}	5.3×10^{-3}	4.8×10^{-2}	4.8×10^{-1}	8.4×10^{-2}	1.6×10^{-1}	1.1×10^{-2}	3.1×10^{-2}
60	2.4×10^{-4}	7.7×10^{-3}	2.2×10^{-2}	3.3×10^{-1}	4.3×10^{-2}	1.6×10^{-1}	5.7×10^{-3}	2.8×10^{-2}
90	1.9×10^{-4}	8.1×10^{-3}	1.8×10^{-2}	3.2×10^{-1}	3.6×10^{-2}	1.6×10^{-1}	4.7×10^{-3}	2.8×10^{-2}

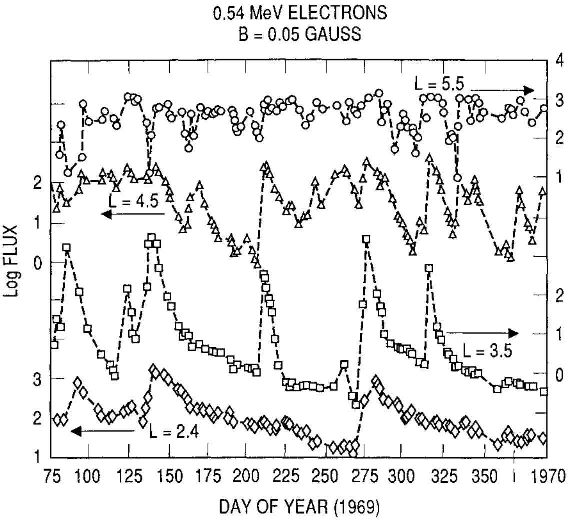

Fig. 1 Response of outer-zone electrons to magnetic storms.

rigorous analysis of the instantaneous heating rate would include an integration of the flux energy spectra, the flux spectra do not change sufficiently over an orbit to invalidate direct use of these curves in comparing the average and peak values listed in Table 1. The error due to uncertainties in the models is greater than the error that results in assuming there is no variation in the energy spectrum. The strong modulation in the flux intensity is due to the passage of the orbit through the South Atlantic Anomaly region.

Discussion of Table 1

For this discussion, "peak" refers to the peak-heating-per-orbit as depicted in Fig. 2, not the peak that will be encountered due to magnetic storms during a long-duration mission. For orbits that have outer-zone electrons or protons as their major heat input, magnetic storms can increase the short-period peak heating (1–2 days) over that listed in the table by a factor of 10. Major interpolations in orbital altitude using Table 1 should not be performed because the proton and electron environments are a strong, nonmonotonic function of altitude. Interpolations on orbital inclination, however, will yield results that are reasonably valid.

400 n.mi. Circular Orbit

The 400-nautical mile (n.mi.) circular orbit encounters relatively little energetic particle flux. For low inclinations, the offset dipole of the Earth's magnetic field effectively raises the trapped population above this altitude. Only in the region of the South Atlantic Anomaly, about $290\pm20°$ east longitude, does the low latitude flux occur at low enough altitudes for significant heat input to be observed in this orbit. Thus, both the average and peak heat inputs are low. The entire heat input occurs during about a 25-min period out of each orbit. At 30-deg inclination, however, larger fluxes of energetic electrons and protons are encountered due to the orbit intersecting the low-altitude extensions of the outer electron zone and the inner proton zone. Since the orbit cuts through this outer-zone extension at an angle, the period during which the maximum heating occurs is spread over about 30 min. Magnetic storm-time increases in the outer-zone electrons will increase the

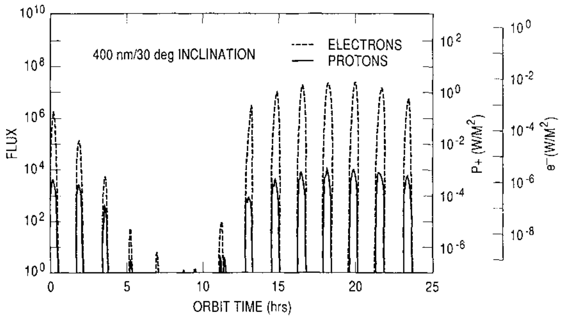

Fig. 2 Heat input vs orbit time.

peak heat input by another order of magnitude over the values shown in the table, since the maximum in the table is due to the outer-zone fluxes and these can increase by a factor of 10 over the average in the models.

At 60- and 90-deg inclinations, the orbit passes through the outer electron zone more rapidly, but it also samples more of the outer zone (all of it, in the case of the 90-deg orbit). Although the peak heating is highest for the 90-deg orbit, it occurs for shorter durations than for the 30-deg inclination, and thus the average heat input is lower than for the 30-deg inclination.

12-h Elliptical Orbit

For these calculations, the apogee was at the equator. This orbit, which at higher inclination is known as the "Molniya" orbit, is the most severe orbit from the point of view of instantaneous trapped-particle heating. Average heating, however, is less than for the 12-h circular orbit. (A 10-h circular orbit would have even higher average heating, but the same peak heating.) In the 12-h elliptical orbit, along with the high heat load, a high-radiation-dose effect is also present. Increasing the latitude of apogee will reduce the average heat input, but may increase the peak heat load. Both the peak and average heat loads decrease monotonically with increasing inclination. This is due to the fact that the peak outer-zone electron and proton fluxes occur well below apogee, and the higher the inclination of the orbit, the farther away from the equator this region is traversed. Since the flux generally decreases monotonically with increasing distance from the geomagnetic equator, the higher inclination orbits encounter less flux.

12-h Circular Orbit

For the 12-h circular orbit, the trapped-particle heat load is primarily due to the 1–10 MeV protons in the outer zone. Protons constitute 80% of the average heat load at low inclination and 70% at high inclinations. Although major magnetic storms will increase the total heat load, an order of magnitude increase in electrons would increase the heat load by only a factor of 3. The average trapped-particle heating is a strong function of inclination up to perhaps 45 deg. The peak heating rate is virtually independent of inclination because the peak heating occurs at the equator and all orbit inclinations pass through the geomagnetic equator at nearly the same *L*-value.

24-h Circular Orbit

In the geosynchronous region, proton energies are relatively low. At the same time, energetic electron fluxes are high and remain near the trapping limit (the maximum equilibrium flux the field line can sustain) most of the time. As a result, the electrons contribute most of the heating at 0-deg inclination. Magnetic storms are not important in this orbit because they do not cause major increases in the electron flux (see Fig. 1). Also, at this altitude, the offset dipole of the Earth's magnetic field does not produce any significant effects. However, the distortion of the magnetosphere due to the solar wind does produce local-time variations. These local-time effects are significant in the energetic electron flux, especially in the >500 keV range, and produce the difference between average and peak heating at 0 deg plus much of the variation seen in the peak heating as a function of inclination.

At geosynchronous orbit, the peak heating in high inclination orbits is due to protons even though the average heating is primarily due to electrons. This is caused by hot plasma conditions beyond $L = 6.6$. In this high-altitude regime, there are usually large fluxes of protons with energy in the tens of keV range, while few energetic electrons are present.

Summary

The geomagnetically trapped-particle population can produce significant heating in some systems. Model calculations indicate that greater than 0.5 W/m^2 instantaneous heat input may be encountered. For some orbits, geomagnetic storms can produce an increase in the energetic particle flux that results in a further increase in the average heat input by half an order of magnitude and an increase of an order of magnitude in the peak heat input. In general, low-altitude orbits are benign and orbits that pass through the heart of the outer zone (the equator at $L = 4$) are fairly severe. The geosynchronous orbit is between these extremes. Also, the higher the inclination of the orbit, the lower the average heating.

Acknowledgments

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Effects of Crucible Wetting During Solidification of Immiscible Pb-Zn Alloys

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Introduction

AN alloy containing a liquid-phase miscibility gap has a two-phase field consisting of immiscible liquids. The Pb-Zn (lead-zinc) system has such a liquid-phase miscibility gap.[1,2] Hundreds of immiscible alloys exist.[3] However, the processing of these alloys is generally considered impractical because of their immiscibility in the liquid state. In the immiscible field the two liquids separate due to their different densities, similar to the way oil and water separate.

The low-g environment of space provides a unique opportunity to process these alloys. In low g, it is possible that the immiscible liquid droplets that form in the parent liquid will not segregate since gravitational Stokes settling forces have been nearly eliminated. The ability to study this large group of alloys without gravity-induced segregation has sparked new interest in these alloys and their possible applications. Liquid-phase miscibility gap alloys are presently being developed for electrical contact applications. Other possible uses are as superconductors, catalysts, permanent magnets, bearings, and superplastic materials.[4,5] To develop immiscible alloys for these applications, ingots are needed with a uniform distribution of phases. Solidification of these alloys in low g will help us to attain this goal and contribute to our understanding of the processes by which immiscible alloys segregate on Earth.

This research was done in support of the design and development of a planned Space Shuttle experiment using a getaway-special canister.[6,7]

Many of the immiscible alloys previously processed in low g have resulted in severely segregated structures due to unexpected fluid flow and other uncertain experimental parameters.[8-12] These experiments have shown the importance of the wetting behavior of the two immiscible liquids and the crucible. Upon cooling into the immiscible phase field, small droplets of at least one of the two liquids form. The two liquids have different compositions and a different equilibrium wetting angle with the crucible. Consider, for example, a Pb-rich droplet in a melt of average composition Zn-40 wt % Pb just touching the alumina crucible containing the melt. If the Pb-rich alloy preferentially wets the alumina relative to the parent liquid, the Pb-rich droplet will tend to spread out on the crucible. This motion will cause fluid flow, thus helping other Pb-rich droplets to contact the crucible. This autocatalytic process promotes further coalescence and segregation of the two liquids. In low-g, this may result in the Pb-rich liquid coating the inside of the crucible and the Zn-rich liquid collecting in the center. Thus, nearly complete segregation of the two phases may result even though gravity-driven sedimentation has been eliminated.

Macrosegregation due to preferential wetting of this type may be avoided in less concentrated alloys ($\simeq 10$ vol % or less) by the majority phase preferentially wetting the crucible.[13,14] This of course does not help us when attempting to process more concentrated alloys. Also, there is evidence that minority-phase droplets that do not wet the crucible may be pushed away from the crucible wall causing flow and macrosegregation.[14] Thus, a knowledge of the wetting behavior is required for the interpretation of structures and the efficient design of crucibles for low-g experimentation.

Cahn's theory states that complete preferential wetting of the crucible by one of the liquids occurs at temperatures near the critical point at the top of the immiscible dome.[15,16] The balance of interfacial energies between the two liquids and the crucible is given by

$$\gamma_{L_1L_2}\cos\theta = \gamma_{SL_1}\gamma_{SL_2} \tag{1}$$

where the angle θ is the dihedral angle shown in Fig. 1, $\gamma_{L_1L_2}$ is the interfacial free energy at the boundary between the two immiscible liquids, and γ_{SL_1} and γ_{SL_2} are the solid-L_1 and solid-L_2 interfacial free energies, respectively. Complete wetting occurs when $\theta = 0$ and at undefined values of $\cos\theta$ such that

$$\gamma_{L_1L_2} < |\gamma_{SL_1} - \gamma_{SL_2}| \tag{2}$$

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