NASA/TM—2007-214707

Future Opportunities for Dynamic Power Systems for NASA Missions

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August 2007

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Prepared for the
International Stirling Forum 2006
sponsored by The Center for Environmental Communication ZUK Der DBU
Osnabruck, Germany, September 26–27, 2007

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Space Administration

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August 2007

Acknowledgments

The work performed in this paper was performed for NASA through the Science Mission Directorate for the Radioisotope Power System (RPS) Program and through the Exploration Systems Mission Directorate for the Prometheus Program for the Fission Surface Power Development Project. The author wishes to acknowledge the contributions of Lee Mason and Jeffrey Schreiber of NASA Glenn.

This report contains preliminary findings, subject to revision as analysis proceeds.

Level of Review: This material has been technically reviewed by technical management.

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Future Opportunities for Dynamic Power Systems for NASA Missions

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Abstract

Dynamic power systems have the potential to be used in Radioisotope Power Systems (RPS) and Fission Surface Power Systems (FSPS) to provide high efficiency, reliable and long life power generation for future NASA applications and missions. Dynamic power systems have been developed by NASA over the decades, but none have ever operated in space. Advanced Stirling convertors are currently being developed at the NASA Glenn Research Center. These systems have demonstrated high efficiencies to enable high system specific power (>8 W_e/kg) for 100 W_e class Advanced Stirling Radioisotope Generators (ASRG). The ASRG could enable significant extended and expanded operation on the Mars surface and on long-life deep space missions. In addition, advanced high power Stirling convertors (>150 W_e/kg), for use with surface fission power systems, could provide power ranging from 30 to 50 kW_e, and would be enabling for both lunar and Mars exploration. This paper will discuss the status of various energy conversion options currently under development by NASA Glenn for the Radioisotope Power System Program for NASA's Science Mission Directorate (SMD) and the Prometheus Program for the Exploration Systems Mission Directorate (ESMD).

1.0 Background

Nuclear systems are usually considered for long life missions and where other systems are not competitive. A typical nuclear (Radioisotope or Reactor) power concept includes the following subsystems: a heat source, an energy conversion system and appropriate controllers, a heat rejection system for removing unused heat, and a power management and distribution system to distribute the power to the remainder of the spacecraft systems. NASA is currently developing two classes of advanced dynamic power systems: 100 W_e class radioisotope power systems (RPS) using a free-piston Stirling convertor and 25 kW_e to 100 kW_e fission surface power systems which are considering both the closed Brayton cycle and free-piston Stirling conversion systems. While dynamic power systems have demonstrated good performance (high efficiency) and better scaling to high power levels, key questions regarding long life operation remain (ref. 1).

Nuclear power systems have enabled or enhanced many of NASA's most challenging missions (refs. 2 to 4). Figure 1 illustrates the applicability of typical electric power conversion technologies used and/or considered for space including photovoltaic (solar), thermal-to-electric (Brayton, Rankine or Stirling cycles), batteries, fuel cells and nuclear (radioisotope and reactor) systems. Shown are the power levels from a few watts to 100s of kW_e along with potential mission life times. Selection of a specific power system is based on the mission specific requirements with consideration given to the availability of the technology at the time of the evaluation.

Radioisotope power systems have played a critical role in NASA space science missions. As shown in figure 2, a total of 23 missions have used the heat provided from the decay of Plutonium (Pu 238) to provide electrical power since 1961. The state-of-practice Radioisotope Thermoelectric Generator (RIG) uses Pu 238 fuel with a half-life of 87.7 years. The Pu 238 is contained in a General Purpose Heat Source (GPHS) module and uses Si-Ge as the thermoelectric couple (refs. 5 and 6). The state-of-practice GPHS

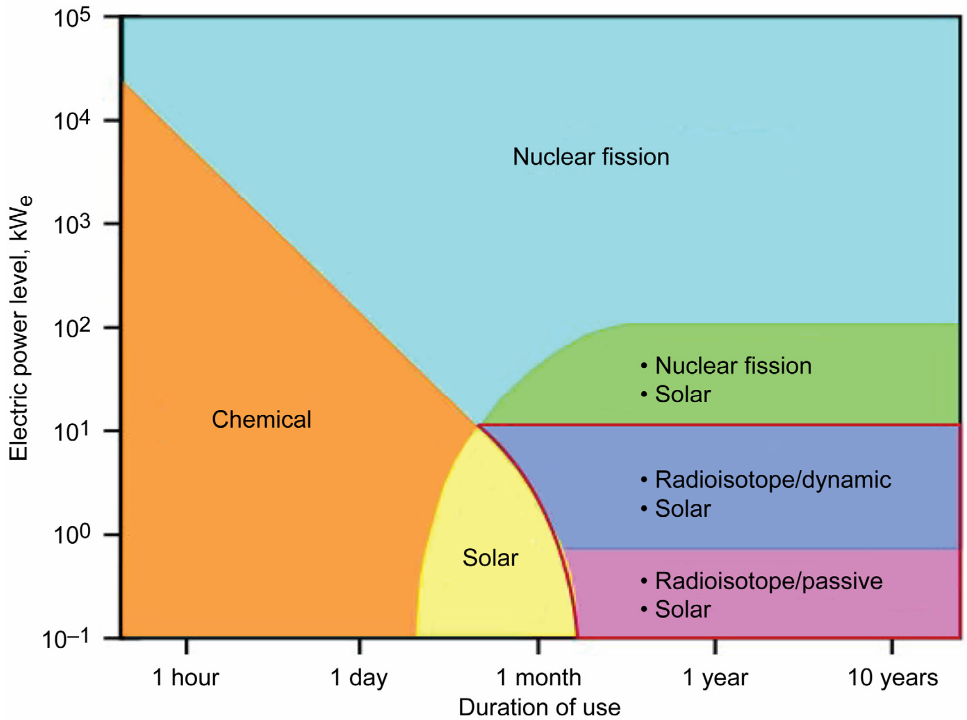


Figure 1.—Applicability of power conversion technologies versus power levels and mission duration.

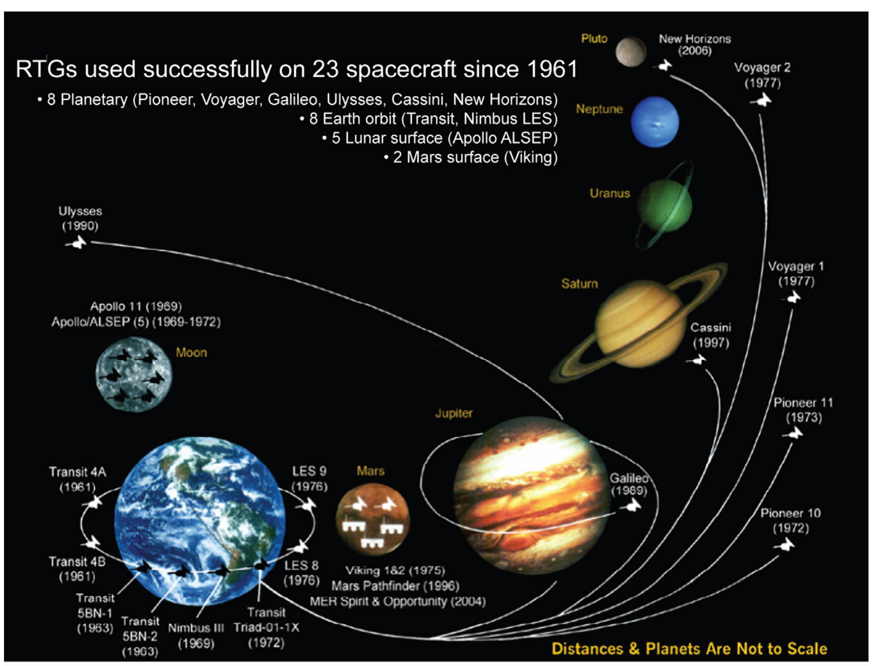


Figure 2.—U.S. radioisotope space power missions.

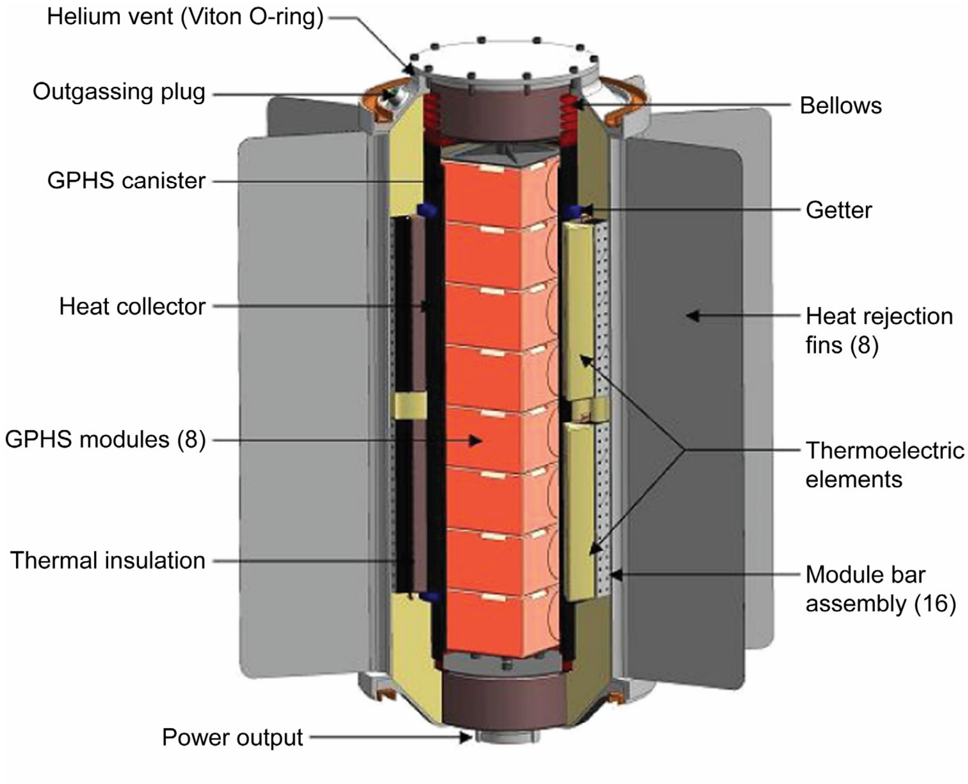
RIG has a specific power of 5.1 W_e/kg with an overall system efficiency of 6.3 percent. Each RIG contains 18 GPHS modules and provides about 290 W_e at the beginning of mission. Past missions that have successfully used the GPHS RTG include the Voyager 1 and 2, Galileo, Ulysses and the Cassini (ref. 7). The most recent NASA spacecraft to use an RIG is the New Horizons Mission launched the January 19, 2006 and is the first mission to the last planet, Pluto. The GPHS RIG is providing continuous rower to the spacecraft which is expected to arrive at Pluto in July 2015 (refs. 8 to 10). The GPHS RIG used on the New Horizons mission was the last Si-Ge RIG available from the Department of Energy (DOE), as these generators are no longer in production.

NASA Headquarters—Science Mission Directorate (SMD) and the Department of Energy (DOE), Germantown, MD have been working together on the development of a new class of RPSs to provide a more efficient, highly reliable and long life energy conversion systems for future SMD missions. The advanced RPS development is a result of competitive procurements by the DOE for NASA's SMD which resulted in two development contracts: (1) for the Multi-Mission RIG (MM RIG) and (2) the Stirling Radioisotope Generator (SRG) which are shown in figure 3. The MM RIG is currently under development by DOE with Rocketdyne, Canoga Park, CA and Teledyne Energy Systems, Hunt Valley, MD. The MM RIG is expected to be first used on NASA Mars Science Laboratory (MSL) is expected to be available for launch in 2009.

The MM RIG uses Pb-Ie/IAGS thermoelectric couples and is being designed for a 14 year life while providing about 125 W_e at the beginning of the mission. Past experience with Pb-Te couples includes the Nimbus, SNAP-19 for Pioneer 10 & 11 in 1972 and 1973, respectively and most recently on Viking 1 & 2 in 1975 (ref. 7). The MM RTG specific power is expected to be about 2.8 W_e/kg while the system (thermal-to-electric) efficiency is estimated to be 6.3 percent. Each MM RTG uses eight GPHS modules and weights about 44.2 kg (ref. 11).

In 1999, an industry/government team evaluated the capabilities of the Technology Demonstration Convertor (TDC) and determined that no technical showstoppers exist for the TDC, and the TDC was ready for the next step towards development into an RPS (ref. 12). NASA Glenn in cooperation with the DOE, Lockheed Martin, and Infinia Corp. worked in a collaborative manner in addressing the key technology development issues to permit the transition of the Infinia's TDC base-lined for the SRG 110 Program. The Glenn tasks focus on providing reliability data to assure the design is valid for long life operation. Included are: materials (both organics and metallics), structures, life analysis and testing, free-piston Stirling convertor and controller tests, linear alternators and magnets, launch environments, EMI and reliability (ref. 13).

The SRG 110 shown in figure 4 is a highly efficient alternate to the RTG using the Stirling convertor and was under development since May 2002 by DOE with Lockheed Martin, Valley Forge, PA and Infinia, Corp. (formerly Stirling Technology Company, Kennewick, WA). Each SRG 110 uses a pair of Stirling Convertor Assemblies (SCA) operated at T_{hot} 650 °C and T_{rej} 80 °C and each producing about 60 W_e (ac). The Infinia Stirling convertor uses a free-piston Stirling engine coupled to a moving iron linear alternator in a hermetically sealed pressure vessel. Helium is the working fluid. Further, non-contact operation is achieved with the use of flexures, which eliminate wear mechanisms associated with rings and/or seals allowing for very long life. The SRG110 is designed for 14 year life while providing about 110 W_e at the beginning of mission. The Infinia SCA specific power was about 15 W_e/kg. The SRG 110 design using the SCAs resulted in a system specific power of about 3.6 W_e/kg while the system (thermal-to-electric) efficiency was estimated to be 23.2 percent. Because of the higher thermal-to-electric efficiency the SRG 110 uses only two GPHS modules per generator and weighs about 32.5 kg (with margin) (ref. 11).



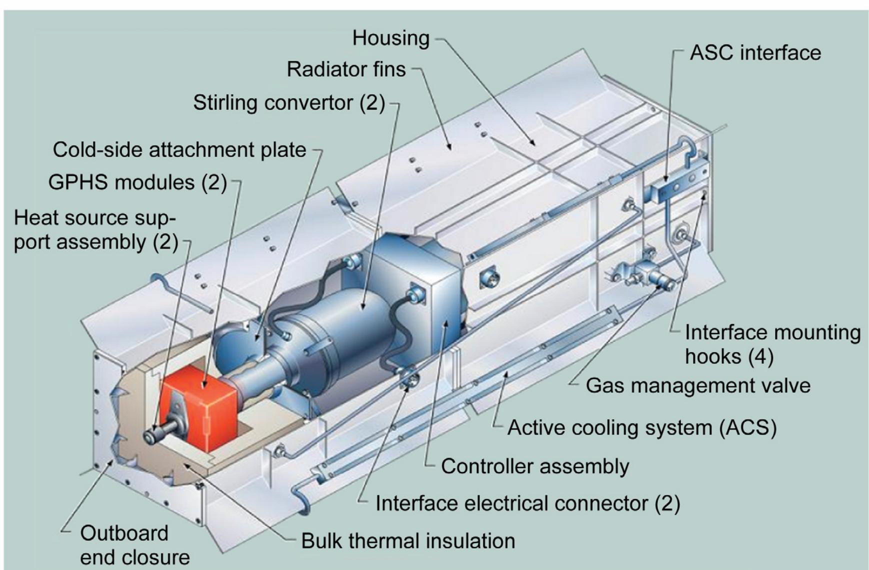


Figure 3.—NASA RPS flight development contract, MM RTG and SRG contracts managed by the U.S. Department of Energy.

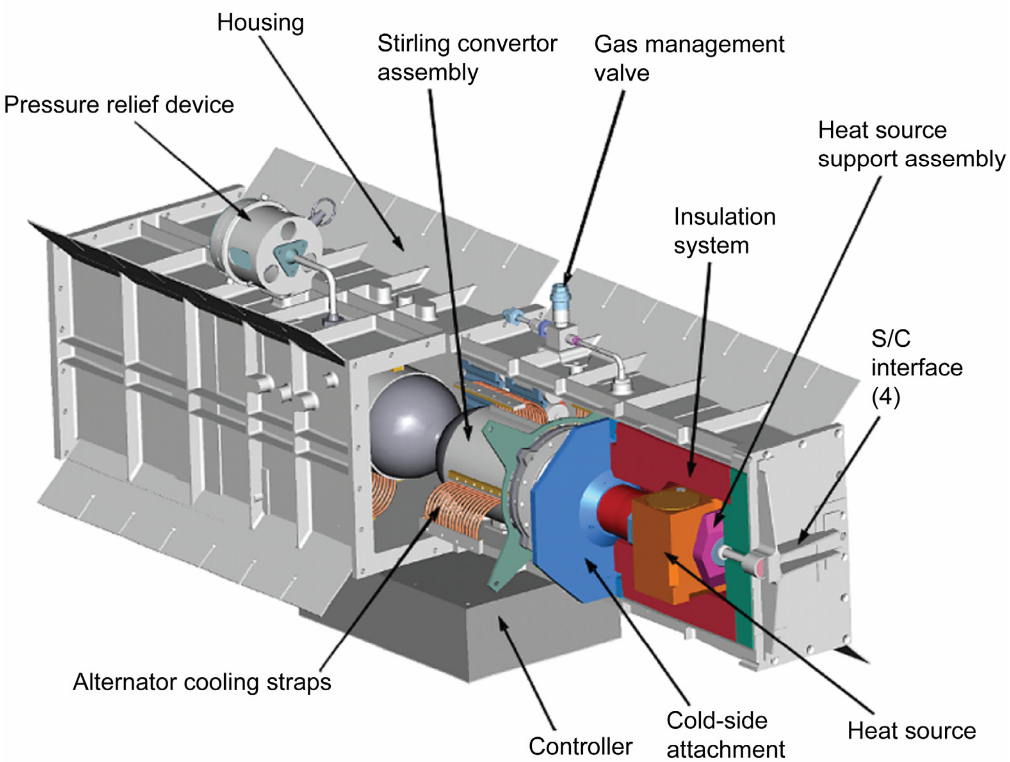


Figure 4.—The 110 We SRG110 design by Lockheed.

TABLE I.—HOURS ACCUMULATED ON THE TECHNOLOGY DEMONSTRATION CONVERTORS (TDCS) FROM INFINIA CORPORATION AT THE GLENN RESEARCH CENTER, CLEVELAND, OH

TDC	Environment	Hours accumulated, ea	Total, hr
#5 and #6	Thermal vacuum	>10,000	>20,000
#7 and #8	In-air	>1000	>2,000
#13 and #14	In-air	>23,000	>46,000
#15 and #16	In-air	>9,000	>18,000
Total			> 84,000

As noted in table I over 80,000 hours of successful operation of the Infinia TDCs (3 pairs of SCAs were operated 24/7 to evaluate performance) were completed in both in-air and thermal vacuum environments with no evidence of wear or degradation (refs. 14 and 15).

As a result of increasing mission requirements and the need for a higher specific power RPS (>6 to 8 W_e/kg) for future science missions, the SRG Project was redirected in May 2006 by NASA to incorporate the Advanced Stirling Convertor (ASC) which is being developed by Sunpower, Inc., Athens, OH under contract to NASA Glenn. The Sunpower convertor uses a free-piston Stirling engine integrated with a linear alternator (moving magnet) contained in a hermetically sealed pressure vessel. Non-contact operation is achieved with a combination of compliance and hydrostatic gas bearings to eliminate any wear mechanisms to ensure long life. The Sunpower ASC has operated at T_{hot} 650 °C and T_{rej} 80 °C providing about 80 W_e (ac) with helium as the working fluid (refs. 15 to 17). The ASC has a convertor specific power of about 90 W_e/kg and is being provided to the DOE and Lockheed Martin (the system integrator) to improve the system specific power by a factor of 2 to about 7 W_e/kg. The advanced SRG

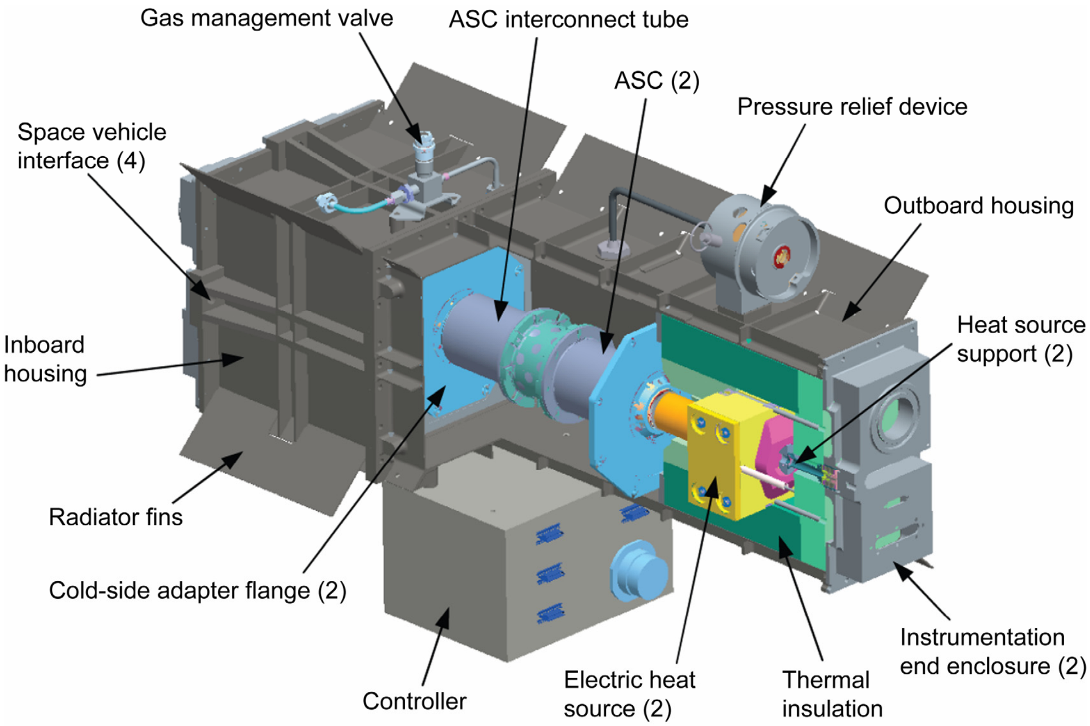


Figure 5.—The advanced SRG design by Lockheed.

(ASRG) shown in figure 5 uses a pair of the Sunpower ASCs operated at T_{hot} 650 °C and T_{rej} at 80 °C. The ASRG is not an optimized system, rather, it uses the existing SRG design with a direct substitution of the ASCs. Modifications for the ASC design include mechanical, thermal and electrical, along with 25 percent reduction in length. Included in the ASRG is a single fault tolerant controller. The ASRG is being deigned for a 14 year life. Initial estimates indicate the ASRG could provide about 160 W_e at the beginning of the mission. NASA Glenn is currently procuring two pairs of hermetically sealed ASCs to evaluate performance and extended (24/7) operation in both air and thermal vacuum environment starting in early 2007. Current plans call for the demonstration of performance for the electrically heated ASRG Engineering Unit for DOE by Lockheed in early 2008.

Table II shows a comparison of the key features GPH S-RIG, MM RTG, SRGI 10 and the ASRG (refs. 11 and 18).

TABLE II.—COMPARISON OF GPHS-RTG WITH MM RTG, SRG110, AND ASRG

	GPHS-RTG	MM RTG	SRG11O	ASRG
BOM Net Elect Power, W_e	285	125	116	160
Hot-end temperature, °C	1000	538	650	850
Cold-end temperature, °C	300	210	80	80
# GPHS modules	18	8	2	2
BOM heat input, Wt	4500	2000	500	500
RPS (system) efficiency, percent	6.3	6.3	23.2	~32
Radiator area, m^2/kW_e	~3.6	~7.4	~6.2	4.0
GPHS modules, kg	25.7	12.9	3.2	3.2
Total mass, kg	56.0	44.2	32.5	~19
Specific power, W_e/kg	5.1	2.8	3.6	>8

Both the MM RIG and the ASRG will be capable of operating in both the vacuum of space and in the Mars atmosphere. While the MSL is currently the only planned mission, a number of potential missions exist for NASA's future solar system exploration. Included are the Europa Explorer, Titan Explorer, Long duration Venus Explorer, Neptune Orbiter with Probe, Jovial Trojan Asteroid Orbiter, Mars Astrobilology Field Laboratory, and a Lander/rover in the permanently shadowed regions of the lunar surface (refs. 16 and 17). In addition a number of missions such as the Trojan Asteroid Orbiter, Neptune Orbiter and an Interstellar Probe would require Radioisotope Electric Propulsion (REP) where the RPS specific power greater than 6 to 8 W_e/kg is required (refs. 19 to 21).

Specific power (W_e/kg) of a complete radioisotope power generator is the critical metric to evaluate advanced power conversion technologies in a complete system context. Included in the radioisotope power system are: the heat source—GPHS modules, heat source support, heat distribution, thermal insulation, power conversion and electrical controls, and the housing with radiator fins. In addition, the RPS must be highly reliable, be able to be designed for long life, and have predictable power production in a wide variety of operating environments for either deep space and/or Mars surface applications. A complete discussion of realistic evaluations of advanced power conversion technologies for 100 W_e class RPSs is thoroughly discussed by Mason (ref. 11).

2.0 Radioisotope Power System (RPS) Technology Developments

While thermoelectric technology (Si-Ge and Pb-Te couples) has been proven and have a long track record of successful operation for NASA missions, the limited availability of Pu 238 for future missions has resulted in the evaluation and development of a number of alternative energy conversion technologies. Dynamic conversion systems such as the Brayton and Rankine cycle using turbine-alternators along with Stirling cycle machines using linear alternators have been evaluated along with a number of advanced static conversion systems such as Thermophotovoltaics (TPV), Alkali Metal Thermal to Electric Conversion (AMTEC) and advanced thermoelectric (TE) materials. In 2003 NASA released a competitive procurement under a NASA Research Announcement (NRA) -2-OSS-01 which evaluated the above alternative energy conversions options to evaluate which were ready to take the next step in development (Technology Readiness Level (TRL) from 3 to 5) for advanced RPSs. Criteria used to evaluate the conversion technologies suitable for advanced RPS included: higher efficiency, higher specific power (W_e/kg), long life, high reliability, scalability, along with multimission capability are being developed under NASA contracts.

In the second half of 2003 five development contracts were awarded to the following: Teledyne Energy Systems to improve the performance and manufacturability of segmented Be-Ti with Pb-Te couples with a goal of 10 to 12 percent efficiency; Creare, Inc. to demonstrate the selective emitter-based TPV power generator with a goal of 15 to 20 percent efficiency; Edtek to improve the performance of the low-band GaSbPV cells for use in a TPV power generator; Sunpower with Rocketdyne to demonstrate advanced Stirling convertor with significant improvements with a goal of greater than 30 percent efficiency; and Creare/Boeing to develop micro-fabrication techniques and demonstrate mini-Brayton operation with a goal of 25 to 36 percent efficiency. Only two of the five development NRA contracts continue, Sunpower for advanced Stirling and Creare for the TPV selective emitter. In addition development of advanced thermoelectric materials with high ZT values at temperatures above 600 °C along and with materials up to 700 °C using skutterudites is being conducted by the Jet Propulsion Laboratory with materials development support from NASA Glenn. The advanced TEs have the potential to allow future RTGs between 6 to 8 W_e/kg (refs. 17 and 18).

3.0 Power System Development for Fission Surface Power (FSP) Systems

NASA is currently studying the use of both solar and nuclear power for lunar and Mars surface applications. Power requirements for human outposts and bases for the lunar surface range from 10's to about 100 kW_e, for the early build-up phases which is expected to take a number of years starting in the

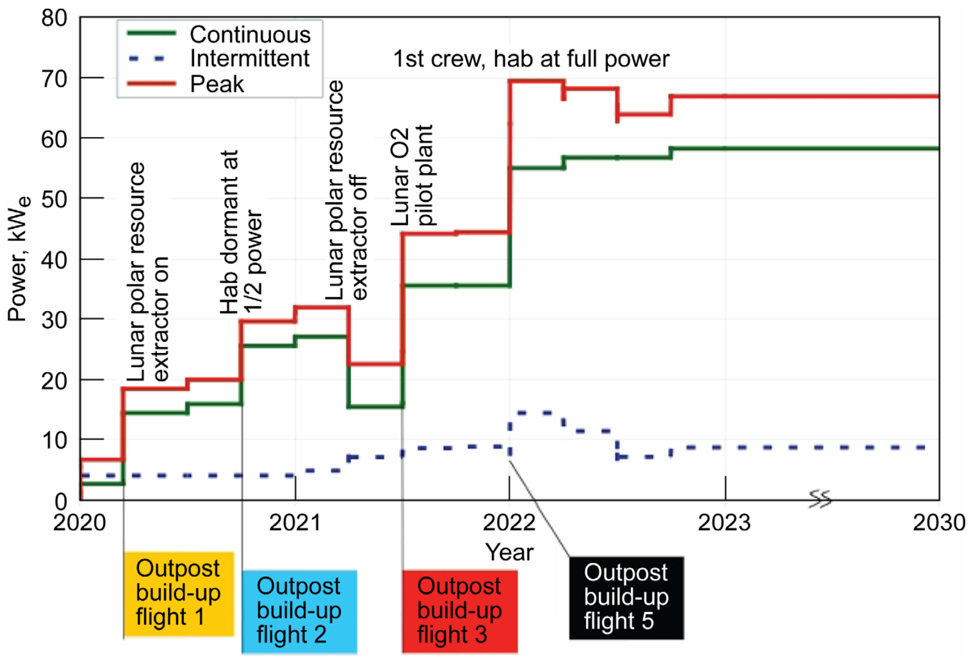


Figure 6.—Notional power requirements for lunar outpost.

early 2020's. A notional Lunar outpost power requirement is shown in figure 6 with power level range from a few kWe, to about 70 kWe, peak power (ref. 22). NASA's Prometheus Program under Exploration Systems Mission Directorate (ESMD) is currently providing the technology development for a future Fission Surface Power System (FSPS). Glenn is responsible for leading the technology development with collaboration from the NASA Marshall Space Flight Center along with support from various DOE labs including the Oak Ridge, Los Alamos, ID, and Sandia National Laboratories. The FSPS includes four primary subsystems: the reactor, an energy conversion system, a heat rejection system and the power management and distribution (PMAD) system. Three reactor options are being considered for potential missions for various surface applications: liquid-metal cooled, gas cooled, and heat pipe cooled. The reactor would be either fast-spectrum or moderated. One current approach assumes a low temperature, stainless steel reactor as a baseline with either liquid-metal or gas primary coolant. Use of stainless steel for the reactor construction should limit coolant temperatures to about 900 K. Potential fuel options for the low temperature reactor include U02 and UZrH. These subsystems assume that the technology is mature with an existing data base and the reactor power system would use off-the-shelf technology. Three power conversion options are also considered: Brayton, Stirling and thermoelectric. Figure 7 shows potential design concepts for the three conversion system options (ref. 22).

In figure 7(a) the Stirling convertor is a dual opposed free-piston engine integrated with a permanent-magnet linear alternator in a common pressure vessel using helium as the working fluid. The Stirling concepts are similar to the designs built in the 1980's. In figure 7(b) the Bayton conversion system is a closed-loop concept integrating the gas turbine that uses a single-stage radial turbo-compressor and a permanent-magnet alternator supported on gas bearings. The working fluid is a mixture of helium and xenon (HeXe) and is contained in a hermetically sealed loop. The closed-Brayton-cycle concepts are similar to the designs that were built and tested during the 1970s. In figure 7(c), the thermoelectric conversion consists of multiple conductively coupled thermoelectric arrays configured in a compact, sandwich heat exchanger similar to the designs of SP-100 Program. Use of the low temperature reactor would use n-leg lead-telluride (Pb-Te) and p-leg TAGS (a solid solution of tellurium, antimony, germanium and silver thermoelectric devices The above power conversion options are all considered mature technologies that can be carried into a low temperature reactor design (ref. 22).

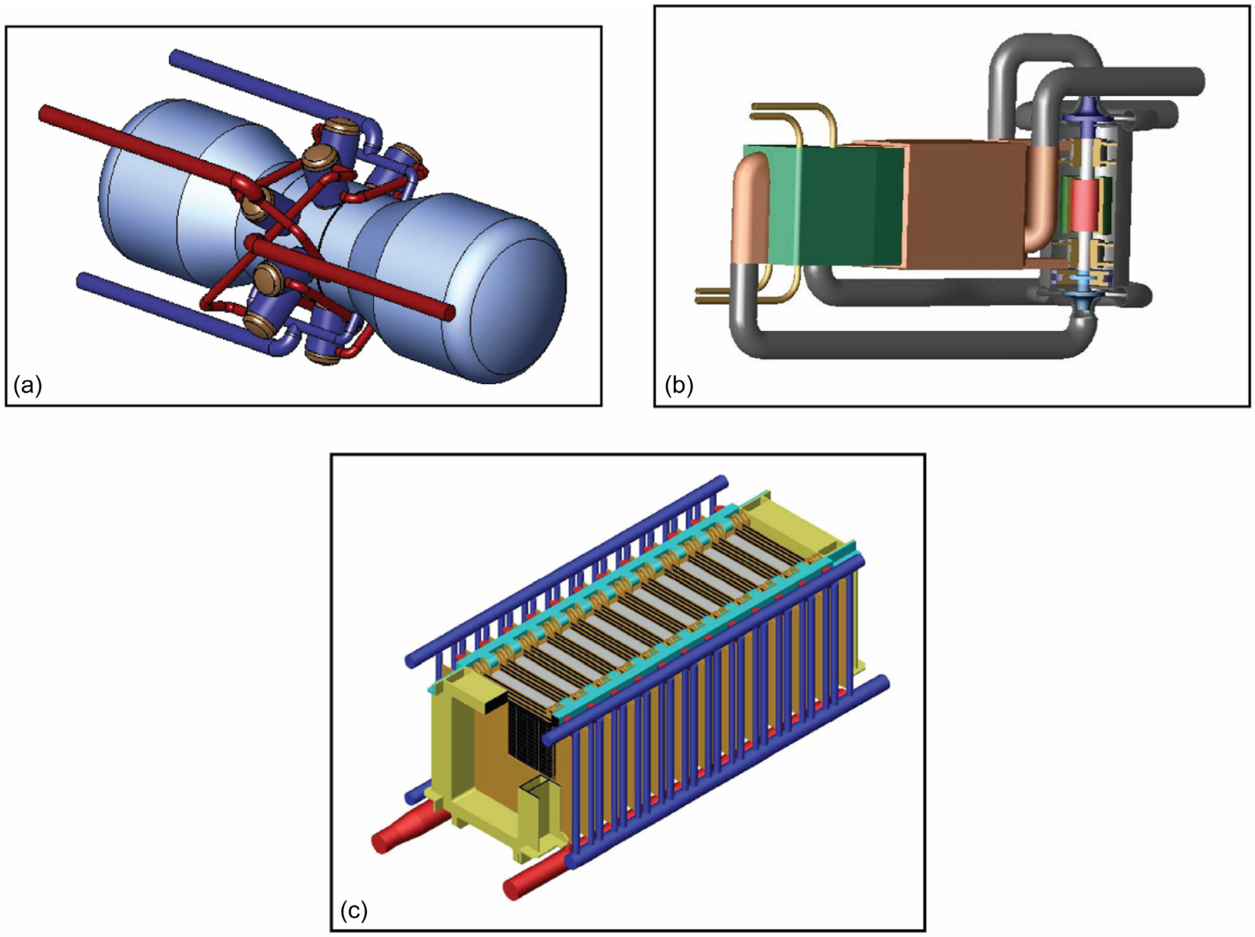


Figure 7.—Power conversion options for Fission Surface Power Systems. (a) Free-piston Stirling convertor. (b) Closed Brayton cycle. (c) Thermoelectric.

Under the SP-100 Program, Mechanical Technology, Inc., Latham, NY developed the 25 kW_e, Stirling Space Power Demonstrator Engine (SPDE) for NASA. As shown in figure 8, the SPDE consists of two free-piston Stirling engines integrated with two 12.5 kW_e, linear alternators, commonly referred to as the Stirling convertor. They two cycles were connected at the heater head with a common expansion space. The SPDE produced 25 kW_e with the thermal to electric conversion efficiency at 20 percent when operated at a temperature ratio of 2.0 (600/300 K). A key accomplishment of the SP-l00 Project was that it demonstrated the viability of Stirling power conversion technology for high power flight development.

The SPDE was a dynamically balanced machine that generated essentially no vibration, but was operated at temperatures lower than what would be used in a space flight reactor system. The SPDE achieved all of its programmatic goals, which was to demonstrate high power operation, high conversion efficiency, non-contacting operation to enable long life, and dynamically balanced operation. It used a system of hydrostatic gas bearings to support the piston and the displacer, and had a moving magnet linear alternator integrated around the piston. The SPDE was operated with T_{hot} 357 °C and T_{rej} 42 °C. Following testing as the SPDE, the two convertors were separated into two single-piston, single displacer Stirling convertors known as the Space Power Research Engines (SPREs) and used for basic research and component development.

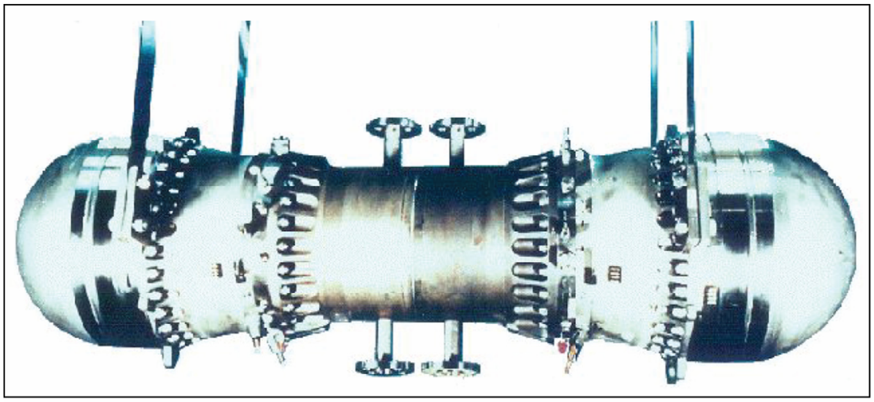


Figure 8.—NASA's Space Power Demonstrator Engine (SPDE).

The Component Test Power Convertor (CTPC) was then built for similar power and performance as the SPDE, but with capability to operate at higher temperatures that would be similar to that used on a nuclear system. The CTPC hot end operated at 777 °C and the cold end at 252 °C, which is appropriate for some reactor systems being studied. The heater head was designed to be made of Udimet 720, but as a cost saving measure, the CTPC was fabricated from Inconel. Also, only one half of a balanced pair was built since the dual Stirling, balanced system had been successfully demonstrated by the SPDE. This resulted in the full 60,000 hour life if operated at reduced temperature, or reduced life if operated at full temperature. The CTPC operated as intended from the first test onward and did not require additional development. By the end of the project, the CTPC operated a little more than 1,500 hours with few problems.

There is currently interest in studying high power Stirling conversion systems to support NASA's Exploration Initiative. Designs from the SP100 era can be updated with advances in materials, joining techniques, heat exchangers, bearing systems, linear alternators, and controllers to achieve levels of performance superior to that achieved previously. Specific power of the SCA could reach as high as 200 W/kg at these high power levels, however system level trades could call for reduced Stirling specific power to gain efficiency for the benefit of the overall system (ref. 23). At this time, studies are ongoing and NASA has not selected the power conversion option or an architecture for future exploration.

NASA is currently conducting design studies on potential approaches to use FSPS for a lunar surface application. A key technical issue is the radiation shielding approach. The use of regolith, either burying the reactor or building a berm surrounding the reactor, significantly decreases the mass of the FSPS. Figure 9 shows a concept for a lunar FSPS with regolith sandbag shielding to reduce reactor induced radiation to acceptable levels for the crew. This particular concept uses a gas-cooled reactor with Brayton power conversion and water heat pipe radiators (ref. 24).

Figure 10 shows a notional progression of the development of Stirling power systems for NASA's science and exploration programs. Phase 1 is a 100 W_e class RPS, the ASRG which is currently being developed for future science missions that require a high specific power (> 8 W_e/kg). Phase 2 is a more ambitious application of isotope power suggesting that a 1 to 2 kW_e class of high performance RPSs is achievable. Phase 3 could be a multi-kilowatt FPS for lunar surface missions (ref. 25).

Figure 9.—Fission Surface Power System (FSPS) with regolith sand-bag shielding.

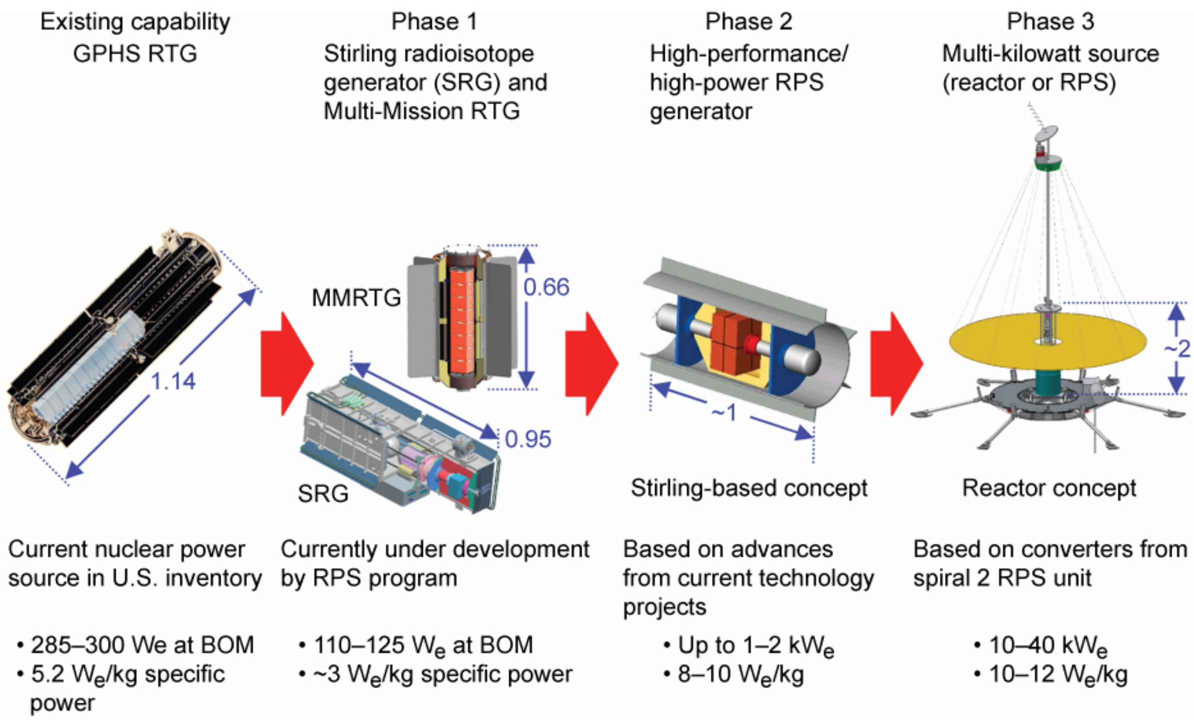


Figure 10.—Notional progression of Stirling Power Systems (ref. 4).

4.0 Conclusions

Dynamic power systems need to provide high efficiency along with reliable and long life operation to be a creditable power choice for future NASA missions. The dynamic power systems have many design challenges because the data required to support long life design is normally not available from the suppliers. The free-piston Stirling convertor has shown impressive performance and is establishing a broad data base on long term operation without any degradation. In addition, NASA is providing a critical technical data base to support the component and system design to ensure performance along with reliable and long life operation which is critical for NASA missions. The ASRG has the potential to meet NASA's high specific power (>8 W_e/kg) for future deep space, Mars and lunar surface applications. However, it is critical that the suppliers provide robust and reliable free-piston Stirling convertors. If the ASRG is successful, the use of dynamic power conversion systems will be accepted by mission planners and spacecraft designers. Mission opportunities include future Lander/rovers on the lunar surface, Interstellar Probes which require REP along with a number of potential Mars surface and deep space missions.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 01-08-2007	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE Future Opportunities for Dynamic Power Systems for NASA Missions	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Shaltens, Richard, K.	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER WBS 138494.04.01.01
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191	**8. PERFORMING ORGANIZATION REPORT NUMBER** E-15932
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	**10. SPONSORING/MONITORS ACRONYM(S)** NASA
	11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2007-214707

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 20
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301-621-0390

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Dynamic power systems have the potential to be used in Radioisotope Power Systems (RPS) and Fission Surface Power Systems (FSPS) to provide high efficiency, reliable and long life power generation for future NASA applications and missions. Dynamic power systems have been developed by NASA over the decades, but none have ever operated in space. Advanced Stirling convertors are currently being developed at the NASA Glenn Research Center. These systems have demonstrated high efficiencies to enable high system specific power (>8 W_e/kg) for 100 W_e class Advanced Stirling Radioisotope Generators (ASRG). The ASRG could enable significant extended and expanded operation on the Mars surface and on long-life deep space missions. In addition, advanced high power Stirling convertors (>150 W_e/kg), for use with surface fission power systems, could provide power ranging from 30 to 50 kW_e, and would be enabling for both lunar and Mars exploration. This paper will discuss the status of various energy conversion options currently under development by NASA Glenn for the Radioisotope Power System Program for NASA's Science Mission Directorate (SMD) and the Prometheus Program for the Exploration Systems Mission Directorate (ESMD).

15. SUBJECT TERMS
Radioisotope power systems; Fission power systems; Stirling conversion systems; Stirling convertors

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	19	**19b. TELEPHONE NUMBER** *(include area code)* 301-621-0390

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18