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Impact of Radiation Hardness and Operating Temperatures of Silicon Carbide Electronics on Space Power System Mass

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Impact of Radiation Hardness and Operating Temperatures of Silicon Carbide Electronics on Space Power System Mass

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Abstract. The effect of silicon carbide (SiC) electronics operating temperatures on Power Management and Distribution (PMAD), or Power Conditioning (PC), subsystem radiator size and mass requirements was evaluated for three power output levels (100 kW_e, 1 MW_e, and 10 MW_e) for near term technology (i.e., 1500 K turbine inlet temperature) Closed Cycle Gas Turbine (CCGT) power systems with a High Temperature Gas Reactor (HTGR) heat source. The study was conducted for assumed PC radiator temperatures ranging from 370 to 845 K and for three scenarios of electrical energy to heat conversion levels which needed to be rejected to space by means of the PC radiator. In addition, during part of the study the radiation hardness of the PC electronics was varied at a fixed separation distance to estimate its effect on the mass of the instrument rated reactor shadow shield. With both the PC radiator and the conical shadow shield representing major components of the overall power system the influence of the above on total power system mass was also determined. As expected, results show that the greatest actual mass savings achieved by the use of SiC electronics occur with high capacity power systems. Moreover, raising the PC radiator temperature above 600 K yields only small additional system mass savings. The effect of increased radiation hardness on total system mass is to reduce system mass by virtue of lowering the shield mass.

INTRODUCTION

During the past few years considerable R&D effort has been devoted to raising the operating temperature limits as well as the radiation hardness (tolerance to neutron fluence and gamma radiation dose) of electronic components (Matus et al., 1997). Significant advances in the use of silicon carbide (SiC) materials for solid state semiconductor components have been especially promising. An expected payoff is that resulting electronic subsystems utilizing such components will be able to operate longer and more reliably, even in a more severe operating environment. For space power systems, high temperature electronics offers additional benefits, namely the reduction of PC radiator size and mass. Moreover, for power systems with nuclear heat sources, increased radiation hardness enables relaxation of shielding requirements for the on-board electronics.

The present study is directed at providing an estimate of just how much system mass savings can be expected from the use of electronic subsystems capable of operation at elevated temperatures and in higher radiation environments. The hypothetical mission for the power system, especially for the 10 MW_e power plant, was assumed to be a precursor cargo spacecraft to Mars with a high specific impulse (I_{sp}) electric propulsion system. Since this power plant was also to provide surface power during the approximately one year Martian stay time, the total mission time of 3 years was assumed for reactor sizing. To perform the study a "Closed Brayton Cycle" (CBC) power system code developed by one of the authors (Juhasz) at the NASA Lewis Research Center was utilized along with a reactor and shield code that was essentially the same as employed by (Dobranich et al. 1987).

To reduce the mass of the high temperature part of the system it was desired to circumvent the need for an intermediate heat exchanger between the reactor and the CCGT. Hence the helium working fluid was assumed to be heated directly in a high temperature epi-thermal pellet bed gas reactor (HTGR), as described in several

publications at the 10th SSNPS, e.g., (El Genk et al. 1993). Although the above references are to reactors capable of heating the working fluid to near 2000 K, the turbine inlet temperature assumed for this study was a relatively modest 1500 K, thus obviating the need for shield cooling. In agreement with prior system studies for megawatt level power systems (Juhasz et al. 1993) required for inter-planetary nuclear electric propulsion (NEP) applications, an initial system optimization showed that for the power system considered here a non-regenerated power plant would actually result in a lower overall system mass. Hence all system calculations were done for a non-regenerated cycle with the temperature ratio kept constant at a value of 3.1, representing the minimum system mass baseline case.

Regarding the low temperature side of the cycle, the need for a gas-to-liquid heat exchanger was eliminated by ducting the He working fluid from the turbine exhaust section to a heat pipe (HP) main radiator featuring direct forced convection heat transfer from the working fluid to the HP evaporator sections. The cycle reject heat would then be conducted from the HP condensers to carbon-carbon (C-C) fins and radiator faceplates for eventual heat transfer by radiation to the space environment. The C-C composite radiator design was based on development work conducted during the SP-100 program (Rovang et al. 1994) and highlighted in an anniversary publication (Juhasz and Peterson, 1994). This radiator conceptual design has also been proposed for a lunar outpost power system based on the CBC, as well as for the multimewatt NEP power system referred to above (Juhasz et al. 1993). The PC radiator was also based on the same technology, albeit simpler since it was required to operate at a constant temperature. For this study there was assumed to be no interaction between the PC and main radiators. The sink temperature for the radiators was assumed to be 230 K.

To determine the heat load on the PC radiator three scenarios of electrical energy to heat conversion levels were postulated. These included assumed combined PMAD and payload efficiencies of 0.9, 0.5, and 0.01, with the highest value representing a power system for which 90% of the power generated was exported as work energy, while the lowest value implied that practically all the power generated was consumed on-board, being eventually converted into heat. The middle value represented an in between case. It should be noted that heat pump subsystems were not included in this study. Study results for the baseline radiation hardness case for the 10 MW_e system show the effect of electronic operating temperatures on the total system, main radiator, PC radiator and the balance of platform (BOP) mass. The BOP included the reactor and shield, the CCGT turbo-alternator components, the PC sub-system and the connecting structure. Effects on total system mass, only, are shown for the larger combined PMAD and payload efficiencies. The effect of radiation hardness, in terms of neutron fluence and gamma dose, on shield weight were also studied and results are reported for the baseline PC temperature case.

RESULTS AND DISCUSSION

First, a study of the effect of electronics temperature on system and PC radiator masses is discussed; for this study the limiting values of neutron fluence (1×10^{13} neutrons/cm²) and gamma radiation (5×10^5 rad) used are assumed to correspond to silicon electronics. Then a study of radiation hardness on shield mass is discussed; for this study the PC electronics temperature was held constant at 400 K (127 C).

Effect of PC Electronics Temperature on System and PC Radiator Masses

The temperature of 400 K (127 C) is approximately equal to the military specification of 125 C which is a current limit that is used for most silicon based electronics applications. It is believed that silicon carbide electronics will be able to eventually operate reliably at 600 C or approximately 875 K, the upper limit used in this study. The information below shows the effect of electronics temperature on system and PC radiator masses. The average PC radiating temperature was assumed to be 30 K less than the electronics temperature; this is believed to be characteristic of a heat pipe radiator. Results are shown for 10, 1 and 0.1 MW_e (megawatt electric) systems.

99% of Power Rejected through PC Radiator

The first results shown assume that 99% of the electrical power generated must be rejected through the PC radiator. This would likely be the case if an insignificant amount of power is rejected via radar, other electromagnetic signals, thermal radiation from the surfaces of the spacecraft, or via direct conversion to work.

Figure 1 shows how total system mass varies with PMAD and payload electronics temperature for the 10, 1 and 0.1 MWe power levels; it is

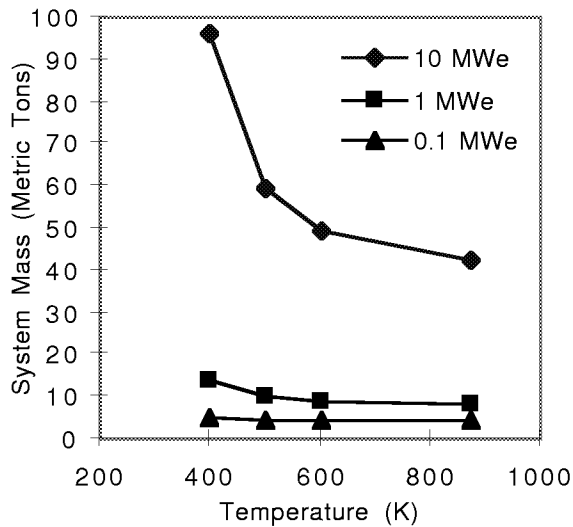


FIGURE 1. System mass as a function of electronics temperature--for 99% of power radiated via PC radiator

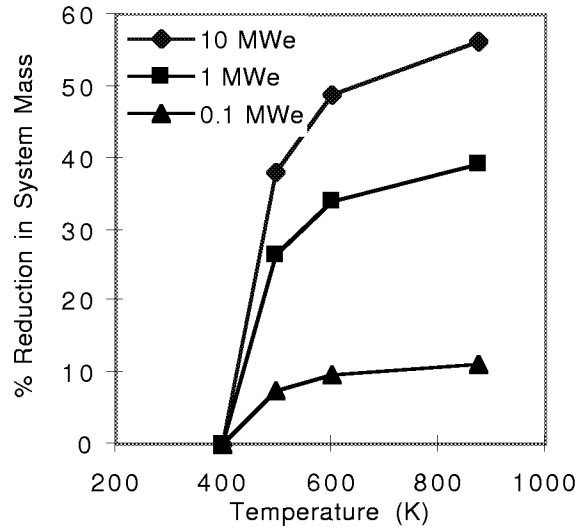


FIGURE 2. Per cent reduction in system mass, relative to that at 400 K --for 99% of power radiated via PC radiator.

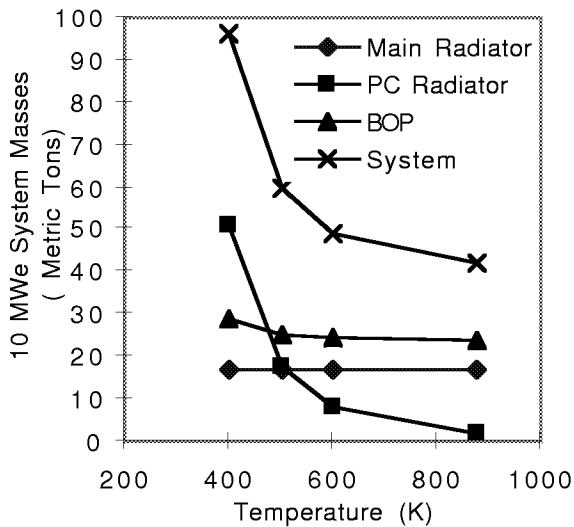


FIGURE 3. 10 MWe system masses as functions of electronics temperature--for 99% of power radiated via the PC radiator.

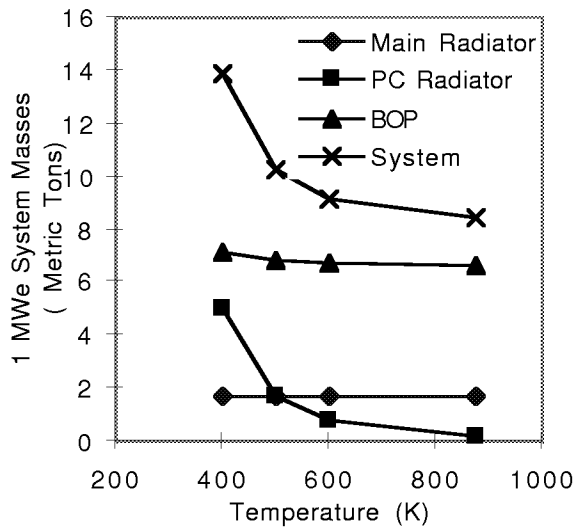


FIGURE 4. 1 MWe system masses as functions of electronics temperature--for 99% of power radiated via the PC radiator.

seen that the larger power systems are more significantly affected by changes in the electronics temperature. Figure 2, based on the same computed data, shows percent reduction of system mass relative to the system mass at 400 K electronics temperature and provides better resolution for the smaller power systems. The plots also show that most of the potential reduced mass benefit can be achieved by increasing the electronics operating temperature to 600 K (or 327 C).

Figures 3, 4, and 5 show system, radiator, and Balance of Platform (BOP) masses for each of the power systems, respectively, as functions of electronics temperature. The BOP mass is the total system mass minus that of the main and PC radiators; it includes the reactor, shield, power conversion system, electronics, and the structural mass.

For the 10 MW system masses shown in Figure 3, it is seen that at 400 K, the PC radiator dominates the other system components; PC radiator mass becomes less significant if the electronics temperature can be increased. In

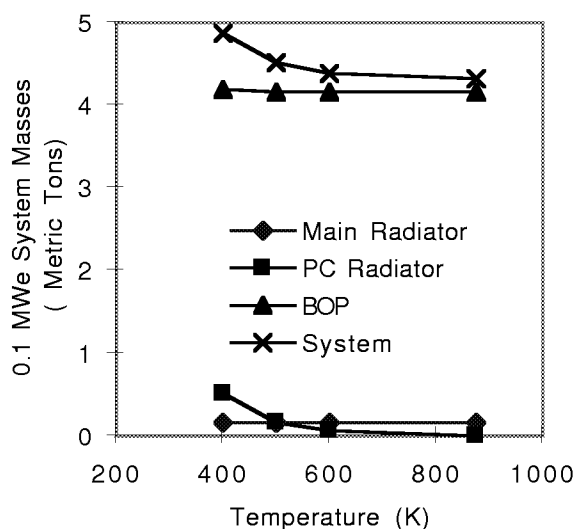


FIGURE 5. 0.1 MWe system masses as functions of electronics temperature--for 99% of power radiated via PC radiator.

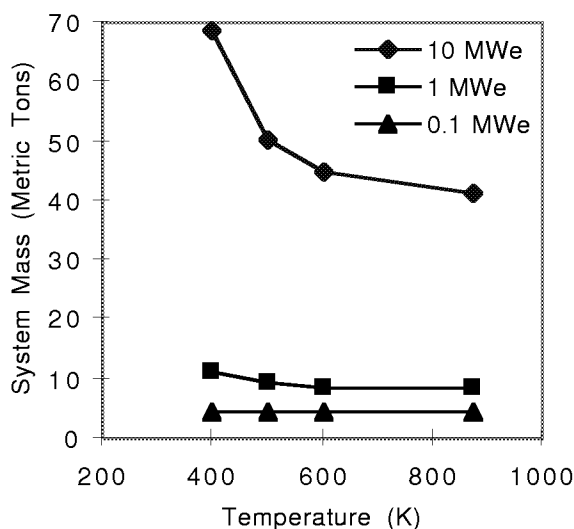


FIGURE 6. System mass as a function of electronics temperature--for 50% of power radiated via the PC radiator

comparison, Figures 4 and 5 illustrate that as the power level of the system becomes smaller, and less waste electronics heat needs to be dissipated--the mass of the PC radiator becomes less significant.

50% of Power Rejected through PC Radiator

If 50% of the electrical power is emitted "directly" from the spacecraft via radar, other electromagnetic radiation or by direct conversion to work, then only the remaining 50% of the electronics waste heat must be rejected via the PC radiator. For each system power level, reducing PC radiator rejected heat from 99% to 50% of the electrical power has the effect, primarily, of reducing the mass of the PC radiator by approximately 50% and also reduces the structural mass. The effect of increasing the operating temperature of the electronics on the system masses for the 50% case is shown in Figure 6. Figure 6 shows that for a 10 MW system, increasing the electronics temperature from 400 to 875 K, produces only about half the reduction in system mass (~ 27,000 kg) that is shown for the 99% case of Figure 1 (which shows a reduction of ~ 54,000 kg).

10% of Power Rejected through PC Radiator

If 90% of the electrical power is emitted directly from the spacecraft, leaving only 10% of the electronics waste heat to be rejected via the PC radiator, the impact on the spacecraft mass of increasing the electronics operating temperature is greatly reduced. This is shown in Figure 7. Here, for a 10 MW system, increasing the electronics temperature from 400 to 875 K produces a reduction in system mass of less than 5500 kg. This is, of course, because the PC radiator is only a little more than 5100 kg at the lowest, 400 K, electronics temperature.

The above results show only the effect of increasing the electronics operating temperature on reducing the PC radiator and system masses. Another benefit to be derived by replacing silicon with silicon carbide electronics is increased radiation hardness. Increasing the radiation hardness of the electronics would reduce the mass of the instrument rated shield for a nuclear reactor power system; it would also reduce any requirement to protect spacecraft electronics from other radiation that might be encountered in space. The results shown below address only the impact of electronics radiation hardness on the mass of instrument rated shielding.

Effect of PC Electronics Radiation Hardness on Shield Mass

The results discussed here are based on a 46 MW_t (megawatt thermal) reactor heat source for a 10 MW_e CCGT power system designed for three years of operation with a shield having a fixed cone half angle of 15 degrees and 25 m separation between the reactor and the payload electronics.

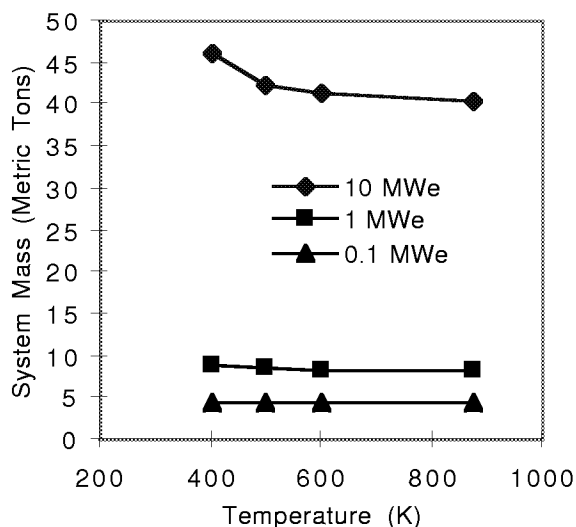


FIGURE 7. System mass as a function of electronics temperature--for 10% of power radiated via PC radiator a

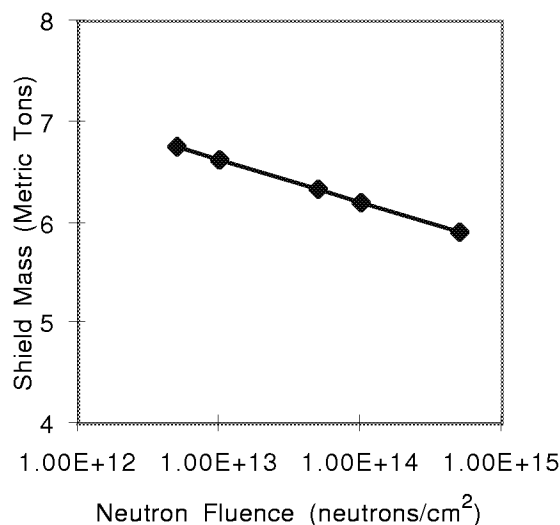


FIGURE 8. Shield Mass as a function of neutron fluence dose limit for a 10 MW_e, (46 MW_t) 3 year system with 25 m reactor-to-PMAD separation distance.

A neutron fluence of 10^{13} neutrons/cm² is assumed to be the upper radiation limit of silicon based electronics. A neutron fluence about an order of magnitude larger, i.e., 10^{14} neutrons/cm², is assumed to be a viable goal for silicon carbide based electronics.

For this study, the neutron fluence was allowed to vary from 5×10^{12} neutrons/cm² (about one-half the assumed limit for silicon electronics) to 5×10^{14} neutrons/cm² (about 5 times the assumed limit for silicon carbide electronics). The variation in shield mass (composed of lithium hydride, or LiH, and tungsten, or W, layers for neutron and gamma attenuation, respectively) over this range of limits is shown in Figure 8 as a function of neutron fluence; the gamma radiation dose was held constant at 5×10^5 rad. Increasing the neutron fluence from 10^{13} neutrons/cm² (upper limit of silicon electronics) to 10^{14} neutrons/cm² (viable goal for silicon carbide electronics) was found to allow a reduction in shield mass of 435 kg.

The gamma radiation dose was held constant at the silicon electronics limit of 5×10^5 rad for this study because (1) the gamma dose is limited by the gate oxide such as that used in power MOSFETs, and (2) the same oxide is used for both silicon and silicon carbide electronics. If (1) the SiC electronics are limited to semiconductor devices that don't use a gate oxide (such as bipolar junction devices) or (2) a more gamma resistant gate oxide is developed, then it might be possible to increase gamma dose by an order of magnitude, also, from 5×10^5 to 5×10^6 rad. Such an increase, for constant neutron fluence of 10^{13} neutrons/cm², would reduce the mass of the shield used in this study by 1630 kg. Total shield mass is much more sensitive to gamma dose than to neutron fluence because of the higher mass density of the gamma-tungsten shield as compared to the neutron-LiH shield.

CONCLUDING REMARKS

Substitution of silicon carbide for silicon electronics would produce substantial reductions in PC radiator and system masses for space power systems of 0.1 MW (100 kW) and larger--when most of the electronics waste heat must be rejected through the PC radiator. When 99% of the electronics waste heat must be rejected through the PC radiator, substitution of 875 K (~600 C) silicon carbide electronics for 400 K (~125 C) silicon electronics, was found to produce reductions in system mass of 56%, 39% and 11% for 10 MW, 1 MW and

0.1 MW power systems, respectively. These percentage reductions in system mass correspond to absolute system mass reductions of approximately 54000, 5400 and 540 kg, respectively. These system mass reductions are almost entirely due to reductions in the size of the PC radiator (there is some reduction in structural mass). When these percentage reductions in system mass were plotted as a function of system power level on a semi-log plot and extrapolated to 0.01 MW (10 kW) and 0.001 MW (1 kW), it seemed clear that the substitution of silicon carbide for silicon electronics would have negligible impact on the PC radiator and system masses for 10 kW and smaller power systems.

If the percentage of electrical power rejected through the PC radiator is reduced from 99 to 50%, then the percentage reduction in system masses fall to 40%, 25% and 6% for 10, 1, and 0.1 MW systems, respectively. A further reduction in the percentage of power lost via the PC radiator to 10% means that the substitution of 875 K capable silicon carbide electronics for 400 K capable silicon electronics would produce reductions in system mass of only 12%, 6%, and 1% for 10, 1, and 0.1 MW systems, respectively.

Suppose that silicon carbide electronics has developed to the point of being capable of operation at "only" 600 K (~325 C) instead of 875 K (~600 C). When 99% of the electrical power is rejected via the PC radiator, substitution of 600 K capable silicon carbide electronics for 400 K capable silicon electronics would produce reductions in system mass of 49%, 34% and 10% for 10, 1, and 0.1 MW systems, respectively. This is not much less than the 56%, 39% and 11% reductions that could be achieved by substitution of 875 K capable silicon carbide for silicon electronics. A similar study reported by (Dobranich, 1987) assumed substitution of 600 K capable for 400 K capable electronics and a system designed for one year of operation, instead of the three years assumed for this study. Dobranich's study showed reductions of 40%, 17% and 7% in system mass for 10, 1 and 0.1 MW systems. Only the 17% reduction reported for the 1 MW system seems somewhat inconsistent with the results found in the current study.

The radiation hardness study showed that substitution of SiC for silicon electronics, with an increase in neutron fluence from 10^{13} to 10^{14} neutrons/cm², would reduce instrument rated shield mass by 435 kg for a 10 MW system (for constant gamma dose of 5×10^5 rad). If the gamma dose could also be increased an order of magnitude, this would reduce shield mass by 1630 kg (for constant neutron fluence of 10^{13} neutrons/cm²). These benefits can be compared with system mass reductions that were found by substituting 600 K capable SiC electronics for 400 K silicon electronics. Such a substitution produced a 47100 kg reduction in system mass when 99% of the power is rejected through the PC radiator; the reduction in system mass was about half as large when only 50% of the power was rejected through the PC radiator.

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