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# Performance analysis of cascaded thermoelectric converters for advanced radioisotope power systems

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## Abstract

Advanced radioisotope power systems (ARPSs) for future planetary missions require higher conversion efficiency than the state-of-the-art (SOA) SiGe thermoelectric converter in order to decrease system mass and reduce mission cost. The performance of three cascaded thermoelectric converters (CTCs) for potential use in ARPSs is investigated at heat rejection temperatures of 375, 475 and 575 K and input thermal powers of 1, 2 and 3 $W_{th}$. These CTCs have top SiGe unicouples that are thermally, but not electrically, coupled to bottom unicouples having one of the following compositions: (a) TAGS-85 (p-leg) and 2N–PbTe (n-leg); (b) $CeFe_{3.5}Co_{0.5}Sb_{12}$ (p-leg) and $CoSb_3$ (n-leg); and (c) segmented p-leg of $CeFe_{3.5}Co_{0.5}Sb_{12}$ and $Zn_4Sb_3$ and n-leg of $CoSb_3$. The top and bottom unicouples in the CTCs are of the same length (10 mm), but the optimized cross-sectional areas of the n- and p-legs for maximum efficiency are different. The nominal hot junction temperature of the top SiGe unicouples at their peak efficiencies is 1273 K and that of the cold junction is 780 K when the bottom unicouple is of composition (a) and 980 K for compositions (b) and (c). The hot junction temperatures of the bottom unicouples are taken 20 K lower than the cold junctions of the top unicouples, but the input thermal powers to the former are the same as those rejected by the latter. Assuming zero side heat losses and a contact resistance of 150 $\mu\Omega\,cm^2$ per leg in the top and bottom unicouples, the calculated peak efficiencies of the CTCs vary from 9.43% to 14.35%. These efficiencies are 40–113% higher, respectively, than that of SOA SiGe (∼6.5%) when operating at the cold junction temperature of 566 K and the same hot junction temperature (1273 K) and contact resistance per leg. Decreasing this

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resistance to a realistic value of 50 $\mu\Omega\,\mathrm{cm}^2$ per leg increases the peak efficiencies of the CTCs by 0.5–0.9 percentage points to 9.93–15.25%.

*Keywords:* Cascaded thermoelectric converter (CTC); Skutterudites; Segmented thermoelectric; Energy conversion; SiGe; Advanced radioisotope power systems (ARPSs); Radioisotope thermoelectric generators (RTGs)

## 1. Introduction

Future exploration of the outer planets requires advanced nuclear power systems capable of providing electric power from a few Watts to hundreds of kilowatts for 7–10 years. For these planets, solar power is not an enabling option due to the progressively weaker solar brightness; on Mars, it is ~45% of that in earth orbit, <4% on Jupiter and essentially nil on other planets farther out. The solar option has been considered for a number of robotic and spacecraft missions to Mars. These missions typically have limited scope and duration from a few days to several months and require only a few to 10's of Watts of electrical power. For higher power missions to either Mars or the farthest planets, such as Jupiter, Saturn and Pluto, the solar option is not a viable one. Future exploration of these planets will require developing advanced energy conversion technologies that could be used with either a radioactive or a nuclear reactor heat source to provide a wide range of electrical power levels for 7–10 year missions, or even longer. These nuclear power systems operate continuously and independently of the sun.

Space reactor power systems (SRPSs) and advanced radioisotope power systems (ARPSs) each *enable* certain classes of missions. The SRPSs use fission nuclear reactors capable of generating hundred to thousands of kilowatts of thermal power continuously for 7–10 years. These reactors do not start until the spacecraft is fully and safely deployed into space. ARPSs use SOA general purpose heat source (GPHS) bricks that have been used in radioisotope thermoelectric generators (RTGs) on numerous planetary missions for more than three decades [1–3]. Each GPHS brick (or module) is loaded with four $^{238}\mathrm{PuO}_2$ fuel pellets that each generates ~62.5 W of thermal power by the radioactive decay of the $^{238}\mathrm{Pu}$ isotope. The relatively long half life (87 years) of $^{238}\mathrm{Pu}$ makes it suitable for missions of 5 or more years with a small decrease in the thermal power to the end-of-mission (EOM). However, because of the low thermal power density of the $^{238}\mathrm{PuO}_2$ fuel (~0.4 $\mathrm{kW_{th}/kg}$) and its high density (>1000 $\mathrm{kg/m^3}$), limited availability and high cost, ARPSs are only practical for those missions requiring a few tens to a thousand of Watts of electricity. Therefore, ARPSs are *enabling* deep space and long duration surface and limited subsurface exploration missions on Mars and the farthest planets in the solar system.

On the other hand, SRPSs are enabling high power interplanetary missions to propel large spacecraft using a multitude of high power electric propulsion engines requiring 100–250 $\mathrm{kW_e}$, and even more. SRPSs markedly shorten the travel time to destination planets, significantly increase the delivered payload mass and provide ample electrical power for the science payload, fast communication and high data transmission rates, surface and subsurface operations and future space colonies. Unlike ARPSs, SRPSs could be designed to operate at variable power levels and for multiple shutdowns and restarts, as needed.