



NASA's Advanced Radioisotope Power Conversion Technology Development Status

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ABSTRACT

NASA's Advanced Radioisotope Power Systems (ARPS) project is developing the next generation of radioisotope power conversion technologies that will enable future missions that have requirements that cannot be met by either photovoltaic systems or by current radioisotope power systems (RPSs). Requirements of advanced RPSs include high efficiency and high specific power (watts/kilogram) in order to meet future mission requirements with less radioisotope fuel and lower mass so that these systems can meet requirements for a variety of future space applications, including continual operation surface missions, outer-planetary missions, and solar probe. These advances would enable a factor of 2 to 4 decrease in the amount of fuel required to generate electrical power. Advanced RPS development goals also include long-life, reliability, and scalability. This paper provides an update on the contractual efforts under the Radioisotope Power Conversion Technology (RPCT) NASA Research Announcement (NRA) for research and development of Stirling, thermoelectric, and thermophotovoltaic power conversion technologies. The paper summarizes the current RPCT NRA efforts with a brief description of the effort, a status and/or summary of the contractor's key accomplishments, a discussion of upcoming plans, and a discussion of relevant system-level benefits and implications. The paper also provides a general discussion of the benefits from the development of these advanced power conversion technologies and the eventual payoffs to future missions (discussing system benefits due to overall improvements in efficiency, specific power, etc.).

1. INTRODUCTION

The solar system is a difficult place to explore! Flight times can be long, payload mass is frequently limited, the flux of sunlight can be too high or too low, atmospheres can be extremely dense or a vacuum, surfaces can be very cold or very hot, and radiation environments can be severe. The National Aeronautics and Space Administration (NASA) has been overcoming these challenges and has a long history

of successful space flight missions that have been enabled by radioisotope-fueled power systems to provide electrical power. A radioisotope power system (RPS) uses the heat generated from the decay of radioisotope material and converts the heat into useful electrical power. RPS applications are most attractive where photovoltaics (PVs) are not viable—such as for deep-space applications—where the solar flux is too low—or for extended surface applications, such as those on Mars or the Moon, where the day/night cycle, settling of dust, and life requirements limit the usefulness of PVs (ref. 1).

NASA has used RPSs reliably in space exploration for more than 35 years. Past RPSs utilizing thermoelectric (TE) power conversion have proven to be highly reliable, long-lived designs. The United States has successfully flown 22 space missions that have used RPSs. The last four missions have used radioisotope thermoelectric generators (RTGs), which incorporate general purpose heat source (GPHS) modules. The GPHS-RTG, which uses silicon-germanium (Si-Ge) thermoelectric power conversion, has been utilized on NASA missions Galileo, Ulysses, Cassini, and most recently Pluto-New Horizons. Although the GPHS-RTG is a proven reliable design that nominally generates ~290 We of electric power, it has a relatively low power conversion efficiency of about 7 percent, a beginning of mission (BOM) system specific power of about 5 W/kg, and is limited to vacuum environment applications (refs. 2 and 3). Future plutonium fuel availability is also a concern. In addition, the GPHS-RTG is not designed to handle the higher launch loads associated with NASA's newest launch vehicles or the landing loads associated with airbag-style landing systems (ref. 4).

Recognizing the need for reestablishing and improving RPSs to address the limitations of the GPHS-RTG, the NASA Science Mission Directorate (SMD) initiated the RPS project. The objective of the RPS project is to develop power systems and technologies that will enable or improve the effectiveness of future space science missions. To provide an RPS for nearer term needs, NASA started the development of two next-generation RPS flight systems: the

Multi-Mission RTG (MMRTG) and the Stirling Radioisotope Generator (SRG) (ref. 5). The MMRTG and SRG both have the ability to operate in the vacuum of space and in a range of planetary environments, and are capable of handling launch and landing loads beyond those of the GPHS-RTG. However, enabling this multimission capability would reduce specific power in comparison to the GPHS-RTG (2.8 We/kg for MMRTG, and ~3.4 We/kg for SRG) (ref. 4). The MMRTG is expected to be available for space missions later this decade and has been baselined as the power source for the upcoming Mars Science Laboratory (MSL) mission in 2009.

NASA anticipates future mission requirements that go beyond the capabilities of MMRTG, requiring advanced RPSs (ARPSs) that offer better performance and higher specific power. Future potential SMD missions require RPS that can work reliably for long periods of time in both vacuum and planetary atmospheres. Since power requirements will vary from mission to mission, future potential missions would also require a technology that can be scaled from a few watts to a few hundred watts.

To meet these future needs, NASA and the Department of Energy (DOE) are developing advanced, high-efficiency radioisotope power generators to enable the next ambitious steps in the exploration of our solar system using safe and cost-effective spacecraft (ref. 6). The ARPSs efforts are intended to mature the ARPS technologies up to technology readiness level 5 (TRL 5). At this point, NASA could select one or more of the technologies for further development by DOE, under NASA sponsorship, into a full-scale RPS flight system. ARPS development is still in its early stages, and thus, flight-qualified ARPSs systems are not expected to become available until around the middle of the next decade (ref. 4).

An Outer Planets Assessment Group (OPAG) report released this year (ref. 6) states “For many missions specified in the Decadal Survey, advanced technology is required to either enable the mission, or enhance it by increasing its scientific return, or decreasing its cost/risk. In the outer solar system few missions can operate with only solar power, making the development and testing of efficient radioisotope power systems a high priority.” The OPAG report goes on to say that high-power, low-mass RPSs are an enabling technology (ref. 6).

2. RPCT PROJECT OVERVIEW

NASA’s Radioisotope Power Conversion Technology (RPCT) project is a main element of the ARPS development. In August 2002 NASA released NASA Research Announcement (NRA) 02-OSS-01 entitled “Radioisotope Power Conversion Technology,” soliciting proposals for the development of next-generation power

conversion technologies applicable to ARPSs (ref. 7). The objective of the RPCT project is to advance the development of radioisotope power conversion technologies to provide higher efficiency and specific power than the state-of-practice GPHS-RTG. Safety, long-life (14 years, with well-understood degradation), reliability, scalability, multimission capability (vacuum and atmosphere), resistance to radiation (from the GPHS or potential mission environments), and minimal interference with the scientific payload are the other important ARPS goals. Advances made under the RPCT NRA will decrease the amount of radioisotope fuel required by a factor of 2 to 4 and will reduce the waste heat generated to produce electrical power, and thus could result in more cost-effective science missions for NASA. The NASA Glenn Research Center (GRC) manages the RPCT project.

The emphasis of the RPCT NRA contracts is the development of the power conversion technology. Therefore, many auxiliary elements of the RPS, such as the radiators, GPHS, and insulation, were considered to be beyond the scope of this NRA, and are not included in this technology development effort. It is anticipated that future development efforts in collaboration with DOE could encompass development of the nonconverter components and integration of these components with the power conversion system.

Phase I of the RPCT project was initiated when 10 NRA contracts were awarded in the summer/fall of calendar year 2003. The selections included five larger “development” contracts using more mature technology (TRL 3 to 5) and five smaller “research” contracts using less mature technology (TRL 1 to 3). The selections included a broad range of conversion technologies, including two free-piston Stirling contracts, one turbo-Brayton contract, four TE contracts, and three thermophotovoltaic (TPV) contracts. Each RPCT NRA contract had a period of performance of up to 3 years, with 1 base year and 2 option years to continue the following phase after the conclusion of the prior phase.

Over the summer of 2004, annual reviews were conducted of all 10 Phase I RPCT NRA contracts. On the basis of the available funding and results of the review, a decision was made to continue 7 of the 10 contracts into Phase II, which started in the November 2004 to January 2005 timeframe.

However, because of a severe RPS Program budget reduction in January 2005, four more of the Phase II contracts were stopped and only three of the Phase II contracts continued. Funding for Phase I of all 10 RPCT contracts totaled \$12.4 million, whereas the reduced funding for the three Phase II contracts was \$5.4 million. Starting in October 2006, additional funding was identified and one of the stopped TPV Phase II efforts could be restarted.

An overview of the RPCT Phase I initiation was presented at the International Energy Conversion Engineering Conference (IECEC) in 2004 (ref. 1), the status of the Phase I accomplishments was presented at the Space Technology and Applications International Forum (STAIF) in 2005 (ref. 2), and a status of the efforts that started Phase II was presented at IECEC in 2005 (ref. 8). A status of the three ongoing Phase II RPCT NRA contracts led by Sunpower, Cleveland State University, and Massachusetts Institute of Technology, was provided at STAIF in 2006 (ref. 9).

This paper discusses the conclusion of the Phase II accomplishments of the Cleveland State University Stirling regenerator research effort and the Phase III accomplishments of the Massachusetts Institute of Technology (MIT) Nano-TE research effort. It also discusses the ongoing status of the Phase III Sunpower Stirling development effort as well as the Phase I accomplishments of and the plans for restarting the Creare TPV development effort.

3. RPCT THERMOELECTRIC TECHNOLOGY

In the last 15 years, two different approaches were investigated for developing the next generation of new TE materials: one using new families of advanced bulk TE materials, and the other using low dimensional materials systems. During the mid to late 1990s, these two approaches developed independently and mostly along different directions. More recently, the two approaches seem to be coming together again. On one hand, the most successful new bulk TE materials are host structures containing nanoscale features such as inclusions, cages, and vacancies. On the other hand, low dimensional material systems are now being assembled as three-dimensional nanocomposites containing a coupled assembly of nanoclusters showing short-range low dimensionality embedded in a host material.

Description of MIT Nano-TE Effort

MIT, acting as the prime contractor, has teamed with Boston College and the Jet Propulsion Laboratory (JPL) on this research contract to design, synthesize, and develop Si-Ge nanocomposites with an improved dimensionless TE figure-of-merit ZT over bulk SiGe. This nanostructure technology has the potential to increase the material's performance by reducing the lattice thermal conductivity without affecting the electrical conductivity (ref. 10). The nanostructured bulk $\text{Si}_{1-x}\text{Ge}_x$ material provides orders of magnitude increases in the density of interfaces that scatter phonons more effectively than electrons (ref. 11). In addition, careful control of the charge carrier concentration and energy was predicted to lead to an enhanced carrier mobility and Seebeck coefficient. The effect of these improvements would be to provide a large gain in ZT values, thus resulting in much higher TE conversion efficiency (ref. 12).

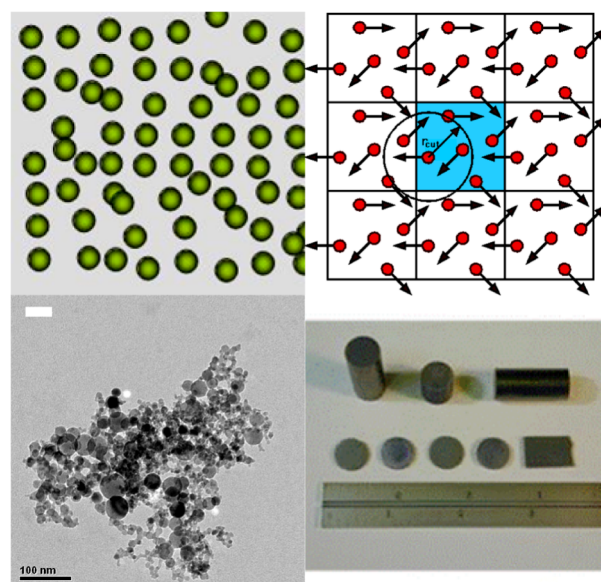


FIGURE 3.1—Illustration summarizing the theoretical and experimental approaches developed in the MIT Nano-TE effort: (top left) nanoparticle composite structure, (top right) Monte Carlo and molecular dynamics transport property calculations, (bottom left) nanoparticle synthesis, and (bottom right) compaction into high-density bulk samples.

The main goal of this effort is to experimentally demonstrate peak ZT values of ~ 2.0 , twice that of state-of-the-art n-type $\text{Si}_{0.8}\text{Ge}_{0.2}$ alloys used in RTGs, which would lead to system conversion efficiency of 14 to 15 percent. Another goal is to develop predictive models based on first principles that could guide the design and engineering of the nanocomposites in terms of nanoparticle size, shape, composition, and distribution. An additional focus is to develop synthesis processes for bulk nanocomposites that can be scaled up to a large-scale manufacturing process that could produce large numbers of TE couples at a relatively low cost. Specific tasks of this research activity, illustrated in Figure 3.1, include nanowire and nanoparticle synthesis, high-pressure sintering, structural characterization, TE properties characterization, and modeling of the nanocomposites.

MIT Nano-TE Accomplishments

Early in Phase I, nanowires and nanoparticles of Si, Ge, and $\text{Si}_{1-x}\text{Ge}_x$ were successfully synthesized. This key challenge was addressed using three different methods: (1) a wet chemistry method carried out at Boston College, (2) a high-energy ball-milling technique developed at JPL, and finally (3) an inert gas condensation method developed at the University of Illinois at Champaign/Urbana.

The first two techniques produced 10 to 15 g of material at a time and have an excellent potential for scale-up to bulk

quantities. Batches of nanoparticles were then hot pressed into Si/Ge and Si/Si_{1-x}Ge_x nanocomposites and nanobulk Si and Si_{1-x}Ge_x samples using a Plasma Pressure Compaction (P²C) apparatus at Boston College and a uniaxial hot press apparatus at JPL. Mechanically strong full-density samples, typically 12 mm in diameter and 2 to 15 mm long, were produced both at JPL and at Boston College (ref. 12). In Phase II and Phase III, nanoparticles 5 to 15 nm in size were routinely produced and compacted. JPL focused on p-type Si_{0.8}Ge_{0.2} and n-type Si nanobulk samples and on p-type Si/Si_{0.6}Ge_{0.4} nanocomposite compositions. Boston College studied in particular the n-type Si_{1-x}Ge_x nanobulk samples and Si/Si_{1-x}Ge_x nanocomposites with $x < 0.3$. In addition, JPL demonstrated that other semiconductors attractive for TEs could be produced in nanoparticle form through dry mechanochemical synthesis and be compacted into high-density samples. A combination of detailed x-ray diffraction (XRD) analysis and transmission electron microscope (TEM) analysis was used to characterize the size of the nanoparticles as synthesized and after hot pressing. In spite of processing temperatures in excess of 1325 K, results showed that only minimal coarsening of the nanostructure occurred. This key finding allowed for systematic studies of the high-temperature transport properties of both nanobulk and nanocomposite samples.

The hot-pressed samples were characterized at room temperature for screening, and promising samples were then characterized up to 1275 K at JPL and up to 1000 K at MIT. The largest increases in ZT to date over state-of-the-art Si-Ge alloys have been obtained on nanobulk p-type Si_{0.8}Ge_{0.2} samples and on n-type Si samples. Such increases are due mostly to a much lower lattice thermal conductivity value, as illustrated in Figure 3.2. High-temperature measurements of these samples produced by both the high-energy milling and P²C methods indicate over a 50 percent decrease in thermal conductivity in comparison to that of typical “large grain” hot-pressed samples produced during the SP-100 program (ref. 13). In fact the 20- to 25-W/cmK values are comparable with earlier results obtained on Si_{0.8}Ge_{0.2} samples that were produced with a special spark erosion technique, mixed with 4- to 12-nm inert insulating inclusions and hot pressed into dense pellets (ref. 14). Results on several samples produced by both JPL and Boston College demonstrated that the determining factor in lowering the thermal conductivity was the nanosized particles and not the compaction technique, in spite of very different processing conditions. Samples using the nano/micro mix of particles had much higher thermal conductivity values (Fig. 3.2). In addition, preliminary extended heat-treatment experiments carried out at temperatures in excess of 1275 K and for up to a month indicated that no significant loss of the nanostructured features occurred. This is illustrated in Figure 3.2, which actually shows a slight decrease in thermal conductivity after a vacuum heat treatment at 1275 K for 720 hr. Although further extended testing is required, the thermal stability of the nanobulk samples appears to be excellent.

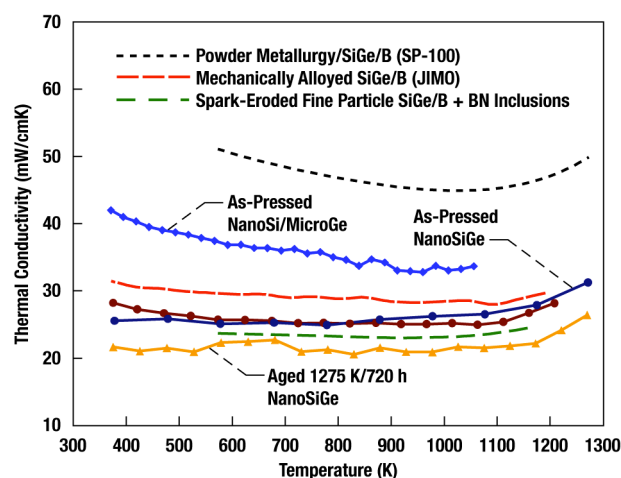


FIGURE 3.2—Temperature dependence of the thermal conductivity of p-type nanobulk Si_{0.8}Ge_{0.2} compared with that of state-of-the-art Si-Ge alloys. Results demonstrate that a 50 percent drop in thermal conductivity is maintained after extended high-temperature heat treatments.

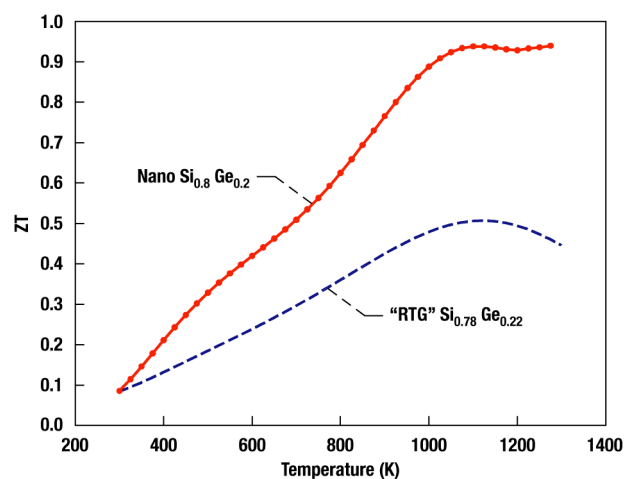


FIGURE 3.3—Temperature dependence of the dimensionless TE figure of merit, ZT , for p-type nanobulk Si_{0.8}Ge_{0.2} compared with that of state-of-practice RTG Si-Ge alloys. Results indicate 80 percent improvement over the full temperature range of application.

Optimization of the carrier concentration of p-type Si_{0.8}Ge_{0.2} samples produced by high-energy ball milling resulted in the highest ZT values ever achieved on p-type Si_{1-x}Ge_x alloys, a factor of 1.8 increase, as shown in Figure 3.3. The best results were actually generated after high-temperature treatments with ZT values as high as 0.92 in comparison to 0.50 for materials used in Si-Ge-based RTGs. These experimental results are attributed to strong interface scattering mechanisms that act as an energy filtering for electrons and scattering boundary for phonons, as discussed in the following section. Because the work on n-type compositions was initiated later, progress has been slower in improving ZT values, with maximum values only comparable to those of materials developed in the SP-100

program, or about a 15 percent improvement over state-of-practice alloys. Preliminary studies conducted on n-type nanobulk Si samples are much more promising, however, with ZT values increased by a factor of 3.5 over single-crystal data.

Model calculations provide an important guide for the design and choice of processing parameters in the synthesis and compaction of nanocomposite and nanobulk structures. Since the reduction of the thermal conductivity is the most important strategy for enhancing the TE figure of merit for nanocomposites, calculations to demonstrate how nanocomposites might be designed to have values lower than those for alloys with the same nominal composition are of great interest. Such calculations suggest the choice of processing parameters and approaches to be taken for doping and other process-sensitive considerations in the actual preparation of nanocomposite materials. Three approaches used by MIT for such model calculations follow:

- (1) The Boltzmann transport equation was solved for a unit cell containing aligned nanoparticles with periodic boundary conditions imposed on the heat flow direction, with a fixed temperature difference across each unit cell in the model nanocomposite, and with the interface reflectivity and the relaxation time used as input parameters.
- (2) A Monte Carlo method was used for the modeling calculations, particularly for the case of random particle size, orientation, and distribution. Checks between the two mathematical approaches were carried out successfully.
- (3) In Phase III, the spectral dependence of the phonon mean free path in Si was extracted through molecular dynamics simulations and used to recalculate the lattice thermal conductivity with the first two methods.

During Phase I and Phase II, in-plane thermal conductivity of nanowires and nanowire composites were calculated by solving the two-dimensional Boltzmann transport equation for a variety of core-shell structures, contributed to the selection of nanoparticles rather than nanowires as the basic nanosized structured unit to be used in preparing the nanocomposite materials (ref. 15).

The thermal conductivity for nanocomposites can fall below that obtained for their parent bulk samples for cases where the composites contain particle sizes in the 10-nm range for alloy compositions of $\text{Si}_x\text{Ge}_{1-x}$ in the range $0.2 < x < 0.8$. Results from the molecular dynamics simulations indicate that bulk nanostructured Si-Ge samples could have a 90 percent reduction in lattice thermal conductivity. This was experimentally demonstrated at JPL on several n-type nanobulk heavily doped Si samples made of 10- to 15-nm nanoparticles, as illustrated in Figure 3.4.

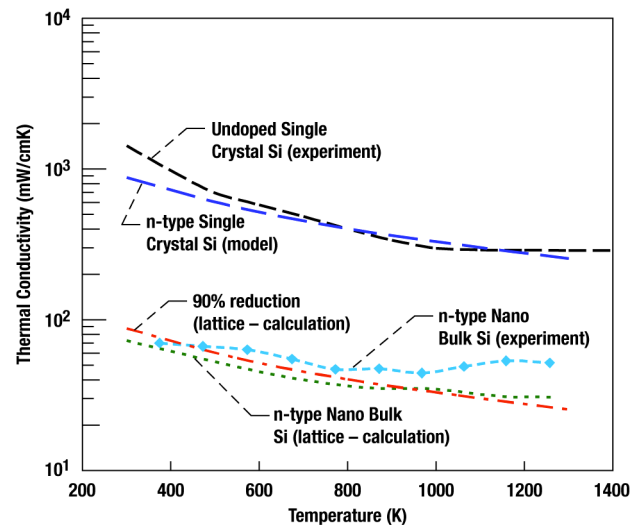


FIGURE 3.4—90 percent reduction in lattice thermal conductivity of n-type nanobulk Si demonstrated experimentally. Results are consistent with detailed molecular dynamics simulations.

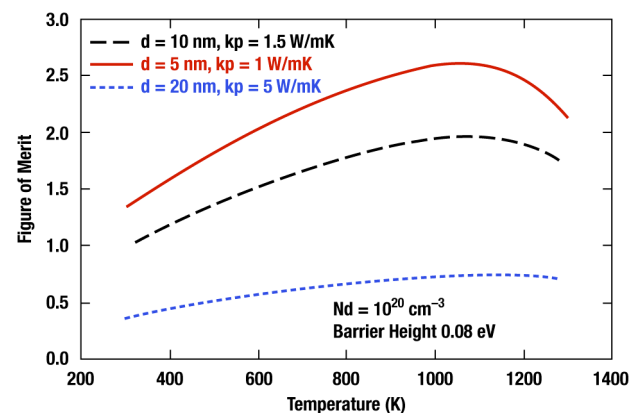


FIGURE 3.5—Predicted temperature dependence of the dimensionless TE figure of merit, ZT , as a function of nanoparticle size for n-type nanobulk $\text{Si}_{0.8}\text{Ge}_{0.2}$. Maximum ZT values of 2.0 to 2.5 were predicted for nanobulk samples with nanoparticle sizes 10 nm or lower.

Modeling in combination with experimental data showed that enhancements in ZT can be achieved in nanocomposite materials through both a reduction in the thermal conductivity and an increase in power factor on the same samples and within a common temperature range. Preliminary predictions for n-type $\text{Si}_{0.8}\text{Ge}_{0.2}$ (Fig. 3.5) indicated a sharp dependence of peak ZT values with nanoparticle sizes. Maximum ZT values of about 2.0 and 2.5 were predicted for nanoparticle sizes of 10 and 5 nm, respectively (ref. 16).

MIT Nano-TE Plans

This effort is slated to continue in a follow-on program continuing to be led by MIT with collaborations from Boston College, JPL, and NASA GRC to pursue the optimization of Si/Ge nanocomposites and nanobulk $\text{Si}_{1-x}\text{Ge}_x$ samples. Although the ZT of p-type materials has nearly doubled, significant progress remains to be made with n-type materials. Key activities will include further developing a detailed and predictive understanding of the large improvement in ZT in nanobulk p-type $\text{Si}_{0.8}\text{Ge}_{0.2}$ samples and n-type Si samples and applying this understanding to the best n-type $\text{Si}_{1-x}\text{Ge}_x$ nanobulk or Si/ $\text{Si}_{1-x}\text{Ge}_x$ nanocomposite compositions. Further reduction of the nanoparticle size should lead to higher ZT values, and experimental nanoparticle synthesis techniques will be refined. In addition, most heat-treatment experiments have been done at a temperature below the melting point. The idea that annealing in the solid-liquid coexistence temperature range should increase the number of interfaces will be pursued.

From a modeling point of view, there will be a two-prong focus for nanobulk and nanocomposite materials: (1) development of a detailed phonon model and (2) development of a full-blown electron transport model. The frequency-dependent phonon mean free path in bulk materials has been extracted for the first time, and this information will be incorporated into a Monte Carlo simulation of the phonon thermal conductivity of nanocomposites. The current model for electron transport in nanocomposites is still primitive since it does not include detailed TE effects at each interface. Models for electron transport that include such detailed processes will be developed and used to further guide the materials development.

An additional activity will consist of fabricating and testing a TE uncouple device to validate the improved materials performance and directly compare with state-of-practice RTG uncouples.

MIT Nano-TE Benefits

The key benefit of the MIT Nano-TE research program will be the transition from the promise of high ZT values in low dimensional structures to the practical realization of high ZT bulk samples that can be readily integrated in advanced RTGs (ARTGs). In addition, the detailed modeling tools that have been developed and that will be further refined in the follow-on program are powerful tools for guiding materials design and engineering for even further performance improvements. The technology payoff is illustrated in Figure 3.6, with preliminary system-level calculations predicting more than a factor of 2 improvement in RTG-system specific power and conversion efficiency for average ZT values in the range of 1.5 to 2.0. The Advanced ThermoElectric Converter (ATEC) project is a RPS research and development project to develop advanced TE technology for integration into the next generation of RTGs with a specific power of up to 76 percent greater than that

for state-of-practice GPHS-RTGs for potential use in future NASA deep-space missions, including Europa exploration missions. JPL leads the project with collaborations from NASA GRC, several university partners, and industry contractors. This project, started in January 2006, is focusing on demonstrating technology at TRL 5 by September 2009 for integration into a first generation of advanced RTG using the most performant materials available early in 2007. On the basis of the very promising results on p-type nanobulk $\text{Si}_{0.8}\text{Ge}_{0.2}$ achieved in the MIT Nano-TE task and on the maturity of Si-Ge alloys for RTG applications, ATEC selected this material as one of the two main candidates for the high-temperature p-type segment that would operate between 1275 and 875 K.

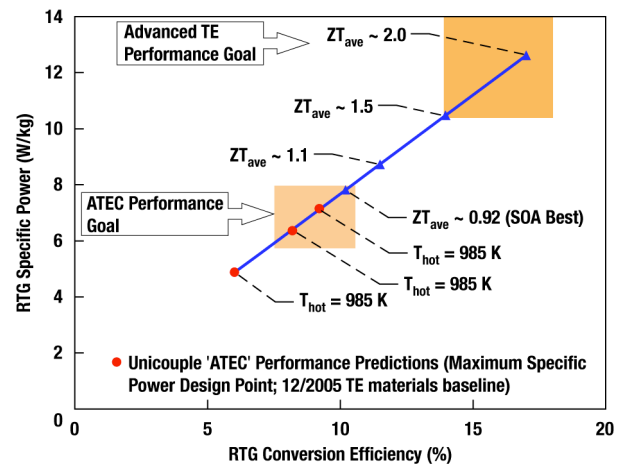


FIGURE 3.6—Preliminary calculations showing predicted RTG-system specific power as a function of system conversion efficiency. Equivalence with average ZT values of the TE materials across the entire operating temperature range is also reported. Average ZT values in the 1.5 to 2.0 range, a goal of this effort, would lead to more than doubling system performance. For reference, the TE hot and cold junction temperatures are 1275 and 550 K, respectively, unless otherwise indicated on the figure (GPHS-RTG: 1275 and 575 K).

4. RPCT STIRLING CONVERTOR DEVELOPMENT

Description of Sunpower Advanced Stirling Convertor Effort

As one of the centerpiece advanced technology development efforts, Sunpower, Inc., (Athens, OH) is leading the development of an advanced Stirling convertor that would enable a Stirling generator with a convertor efficiency greater than 30 percent. This factor of 4 efficiency improvement over the state-of-practice allows for a factor of 2 improvement in the system specific power to $>8\text{W/kg}$. In this Advanced Stirling Convertor (ASC) effort, Sunpower is partnered with Pratt & Whitney Rocketdyne (PWR), Cleveland State University (CSU), the University of Minnesota, and several Stirling engine consultants.

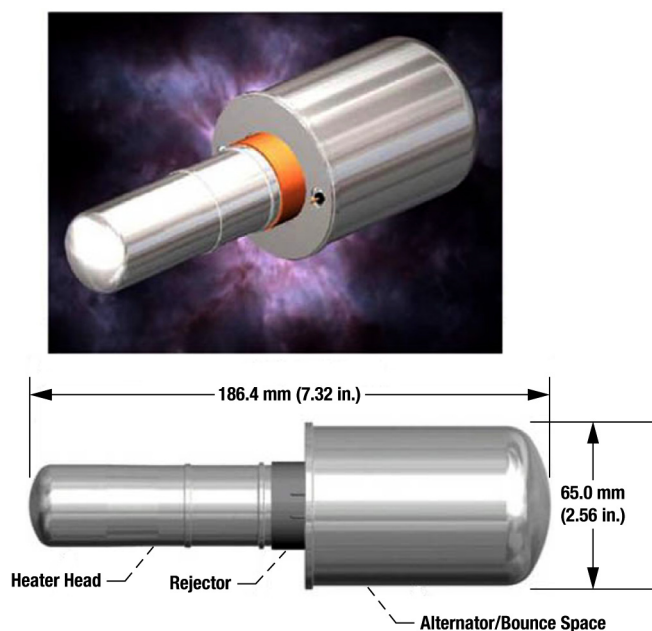


FIGURE 4.1—Sunpower Advanced Stirling Converter (ASC) artist concepts.

Sunpower Advanced Stirling Converter Accomplishments

The ASC development is phased in three parts, the first two of which are now complete. During Phase I a frequency test-bed (FTB) convertor was designed and a pair of convertors were fabricated and demonstrated. The units were designed as a testbed to operate at a hot temperature of 650 °C and a rejection temperature of 30 °C. This temperature ratio of 3 is equivalent to the final ASC design, which will operate at a hot end temperature of 850 °C and a rejection temperature of 90 °C. These nonhermetic pathfinder units were made operational in 5 months allowing frequency and component investigations. At the FTB design temperature ratio, the convertors exceeded performance goals and achieved 36 percent conversion efficiency (AC power out/heat in), providing 80 W_e output power (ref. 17). An additional task in Phase I was to incorporate the lessons learned from the FTB into the initial design of the first-generation ASC convertors, designated the ASC-1.

The end goal of the contracted effort is to design, fabricate, and demonstrate operation of hermetically sealed ASC convertors (see Fig. 4.1). The units are expected to produce 88-We AC power at approximately 40 percent conversion efficiency with an input thermal power of 220 W (ref. 18). A key technological issue to overcome is to increase the hot-end operating temperature to 850 °C. This increase over the state of practice will be accomplished by using MarM-247 as the heater head material provided under subcontract by PWR. NASA GRC conducted an investigation of candidate materials, which included high-temperature creep testing. The results provided to the ASC team during Phase I, along with engine performance analysis, showed that a 1 percent creep in the thin-walled pressure vessel over a 14-yr life would have no impact on performance. The Phase II effort focused on the fabrication and demonstration

of the ASC-1 units. During Phase II, four ASC-1 convertors were fabricated. Being development units, all four were nonhermetic, but allowed for the demonstration of heater head and other critical component material processing strategies. The first two units incorporated an all MarM-247 heater head, whereas the second two units had an inertia-welded transition joint from MarM-247 to Inconel 718. Figure 4.2 provides a photograph of the four ASC-1 engines. During testing, the nonoptimized ASC-1 engine demonstrated 88-We power output at an efficiency of 38 percent at the design temperature range of 850 °C hot end and 90 °C rejection. A key component to the engine was an internally fabricated iron-chromium alloy (FeCrAlloy) regenerator provided by NASA GRC.



FIGURE 4.2—Four ASC-1 engines built during Phase II.

In addition to the high-temperature heater head and high-porosity regenerator materials, key convertor technologies in the ASC development effort include hydrostatic gas bearings, moving magnet alternators, high-frequency operation, and an active power factor controller. Since the goal is to transfer the technology to further system development, resources are also being expended in the areas of reliability assessment, thermodynamic analyses, and extended-duration testing.

Description of CSU Regenerator Effort

As part of the RPCT NRA, a CSU-led team is developing microfabricated Stirling regenerators with the key benefits of increased performance and structural robustness. The CSU team includes the University of Minnesota, Gedeon Associates, Sunpower, Infinia Corp., and International Mezzo Technologies. The microfabrication effort has developed a new involute-foil matrix geometry. The advantage of the design is that it eliminates any geometric uncertainty and can be directly modeled with optimization of pressure drop and heat transfer characteristics (ref. 19). Key technology issues revolve around developing fabrication techniques to generate <100-μm features on a regenerator with a length on the order of 10 cm. In the early phase of the project, several geometries were considered; however, final selection was for a combined LIGA-EDM

process done by Mezzo. The design consists of stacks of hundreds of 0.265-mm-thick disks with involute patterns. The involutes are alternated to increase flow mixing and improve heat transfer (Fig. 4.3).

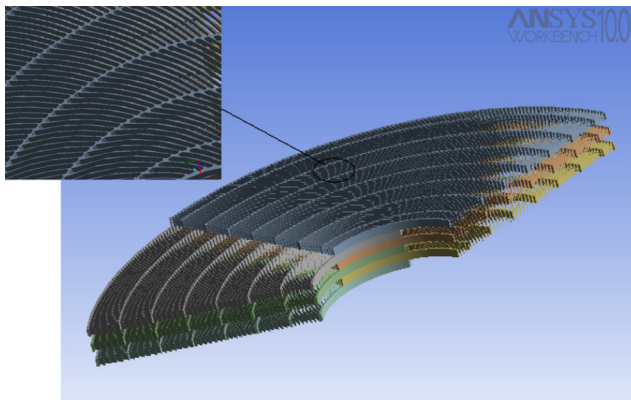


FIGURE 4.3—Involute-foil regenerator disks.

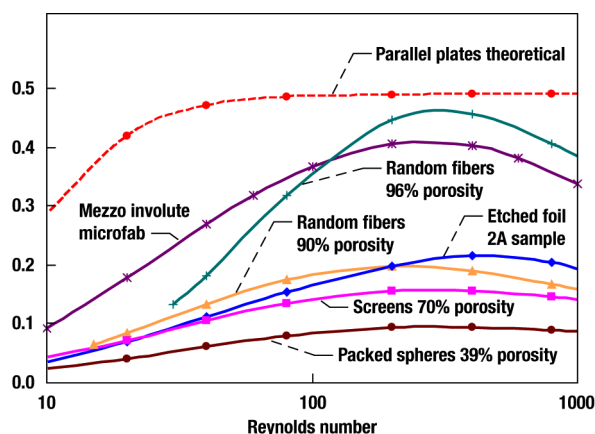


FIGURE 4.4—Figure of merit vs. Reynolds number.

CSU Regenerator Accomplishments

The project is working in three key areas: (1) involute foil fabrication demonstration, (2) empirical and analytical characterization of the heat transfer and pressure drop using the Large-Scale-Mock-Up (LSMU) combined with Computational fluid dynamics (CFD) analysis, and (3) actual hardware testing in a Stirling engine oscillating flow simulator. A CFD model has been developed to determine the velocity contours inside the flow channels of the involute foil disk and is used to predict resultant friction factors. Validation of the CFD is provided through the experimental results from the LSMU. Those results feed directly into hardware design. Nickel microfabricated involute foils were successfully fabricated and assembled into a stacked-element regenerator. The regenerator was subsequently tested in the Sunpower Oscillating Flow test rig. The data showed impressive results with a figure of merit (effectively the ratio of radial heat transfer to fluid friction factor) reaching twice that of the 90 percent porosity random fiber materials which are state of practice. (Fig. 4.4)

Projections indicate a 6 to 9 percent increase in performance in an optimized Stirling engine. The logical next step in the effort is to build a regenerator for testing in an ASC-heritage engine to verify performance improvement predictions.

Sunpower Advanced Stirling Convertor Plans

With the early successes of the ASC effort, the NASA-sponsored, DOE-managed SRG 110 effort was redirected to incorporate the new technology into an Engineering Unit (EU) for assembly and test by March 2008. An excellent review of the current status of this Advanced Stirling Radioisotope Generator (ASRG) project is provided by Chan's STAIF 2007 paper ref. 20). To support that effort, NASA GRC will provide to the DOE prime contractor, Lockheed Martin, two FTB units for controller development and two hermetic Stirling convertors plus a spare for the EU, designated ASC-E. The key objective of the EU generator development is to demonstrate that a highly reliable Stirling system can be built and demonstrated to meet NASA space science mission requirements. To meet the rapid schedule while still aligned with the key objective, researchers will incorporate an Inconel 718 heater head in the convertors provided to the EU effort and will design the convertors to operate with a 640 °C hot end and a 60 °C rejection temperature. In addition, the EU will make maximum use of existing SRG 110 hardware and hence will be not be optimized. However, the generator is expected to provide 140 We with a generator mass of 20.8 kg. The resultant specific power of 6.7 W/kg for the ASRG is a significant improvement over the 3.4 W/kg expected for the SRG 110. Optimization of the generator housing would allow for specific powers exceeding 7 W/kg.

As part of an effort to accelerate the acquisition of a database of testing and convertor operation experience, two additional pairs of hermetic convertors are being fabricated for early delivery in Phase III. The first hermetic pair, designated ASC-0 will incorporate Inconel 718 heater heads and will be put on extended duration testing at NASA GRC with a temperature ratio of 3, but with a hot-end temperature limit of 650 °C. The next accelerated pair are derived from the ASC-1 design and are designated ASC-1HS. This pair will have MarM-247 technology allowing operation up 850 °C and will be put under extended thermal-vacuum testing in the GRC Stirling laboratory.

NASA is committed to the success of the ASC and ASRG efforts and is committing its core competence in several direct areas. GRC will provide all long-duration testing for the ASC convertors and for the ASRG EU. GRC and JPL are teamed to provide electromagnetic interference (EMI) characterization and suppression, including providing design guidance on EMI, shield design, and evaluation and characterizing the EMI/electromagnetic compatibility (EMC) of the linear alternator. Additional environmental testing provided by NASA laboratories will include structural dynamics characterization. A key technological milestone is to operate dual-opposed engines in a stable

mode. GRC active power factor controller experience is being transferred to the contractor team for the ASRG development. Materials and structures are a limiting technology for Stirling engines. GRC's materials competency is being applied to the assessment of the hot-end materials, the development of alternate MarM-247-to-Inconel joining methods, regenerator processing and reliability investigation, accelerated structural testing of components, life analyses of the heater head, and assessment of the optimal cure cycle, bond strength, aging, and outgassing of the organics. The reliability assessment is led by Lockheed Martin as the DOE system integrator. In support of that effort, NASA personnel are providing physics-based probabilistic modeling of the convertor, system dynamics modeling, gas bearing analysis, magnet aging characterization, linear alternator demagnetization analysis, and structural modeling.

Advanced Stirling Convertor Benefits

In summary, the accomplishments and benefits of the advanced Stirling research and development efforts are as follows:

1. Sunpower Phase I FTB demonstration surpassed performance goal, demonstrating 36 percent conversion efficiency.
2. Sunpower Phase II ASC-1a was completed and is operational; testing to date at lower than design temperature provides encouraging results that design performance goals (88-We AC, 40 percent efficiency) will be met later in Phase II.
3. Projected ASC performance and mass led to significantly higher RPS specific power of >8 W/kg, enabling or enhancing future mission capabilities.
4. Development of an advanced regenerator offering improved structural robustness for higher reliability, controlled manufacturability, and improved Stirling convertor performance (projected 6 to 9 percent power increase).
5. Microfabricated regenerator permits use of progressive materials for strength and corrosion resistance.
6. Success of this NASA-sponsored technology is spinning off into potential Department of Defense applications.

Microfabricated regenerator technology can also benefit NASA missions employing cryocoolers:

1. Broad benefits—Microfabricated regenerator technology can be used in Stirling cryocooler regenerators and microscale heat exchangers.

2. Cryocoolers are essentially Stirling convertors run in reverse as “motors.”
3. Cryocoolers (<100 K) are used in missions requiring infrared sensors and low-noise amplifiers.
4. Improved cryocooler regenerators could boost overall efficiency by 40 percent or more.
5. Regenerator thermal loss comes directly off the payload in cryocoolers.

Even further increases in ASRG system performance could be achieved by infusion of the MarM-247 convertor technology. During Phase III, four second-generation (ASC-2), convertors that are hermetically sealed and that incorporate the MarM-247 technology will be built and tested, although no decision has been made to further develop beyond the ASRG EU. Future units on the path to flight development should be able to achieve specific power levels beyond 8 W/kg as a result of the full ASC technology effort.

5. RPCT THERMOPHOTOVOLTAIC CONVERTOR

Description of Creare TPV Convertor Effort

A team led by Creare Inc. and including EMCORE Corp., NASA GRC, Polytechnic University, Oak Ridge National Laboratory, Rugate Technologies, and the Naval Research Laboratory (NRL) was awarded an NRA development contract to demonstrate a radioisotope TPV (RTPV) power generator with a simulated radioisotope thermal source and a target 15 to 20 percent converter efficiency, ~15 W/kg system level specific power and an end of mission (EOM) power remaining factor of 85 percent including both radiation and optical degradation mechanisms. The Creare TPV system concept was based on TPV component technologies developed under the Naval Reactors program and leveraged a system design concept originally proposed by Schock (ref. 21), shown in Figure 5.1. The proposed system included high-temperature selective emitters, tandem optical filters, and advanced lattice-mismatched indium gallium arsenide (InGaAs) monolithic interconnected module (MIM) PV cells. Creare expected to demonstrate a system conversion efficiency of 15 to 20 percent, a system specific power of 10 to 15 W_e/kg, and a TRL of 5 at the end of the 3-yr program. The TPV converter test stand developed and tested under Phase I represented one half of the full TPV system. This system demonstrated an efficiency of >19 percent and more than 50 W_e (100 W_e for the full TPV system) for a prototypical array size of about 100 cm² with an emitter temperature of 1350 K and a heat-rejection temperature of 300 K. Creare began work on a detailed design of a test article that would improve upon the baseline converter when NASA funding cuts required a temporary suspension of this contract (ref. 22). Recognizing the potential benefits of TPV, a reduced effort was restarted in fiscal year 2007 when partial funding was restored.

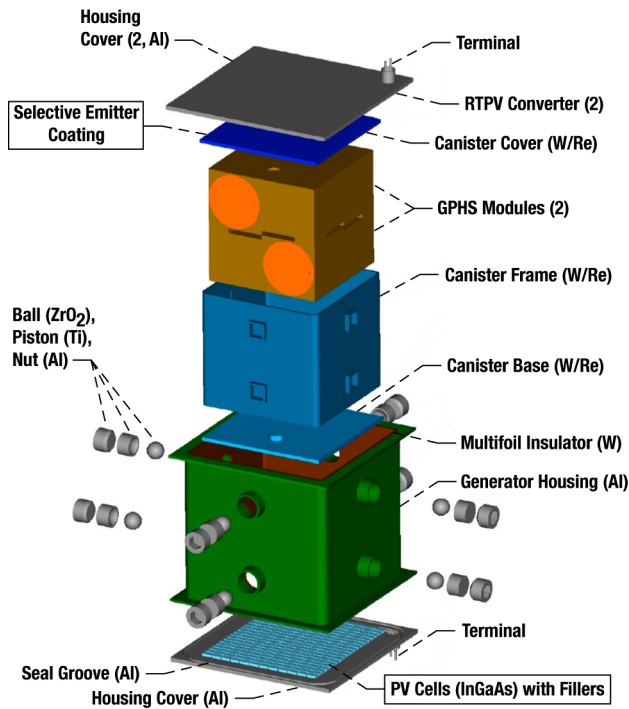


FIGURE 5.1—Diagram of Creare RTPV system concept, after Schock. The GPHS bricks are contained in a tungsten/rhenium (W/Re) container insulated on four sides. The top and bottom of the canister radiates infrared (IR) photons to the filtered MIM arrays.

Creare TPV Converter Accomplishments

The efficiency of an RTPV system can be viewed as the product of the following subelement efficiencies:

$$\eta_{\text{RTPV}} = \eta_{\text{housing}} \times \eta_{\text{cavity}} \times \eta_{\text{spectral}} \times \eta_{\text{PVcell}} \times \eta_{\text{PV network}} \times \eta_{\text{DC}}$$

The “housing” efficiency term describes the efficiency of heat transfer from the GPHS bricks to the power-producing TPV cavity. The “cavity” efficiency term describes the efficiency of coupling light from the hot emitter to the PV array. The “spectral” efficiency term describes the ability of the filter to preferentially transmit convertible photons to the PV array while reflecting nonconvertible photons back to the emitter. The “PVcell” efficiency term describes the ability of the PV device to convert the filtered photon flux into electricity. The “PVnetwork” efficiency term accounts for losses in the system due to the series/parallel connection of PV devices that may not be at the same temperature, have the same performance, or have the same photon flux. Finally, the “DC” efficiency term describes the efficiency of the DC-to-DC converter used to regulate the RTPV output power. The Creare effort demonstrated and accurately measured four of these subelement efficiencies (cavity, spectral, PVcell, and PVnetwork). The remaining two terms were estimated in order to estimate a complete RTPV system efficiency.

The primary focus of the Creare effort was to design a system that would maximize the TPV converter output power. This was accomplished by creating an efficient optical cavity and array design to minimize parasitic heat losses, matching the GPHS source temperature and heat flux constraints and quantifying losses due to nonuniform illumination of the MIM array as well as array network losses. Following that design effort, the Creare team selected, developed, and optimized key converter components (PV cell, optical filter, emitter material, etc.). Screening of the chosen component technologies for thermal and radiation stability was also initiated.

The PV cell chosen for this application was a lattice-mismatched 0.6-eV InGaAs device produced on a semi-insulating indium phosphide (InP) substrate. The use of an electrically insulating substrate enabled the formation and series interconnection of individual PV cells on the common substrate. Series connecting these cells built voltage, while keeping the total current flow low, thereby reducing resistive losses. In addition, the semi-insulating InP substrate is transparent to photons of interest in TPV, thus a gold (Au) reflector was deposited on the back surface of the cell to reflect unabsorbed photons back to the cell for a second opportunity for collection (ref. 23).

The MIM design settled on a die area of 2.3×2.3 cm, consisting of 25 PV cells connected in series. This configuration resulted in a typical output of 8 Vdc and 0.5 A per MIM device. The MIMs were connected into two different array designs, 3×3 and 4×4, meaning three parallel strings of three MIMs in series or four parallel strings of four MIMs in series. The 3×3 MIM array without tandem filters is shown in Figure 5.2. The arrays were bonded to a highly reflective 100-cm² Au-coated plate. The variation in plate packing fraction (48 percent for the 3×3 and 85 percent for the 4×4) was intended to examine the effect of packing fraction on emitter temperature uniformity and MIM current uniformity. Previous TPV system developments had noted a significant nonuniformity in view factor and photon flux from the center of the array to the edge. Characterization of individual MIM devices demonstrated an efficiency of 28 percent (η_{PVcell}) at a cell temperature of 300 K.

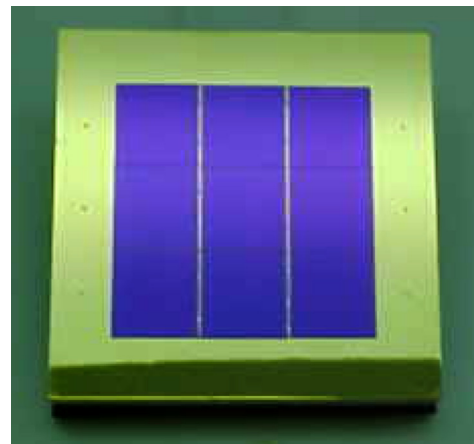


FIGURE 5.2—Creare RTPV 3x3 MIM array.

Bonded on top of the MIM devices were tandem optical filters consisting of a dielectric interference filter stack ($\text{SbSe}_3/\text{YF}_3$) deposited on an indium arsenide phosphide (InPAs) plasma filter epitaxially grown on a semi-insulating InP substrate. The dielectric stack has a very sharp reflection turn-on bandedge, but a limited spectral region of high reflectance (2 to $\sim 5\ \mu\text{m}$). Beyond that wavelength, the dielectric stack becomes transparent. It is in this long wavelength region where the plasma filter becomes highly reflective. Thus the combination of the dielectric and plasma filter results in a filter with a sharp turn-on and a long spectral region of high reflectance. The tandem filters have a measured spectral efficiency of 82 percent (η_{spectral}). Careful attention was paid to the selection of the individual filter and the individual MIM to assure that the filter turn-on wavelength coincided with the bandedge of the MIM quantum efficiency (ref. 24).

Creare designed and assembled a fully instrumented RTPV converter test facility that replicates one half of the full RTPV system and is housed in the vacuum chamber (nominal 1×10^{-6} torr), shown in Figure 5.3. The facility utilizes Boralectric heaters coupled to Poco graphite heat flux plates to simulate the GPHS brick. Emitter plates are mounted to the front surface of the graphite plate and then radiate to the filtered MIM array located $\sim 2\ \text{mm}$ away. Several emitter materials were considered and tested in the facility, including plasma-sprayed tungsten on either molybdenum or graphite, bare graphite, or roughened tungsten. The bias toward tungsten-based emitters can be attributed to the favorable optical properties of the tungsten as well as its extremely low vapor pressure. The low vapor pressure suggests that contamination of cold optical surfaces by sublimation losses from the hot components within the RTPV cavity may be limited if tungsten is used. Polished tantalum (Ta) foil plates were used to optically seal the cavity and prevent photons from escaping. Tests indicate that this cavity design (2-mm array-emitter spacing, Ta optical seals, and refined array design) was highly efficient ($\eta_{\text{cavity}} = 89$ percent). Further improvement in this performance is possible by recessing the MIMs and filters, thereby preventing photons from being lost to the edges of the filter and MIM.

Tests using the 4×4 filtered MIM array with a tungsten emitter in the RTPV test facility demonstrated an array efficiency of 95 percent ($\eta_{\text{PV network}}$), indicating that the individual MIM devices were well matched, of reasonably uniform temperature, had well matched tandem filters installed, and were not significantly affected by edge effects (view factor variations). This impressive result is largely attributed to the small (2-mm) gap between the array and the emitter as well as the over sizing of the emitter ($\sim 4\ \text{mm}$ on each side). Figure 5.4 graphically depicts the component efficiencies measured in the Creare tests. Excluding housing thermal losses, the RTPV converter demonstrated an efficiency of >19 percent. With an assumption of 10 percent housing losses, the total RTPV system efficiency is

projected to be ~ 18 percent. The total mass for the converter, including radiators, is estimated to be $\sim 7\ \text{kg}$, resulting in a mass specific power of $\sim 14\ \text{W/kg}$.

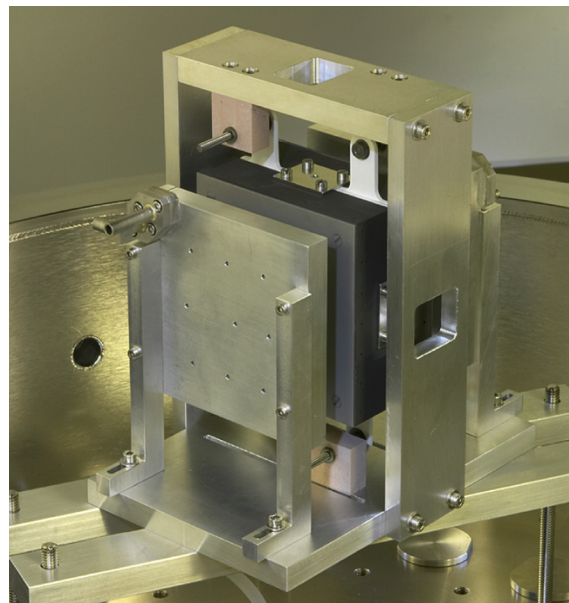


FIGURE 5.3—Creare RTPV converter test facility.

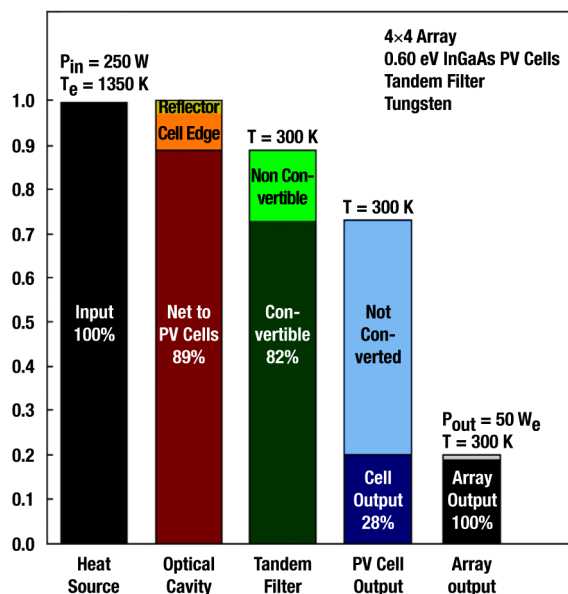


FIGURE 5.4—Creare RTPV converter test data showing measured component efficiencies (in white) for the η_{cavity} (optical cavity), η_{spectral} (tandem filter), η_{PVcell} (PV cell output), and $\eta_{\text{PV network}}$ (array output). The testing demonstrated a converter efficiency of greater than 19 percent. Using estimates for the η_{housing} and η_{DC} , Creare predicts a complete RTPV system efficiency of ~ 18 percent.

In addition to the RTPV converter demonstration, the Creare team also began to perform longevity testing on critical

components. For example, the 0.6-eV MIM devices, tandem filters, and optical adhesives were tested by NRL to determine their degradation caused by 14 years of radiation exposure from the GPHS bricks. The results of the testing predict that the tandem filters and optical adhesives will be unaffected and that the MIM will degrade by 20 percent. This is comparable with the 16 percent degradation demonstrated by the TE elements in the RTG system.

To address the materials sublimation concern, NASA GRC assembled an ultra-high-vacuum furnace to characterize the sublimation rate of materials used to construct the hot portions of the RTPV system. System construction and preliminary checkout testing were completed at the time the effort was suspended because of a funding cut to the project.

A synopsis of Creare's major accomplishments for Phase I and early Phase II follows:

1. Converter efficiency of greater than 19 percent was demonstrated with a PV cell array in a test configuration that lacked only a housing and DC-to-DC power regulation.
2. A detailed performance model was developed that includes radiation, conduction, convection heat transfer, and PV cell electrical performance that compares well with experimental data.
3. InGaAs PV cells were consistently fabricated with high performance.
4. High-performance tandem filters were consistently fabricated.
5. An ultra-high-vacuum facility was prepared to perform materials evaporation and deposition tests for operation.
6. The GPHS heat source neutron irradiation was determined to not affect the optical characteristics of the PV cells, tandem filters, and adhesives over the 14-yr mission.
7. The PV cell output power was determined to degrade by 20 percent because of to the neutron irradiation over the 14-yr mission (EOM power = $0.8 \times \text{BOM}$).

Creare TPV Converter Plans

In the Phase I effort, the Creare team successfully demonstrated the potential for a high-efficiency, low-mass RTPV system. Several issues and concerns were raised as a result of that activity, including the need to

1. Redesign the array plate to improve the robustness of the electrical feed-throughs
2. Recess the cells and filters so that the top surface of the filter is level with the surrounding reflector in order to improve the cavity efficiency
3. Determine the sublimation rates for the hot side materials and determine the effect on EOM performance

4. Complete MIM radiation degradation testing and examine hardening options via device optimization
5. Verify the ability of the MIM device to operate at elevated temperatures and high current density for extended periods of time (14 years)
6. Verify the ability of the tandem filter to operate at elevated temperatures for an extended period of time
7. Examine the tradeoff of RTPV system efficiency and specific power versus MIM temperature, addressing the concern about excessive radiator area
8. Redesign the RTPV test facility to permit better thermal analysis of the RTPV converter

Recent efforts in the Naval Reactors program resulted in advancements that relate to item (6). The material used for the tandem filter (antimony selenide, Sb_2Se_3) in the Phase I activity was subsequently shown to have a catastrophic failure mode at $\sim 150^\circ\text{C}$ (the transition from transparent to absorbing). This failure is caused by the recrystallization of the Sb_2Se_3 material. Recently, Rugate Technologies developed a replacement material (gallium telluride, GaTe) that is stable well above 150°C . At the Knolls Atomic Power Laboratory, these new filters were tested up to 90°C for over 1000 hr with no degradation in performance (ref. 25). In a follow-on effort, the Creare team would transition to this new material approach.

In regards to item (7), researchers at the Knolls Atomic Power Laboratory (KAPL) recently performed a system modeling tradeoff study based on the Creare development approach that suggested that increasing the MIM temperature from 42 to 143°C would decrease the radiator area by 50 percent, while only reducing the specific power by 15 percent (ref. 24). Thus, there exists a parameter space for optimization of RTPV performance characteristics to suit the requirements of the specific mission.

TPV Converter Relevant Benefits

Radioisotope TPV systems offer a potentially higher efficiency ($2\times$) and lower mass ($2\times$) power system alternative to the RTGs currently used for NASA's deep-space missions. RTPV is a static conversion process, thus vibration and electromagnetic interference (EMI) concerns are nonexistent. RTPV has the potential for high reliability because it contains no moving parts, has no single-point failure modes, and is modular in small power increments.

6. BENEFITS AND PAYOFFS TO FUTURE MISSIONS

This section provides a general discussion of the benefits from the development of these advanced power conversion technologies and the eventual payoffs to future missions (discussing system benefits due to overall improvements in efficiency, specific power, etc.).

Advanced Power Conversion System Benefits

The Cassini spacecraft utilized three GPHS-RTGs with a total of approximately 30 kg of plutonium oxide (PuO_2) in

its 54 GPHS. This was the maximum amount of PuO₂ fuel ever used on a single U.S. mission, and it may represent a practical upper limit on the amount of fuel that the existing DOE infrastructure could process. The PuO₂ mass and number of GPHS thermal sources requirements as a function of power level and conversion efficiency is illustrated in Figure 6.1. The advanced high-specific-power RPS currently under research and development will be capable of small, medium, and flagship-class applications; could enable the use of radioisotope electric propulsion for deep-space science missions, and could provide surface power levels of greater than 3 kW for the exploration of the Moon and Mars. High-power applications with conversion efficiencies twice that of the MMRTG would still exceed the total amount of PuO₂ used on Cassini. However, with RPSs with greater than 20 percent efficiencies, these higher power levels could be met with GPHS and PuO₂ requirements comparable to what was used for the Cassini mission (ref. 26).

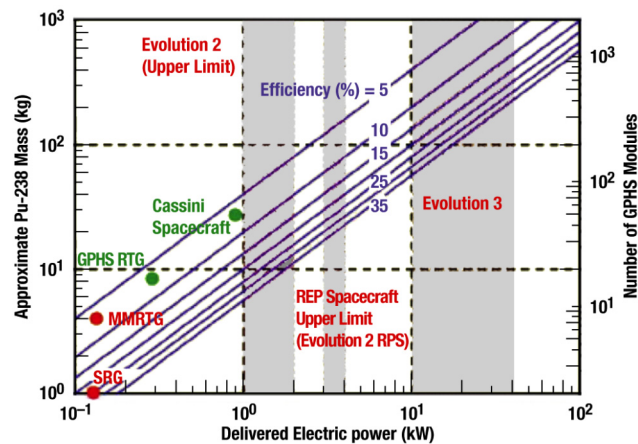


FIGURE 6.1—Plutonium requirements vs. delivered power.

Eventual Payoffs for Future Missions

The science and exploration communities have identified a broad range of high-priority missions for the next two decades, many of which may require RPSs (Table 6.1). ARPSs have the potential to enhance, and possibly enable, these missions by virtue of their greater specific power and higher conversion efficiencies compared with those of existing RPSs, such as the GPHS–RTG and the MMRTG.

In 2005, a series of high-level mission concept studies were performed to understand the system and mission impacts and relative tradeoffs of using ARPS technology (ref. 4). These studies include a Titan orbiter with a probe, a Titan rover, a Europa lander, and a long-lived Venus rover. The science goals of each mission study were derived from the priorities of the Solar System Exploration Decadal Survey

(ref. 27) and the Solar System Exploration Strategic Roadmap (ref. 28).

The results of the mission studies show that ARPSs enable significantly larger scientific payloads, compared with using existing RPSs, and in certain cases, could potentially permit the use of smaller, and commensurately less expensive, launch vehicles. Although low-power applications would see a moderate mass advantage from using RPSs, it is really the higher power Galileo- and Cassini-class missions (>500 W) that would benefit the most from the higher specific power of these power systems. Lastly, ARPSs would be mission-enabling for a long-lived Venus surface mission, because none of NASA’s current RPS systems have the capability to operate in this extreme environment. Other potential missions have been postulated with RPS-based electric propulsion; a combination of higher power output and lower generator mass will be needed to further increase the specific power (ref. 29).

TABLE 6.1—Science and Exploration Missions Potentially Requiring Radioisotope Power Systems

Missions Potentially Enabled by ¹ Radioisotope Power Systems	SSEDs ² Time Frame	SSESrM ³ Time Frame	VSE ⁴ Time Frame	Source
Venus Surface Explorer		2015–2025		SSESrM
Lunar Lander			≥2009	VSE
Lunar Rover			≥2011	VSE
Lunar Base			>2020	VSE
Mars Long-Lived Lander Network	2003–2013			SSEDs
Mars Science Laboratory	2003–2013			SSEDs
Mars Astrobiology Field Laboratory				MEPAG ⁵
Io Observer	>2013			SSEDs
Europa Geophysical Explorer/Observer	2003–2013	2005–2025		SSEDs and SSESrM
Europa Lander	>2013	2005–2025		SSEDs and SSESrM
Ganymede Observer	>2013			SSEDs
Saturn Ring Observer	>2013			SSEDs
Titan Explorer	>2013	2015–2025		SSEDs and SSESrM
Uranus Orbiter with Probes	>2013			SSEDs
Neptune Orbiter with Probes	>2013	2015–2025		SSEDs and SSESrM
Neptune Orbiter with Triton Explorer	>2013	2015–2025		SSEDs and SSESrM
New Horizons—Kuiper Belt-Pluto Explorer	2003–2013			SSEDs
Trojan Asteroid/Centaur Reconnaissance	>2013			SSEDs

¹Missions are in order of Sun proximity (not in science priority)

²SSEDs = Solar System Exploration Decadal Survey (Space Studies Board, 2003)

³SSESrM = Solar System Exploration Strategic Roadmap (NASA, 2005)

⁴VSE = Vision for Space Exploration (Bush, 2004)

⁵MEPAG = Mars Exploration Program Analysis Group

A brief description of the results of the ARPS mission concept study follows:

Europa Lander Mission

A Europa Geophysical Explorer mission was identified in the Solar System Exploration Decadal Survey (ref. 28) the highest-priority flagship-class outer solar system mission for the next decade. Although that recommendation was for an orbiter mission, it is widely recognized that a landed science package would dramatically increase the value of any Europa mission (Fig. 6.2).

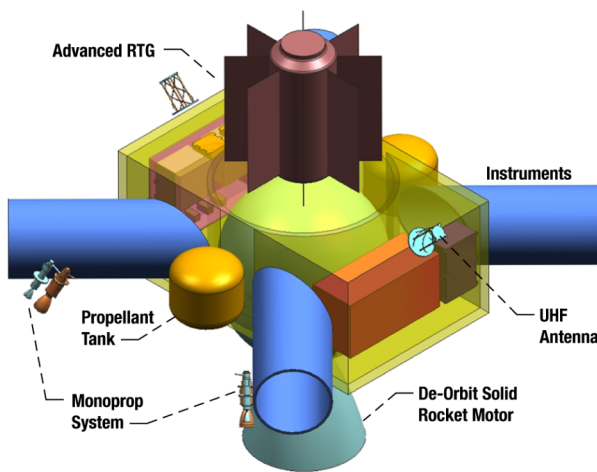


FIGURE 6.2—Europa lander concept using ARPS.

This study demonstrates that long-lived in situ surface exploration would greatly benefit from the use of ARPS technologies. A key advantage of ARPSs for a Europa lander mission is their higher specific power, which would provide a mass savings that could be used to increase payload capability or lander design margins. RPSs, in general, are suitable for Europa in that they do not require solar insolation; they are long lived; and they can be used to keep the lander electronics warm during the long cruise phase and on the very cold Europa surface. Certain RPSs are also inherently radiation tolerant, which is a key consideration for missions operating in the intense ionizing radiation of the Jovian system. Solar array power options would have significantly more mass and would be very sensitive to the radiation environment. The use of RPS technologies would enable sustained geophysical measurements over several 3.55-day Europa tidal cycles.

Table 6.2 compares the lander mass for the four ARPS options considered in the mission concept study: namely, ARTG, ASRG, TPV, and Brayton. The TPV option had the lowest launch and landed mass; however, the TPV's requirements for additional shielding in a high-radiation environment were not well defined, and there were unaccounted for mass impacts because of the need for a large (and heavy) cruise stage thermal radiator. The Stirling option was among the heaviest options, along with Brayton, because of the former's need for three Stirling units (two prime plus one redundant) and significant shielding for the controller. The ARTG option was determined to be the most attractive option for the Europa lander concept because of the ARTG's inherent radiation tolerance and excess heat, which could be used to maintain system operating temperatures without the need for electrical heaters.

TABLE 6.2—Europa Lander Concept Mass Comparison (With Contingency)

Subsystem	Mass, kg			
	Adv. RTG	Adv. Stirling	TPV	Brayton
Lander Total—Dry	778.8	786.0	750.9	791.2
Propellant and Pressurant	46.5	48.7	44.8	47.2
Lander Total—Launch Mass	825.3	834.7	795.7	837.7
Lander Total—Landed Mass	400.1	418.9	384.7	407.0

As mentioned, RPS is an enabling technology for a long-duration (i.e., more than several weeks) Europa surface mission and would allow science data collection over several tidal cycles. The spacecraft design using the ARTG option had a launch mass of 825 kg and a landed dry mass of 400 kg. Using a Delta IV-Heavy to launch onto a 2015 ΔV-EGA trajectory would allow a launch mass of 5580 kg. This could accommodate an orbiter of 1500 kg (inserted into Europa orbit) along with the 825-kg lander.

Titan Orbiter with Probe Mission

The Titan orbiter with probe concept study (Fig. 6.3) was envisioned as a follow-on Titan orbiter mission that would provide full global topographic coverage, surface imaging, and meteorological characterization of the atmosphere over a nominal 2-yr science mission. The baseline power requirement is ~1 kWe at EOM and is driven by a high-power radar instrument that would provide three-dimensional measurements of atmospheric clouds, precipitation, and surface topography. Although this power level is moderately higher than that of the Cassini spacecraft, higher efficiency ARPSs could potentially reduce ²³⁸Pu usage to less than one-third that used on the Cassini spacecraft.

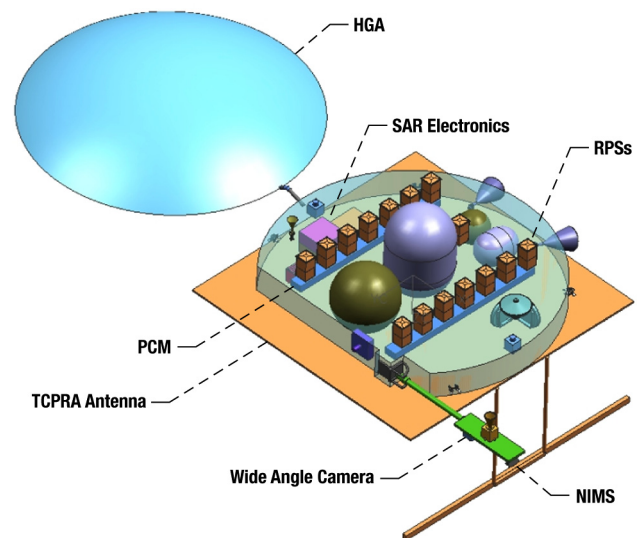


FIGURE 6.3—Conceptual Titan orbiter spacecraft.

The Titan orbiter mission is assumed to launch in 2015. It would utilize ARPSs to provide all onboard power and would employ an aeroshell to aerocapture into Titan orbit. In addition, a 500-kg “black box” deployed probe, with unspecified science instrumentation, was included in the design.

The baseline Titan orbiter mission would use conceptual ASRGs for all electrical power generation. Although other ARPS options were considered for this mission (i.e., ARTG, TPV, and Brayton), the higher efficiency and specific power

of the ASRG yielded the lightest overall orbiter configuration and, subsequently, the largest probe size. Each ASRG was assumed to generate 80 We at BOM with a conversion efficiency of 32 percent. A single 250-Wth (BOM) GPHS module would be used for this RPS design. Thermal control would be performed via heat rejection from the Stirling housing and small external fins, and via an integrated cooling loop that interfaces with the Titan orbiter spacecraft cooling system for maintaining spacecraft operating temperatures and for energy storage during the aerocapture maneuver. An active vibration compensator would be used to limit vibration levels associated with a single convertor system (i.e., as opposed to the balanced two-convertor system of the SRG, which would nominally not require a compensator).

A total of 15 ASRGs would be used on the Titan orbiter, 14 required for the mission design power level of 1120 We at BOM, and one included for redundancy. The electrical power produced by the redundant ASRG does not count toward the design power level, but it could be used to enhance the mission if the 14 prime RPSs were operating nominally. However, the spacecraft thermal control system must account for the heat generated by all 15 RPSs. The design EOM power level is estimated at ~1033 We after 10 years and assumes a ^{238}Pu fuel decay of ~0.8 percent/yr and no generator degradation during the mission.

Titan Rover Mission

The Solar System Exploration Decadal Survey (ref. 27) identified Titan as one of the top priority science destinations in the large moons category. The exploration of Titan in the form of future orbiter and/or lander missions was also rated high in the Solar System Exploration Strategic Roadmap (ref. 28). In fact, Titan ranked second in this list after a projected Europa Geophysical Observer mission. A key goal of this study was to assess the benefits of ARPS in powering the Titan rover concept (Fig. 6.4). Newer, more efficient power conversion technology with higher specific power would enable greater amounts of payload and potentially new mission architectures or the use of smaller (less expensive) launch vehicles.

Alternative power sources were looked at for powering the Titan rover concept, including solar power generation, batteries, and fuel cells. Because of the length of the surface mission (3 years), the use of fuel cells would be impractical because of the mass of the fuel itself. Similarly, an all-battery design could not last long enough on the surface to meet the 3-yr requirement. Because the mission concept is to land in the polar regions to allow a nearly constant view of the Sun, solar power may at first seem to be a feasible option; however, at 9.5 AU, the Sun's solar insolation is only ~1 percent that in Earth orbit, without taking into account any loss due to Titan's clouds and thick obscuring atmosphere. Titan's extremely cold environment would

require the use of low-intensity, low-temperature (LILT)-tolerant PV arrays. The LILT solar arrays on the European Space Agency's Rosetta spacecraft produce ~395 We for 64 m² at 5.25 AU. Assuming the same power efficiency for the Titan rover concept, ~45 m² of solar arrays would be required to generate the same power level as just one ARTG. In addition, a solar-powered rover would need resistance heaters for its thermal management system, requiring an array much larger than this. Furthermore, to power the spacecraft during cruise, a second solar array almost as large as the first would be needed in addition to the array on the rover. The mass of these two large arrays, combined with the structural support, gimbals, and associated equipment to allow the concept to maneuver with the array without blocking the telecom system would be prohibitively massive and complex in comparison to the simple and efficient configuration with a single ARTG.

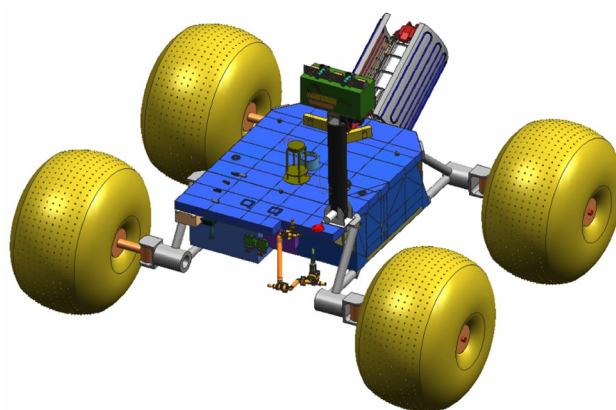


FIGURE 6.4—Illustration of the conceptual Titan rover.

On Titan, the ARTG would benefit from the extremely cold temperatures and convective atmosphere; eliminating the need for radiator fins (the ARTG housing has enough surface area in itself to not require fins). However, the ARTG would require active cooling while in cruise to remove the heat while with its protective aeroshell. Assuming an auxiliary coolant loop was used similar to that on the MMRTG, the cruise heat-rejection system would be connected to the ARTG during prelaunch and discarded prior to Titan entry.

The baseline configuration of the Titan rover uses a single ARTG as its power source; however, the mission could potentially be accomplished with the ASRG, Brayton, or TPV RPSs, with an associated increase in power system mass and/or integration complexity. As shown in Table 6.3, there is a moderate mass difference between the four ARPS options considered for the present mission; note, however, that system-level mass ripple effects are not in the table. These effects would increase the mass differences even further. The rover in its baseline configuration has a mass of 376 kg with a 30 percent contingency.

TABLE 6.3—ARPS System Mass Comparison for the Titan Rover Mission Concept

	Adv. RTG (kg) 1 unit	TPV (kg) 1 unit	Adv. Stirling (kg) 3 units	Brayton (kg) 1 unit
Total Advanced RTG System Mass	25.5	15.9	41.1	28.9
Difference from Advanced RTG Baseline		−9.6	15.6	3.5
*Mass values are without contingency and do not reflect system ripple effects.				

Venus Rover Mission

This concept study illustrates how a long-lived Venus rover mission (Fig. 6.5) could be enabled by a novel application of ARPS technology. The extreme temperature and pressure of Venus and the requirement for a long-duration surface mission limit the type of power system that could be used for this conceptual mission. Previous missions to the Venus surface have been powered by batteries with surface durations on the order of a few hours. Because the present mission duration requirement is for a minimum of 60 days, it is clear that battery power alone is insufficient for this concept. Solar arrays were likewise considered, but the caustic and high-temperature Venus atmosphere would rapidly degrade their performance, making them impractical for this application. Existing RPSs such as the GPHS–RTG and MMRTG were not designed for the intense pressure and temperature of the surface of Venus, and thus are not viable candidates for this mission. This rover mission concept uses an ARPS in a novel way to survive on the surface of Venus.

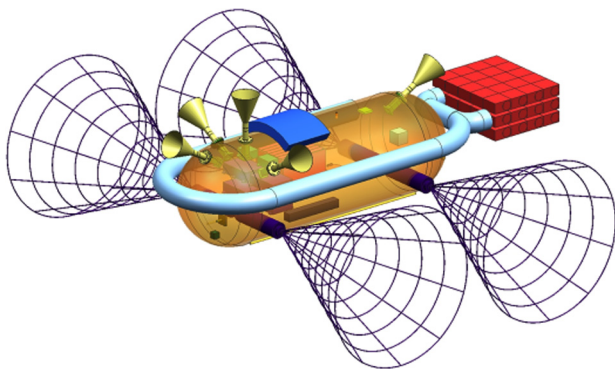


FIGURE 6.5—Venus surface rover concept.

Because a key mission requirement is the need for active cooling of rover subsystems, mission-specific dynamic RPSs systems are a natural choice. Stirling and Brayton RPSs are two such systems that could be directly coupled to a cryocooler to efficiently generate electrical power for the rover's subsystems and cooling to maintain steady-state temperatures within the rover pressure vessel. Such ARPSs are considered enabling for this mission concept.

The Thermoacoustic Stirling Heat Engine (TASHE) could potentially provide this enabling capability. Multiple GPHS modules would be used to drive the TASHE, while a pulse tube refrigerator and linear alternator would provide cooling and electric power to the rover. TASHE is a system for converting high-temperature heat into acoustic power,

which then drives a pair of flexure-bearing linear alternators to produce electric power. Heat would be provided by GPHS modules, and the “cold” side would be furnished by the Venus ambient atmosphere (460 °C).

The present Venus rover concept would use 53 GPHS modules to generate the 80 W of electrical power and 414 W of thermal cooling used by the payload and other rover systems.

Although TASHE is not currently one of the technologies being developed under the RPCT NRA, it has been the subject of a past NRA and current SBIR development, and it is gaining interest in the ARPS project.

7. CONCLUSIONS

NASA has successfully used radioisotope fuel to power numerous past missions in applications where PV arrays are not practical. Next-generation conversion technologies suitable for future radioisotope power systems (RPS), with higher efficiency, higher specific power (watts per kilogram), long life, high reliability, scalability, and multimission capability are being developed under contracts awarded as part of the Radioisotope Power Conversion Technology (RPCT) project. Results from the four RPCT NASA Research Announcement (NRA) contracts in the areas of Stirling, thermoelectric, and thermophotovoltaic power conversion technologies have been summarized. Emphasis of these advanced conversion technology development and research efforts is on improving performance, increasing system specific power, and providing reliability for long life. These attributes allow for improved RPSs that will require less plutonium fuel, are more cost effective, have lower waste heat-rejection requirements, and will enable or enhance future mission capability. These ARPS systems will provide NASA with attractive power system options that will enable future space science and exploration missions, such as outer-planetary exploration and Moon and Mars exploration missions.

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BIOGRAPHIES



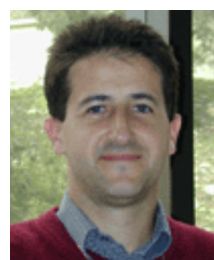
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He is currently the deputy project systems engineer for the Juno mission to Jupiter, the lead systems engineer for JPL's Europa Explorer concept study, and the Cog-E for JPL's RPS engineering analysis task. He has held lead positions in the International Space Station program at Boeing, Rocketdyne working mission operations and electrical power system test, and in the Missile Defense Program at Boeing, Anaheim. He has a B.S. in Mechanical Engineering, an M.S. in Nuclear Fission Engineering, and a Ph.D. in Mechanical and Fusion Engineering from the University of California, Los Angeles.

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14. ABSTRACT NASA's Advanced Radioisotope Power Systems (ARPS) project is developing the next generation of radioisotope power conversion technologies that will enable future missions that have requirements that cannot be met by either photovoltaic systems or by current radioisotope power systems (RPSs). Requirements of advanced RPSs include high efficiency and high specific power (watts/kilogram) in order to meet future mission requirements with less radioisotope fuel and lower mass so that these systems can meet requirements for a variety of future space applications, including continual operation surface missions, outer-planetary missions, and solar probe. These advances would enable a factor of 2 to 4 decrease in the amount of fuel required to generate electrical power. Advanced RPS development goals also include long-life, reliability, and scalability. This paper provides an update on the contractual efforts under the Radioisotope Power Conversion Technology (RPCT) NASA Research Announcement (NRA) for research and development of Stirling, thermoelectric, and thermophotovoltaic power conversion technologies. The paper summarizes the current RPCT NRA efforts with a brief description of the effort, a status and/or summary of the contractor's key accomplishments, a discussion of upcoming plans, and a discussion of relevant system-level benefits and implications. The paper also provides a general discussion of the benefits from the development of these advanced power conversion technologies and the eventual payoffs to future missions (discussing system benefits due to overall improvements in efficiency, specific power, etc.).					
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