Advanced Stirling Radioisotope Generator Development

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***Abstract* - For more than forty years, Radioisotope Thermoelectric Generators (RTGs) have provided safe, reliable electric power for NASA missions where solar power is not feasible. NASA and the Department of Energy (DOE) are now developing the next generation of Radioisotope Power Systems (RPS), which will produce power more efficiently, reducing the Plutonium-238 fuel requirements and significantly increasing specific power. The Advanced Stirling Radioisotope Generator (ASRG) will produce approximately 7 We/kg, and will use only 25% of the Pu-238 that would be required for a comparable RTG. A flight-like engineering unit generator is currently being fabricated, scheduled for completion in December 2007. The generator will undergo a series of performance and characterization tests, including subjection to dynamic and thermal vacuum environments, through April 2008, after which it will be placed on life test. If the engineering unit tests are successful and the program proceeds to qualification, a flight generator could be available for mission use as early as 2012. This paper describes the development progress to date, system requirements and performance predictions, and near-term plans for generator fabrication and testing.**

BACKGROUND

The Department of Energy (DOE) is responsible for the development, production and deployment of Radioisotope Power Systems (RPS) to provide electric power for NASA missions where solar and other power sources are not feasible. DOE and its contractors design and fabricate the RPS, which consist of a heat source based on the radioactive decay of plutonium-238 (Pu-238) and a thermal-to-electric power conversion system. All of the RPS-powered missions flown to date have used Radioisotope Thermoelectric Generators (RTG), which use thermoelectric materials to convert the decay heat of Pu-238 to electric power. RTGs have been successfully used on many missions, including both Viking landers, Pioneer 10 and 11, Voyager 1 and 2, and the Cassini-Huygens mission to Saturn, just to name a few. An RTG was also used to power the New Horizons mission to Pluto, launched in 2006, and another will be used on the Mars Science Laboratory, planned for launch in 2009.

Although RTGs have performed with exceptional reliability over very long mission durations, they are limited by the low conversion efficiency of thermoelectric materials, with system efficiencies typically ranging from about 5-7%. Because Pu-238 is an extremely limited resource, for which the United States currently has no production capacity, DOE and NASA are pursuing higher-efficiency systems that would reduce the amount of Pu-238 required for a given electric power output. The most promising of these uses a free-piston Stirling engine coupled to a linear alternator, resulting in a more than four-fold reduction in the amount of required Pu-238 compared to current-generation RTGs. The Advanced Stirling Radioisotope Generator (ASRG), now under development, has a projected system efficiency of 28%. Its 7 W_e/kg specific power is also a significant improvement over RTGs.

The benefits of advanced RPS do not come without trade-offs. Unlike RTGs, the ASRG is a somewhat complex thermodynamic system with moving parts. Like any dynamic system, it requires a controller to maintain optimum performance, to prevent piston overstroke and to convert the AC output of its alternators to DC suitable for a spacecraft bus. This level of complexity is manageable and appears to be worth accepting to gain the benefits offered by the ASRG, if it can be proven to offer the high reliability demanded of spacecraft power systems. Cryocoolers using similar technology have been used on NASA missions, but no dynamic system has yet been used in space for power production. Before the ASRG can be considered as an alternative to RTGs for NASA missions, a flight-like system must be built and demonstrated, and its reliability must be well understood. These are the primary near-term goals of the ASRG project.

The ASRG is being developed by Lockheed Martin Space Systems Company, under contract to DOE. It has been designed to meet a generic "multi-mission" requirements set that includes both deep space and Mars surface environments. The current project phase includes fabrication of a flight-like Engineering Unit (EU) generator, which will include all major subsystems, to demonstrate Technical Readiness Level (TRL) 6. The EU will undergo testing to demonstrate its conformance to requirements and its suitability for near-term flight qualification. This initial system demonstration is scheduled for completion in April 2008, after which the EU will be placed on life test. A parallel reliability modeling effort will use analysis and test results to assess the system reliability as it is currently known and to generate recommendations for future testing.

ASRG DESCRIPTION

The ASRG is presented in Fig. 1. It is designed as a modular, self-contained unit. Its major components are enclosed in a beryllium housing, except for the controller and gas management system, which are mounted on the housing exterior. The ASRG is designed to be attached at one end to a spacecraft, either directly or with an optional, vibration-reducing adapter.

The ASRG heat source consists of two General-Purpose Heat Source (GPHS) modules, which generate heat through

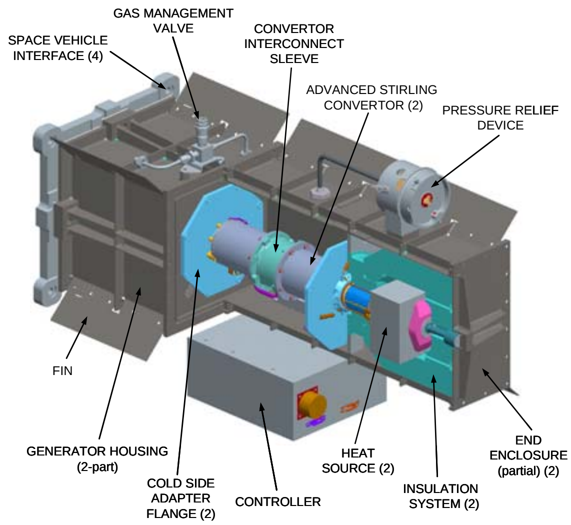

Fig. 1. Advanced Stirling Radioisotope Generator

the radioactive decay of Pu-238. The GPHS is a standard heat source design, which is also used in RTGs and has a long flight heritage. Each GPHS module will nominally produce 250 thermal watts at launch, with an exponential decay to approximately 224 watts by the end of a 14-year mission. The modules are held in place by heat source supports attached to the generator housing and are surrounded by bulk thermal insulation. The ASRG EU will use electric heat sources to simulate the thermal and mass properties of the GPHS modules.

Thermal-to-electric power conversion is performed by two free-piston Advanced Stirling Convertors (ASCs), mounted in linear opposition with synchronized pistons to reduce the potential transfer of vibration from the ASRG to a spacecraft. Each hermetically-sealed ASC converts the heat from one GPHS module into reciprocating motion, driving a linear alternator to produce AC power output. The ASC is shown in Fig. 2, with and without the interface hardware used for structural attachment and heat transfer in the ASRG. The ASC is being developed by Sunpower, Inc. under contract to the NASA Glenn Research Center. Ref. [1] provides technical and programmatic details on the ASC development effort. Although the ASC is being designed for potential use at higher temperatures with increased efficiency, the convertor in the ASRG will include an Inconel heater head and will operate with a hot end temperature of 640°C. This operating point was selected to minimize the development effort and risk associated with achieving the project's near-term goal, which is to demonstrate that the ASRG can reliably meet its multi-

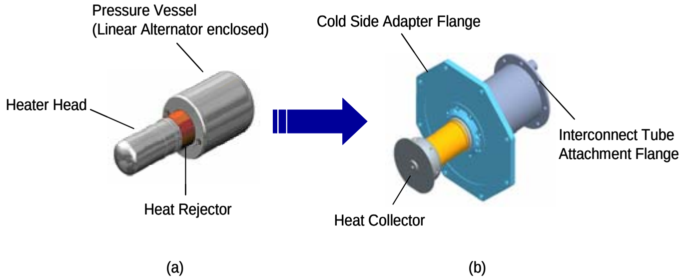

Fig. 2. Advanced Stirling Convertor (a) as designed, and (b) with ASRG interface hardware

mission system requirements, as described in the next section of this paper. Any efforts to raise the hot-end temperature to take full advantage of the ASC design while continuing to meet these requirements would require generator redesign. While this may be considered in the future, it is not part of the current project scope.

The controller assembly, mounted on the generator housing exterior, uses an active power factor control scheme to regulate the power output of both ASCs; maintains synchronization of the ASC pistons; converts the output of the linear alternators to DC and serves as the electrical interface to the spacecraft, supplying power to the bus, providing telemetry and responding to external commands. Conceptually, the controller is designed so that the generator can function autonomously to simplify operational interfaces with the spacecraft. However, it also accepts several external commands, including one that can reduce the ASC piston stroke at the nominal operating frequency. This feature enables optimum use of diminishing heat from the GPHS modules over the mission life. The controller design includes a separate control card for each ASC, with a fully redundant card that can control either. If one ASC fails, the generator is designed to continue operating with the remaining ASC, but can be commanded to disable the functional ASC to reduce vibration. The baseline controller is being built and tested to demonstrate reliable performance of its core functions, including synchronization of the ASCs, autonomous control, accurate telemetry and responsiveness to spacecraft command functions. In later project phases, there will be some flexibility to tailor the controller firmware for the needs of different missions to balance ASRG autonomy with commanded control.

The externally mounted gas management valve (GMV) is used to charge the cavity surrounding the GPHS module with inert gas during all ground operations, preventing oxidation of hot components. During launch ascent, the pressure relief device (PRD) is actuated barometrically to vent the cover gas and helium generated by isotope decay. This feature has been successfully demonstrated on several missions as part of a RTG design. For missions involving operation on Mars, atmospheric gases (primarily CO_2) would be allowed to fill the generator interior. An analysis of the chemical interaction between CO_2 and graphite indicates an insignificant loss of mass from the GPHS aeroshell, with no impact on ASRG performance. This scheme eliminates the need for selective venting or getter material, and allows use of the same generator design in either a vacuum or Mars environment.

ASRG SYSTEM REQUIREMENTS

The current RPS development approach is to design systems with flexibility to meet a variety of mission requirements. The ASRG is being designed to a broad set of requirements, to allow its use in space vacuum or on the Martian surface for mission durations of up to 14 years. Its design features intentional flexibility to allow limited, mission-specific customization without major redesign. For example, the ASRG controller is designed to be mounted externally on the generator housing to ease ASRG assembly integration, provide accessibility during ground operations, and allow relocation elsewhere on the spacecraft with minimal effort. Similar concepts have been considered for the addition of active cooling loops on the housing and for the inclusion of shielding to reduce electromagnetic interference, should specific missions require it.

While mission-specific customization options have been conceptually considered, these have not been designed in detail and they are not included in the ASRG baseline. The requirements adopted for the baseline design are those considered common to most missions that may use the ASRG, known as the "multi-mission" requirements. The goals of the current project phase are to document the detailed multi-mission requirements adopted for the ASRG; to design a baseline system meeting these requirements; to conduct subsystem development and testing; to fabricate a complete, electrically-heated EU and demonstrate its conformance to requirements; and to subject the EU to certain qualification-level testing to confirm readiness to proceed toward flight qualification. The ASRG EU final design review was completed in February, 2007. Its requirements and baseline design are now considered complete, and fabrication of the EU is in progress. The detailed requirements are documented in system and subsystem specifications, and in a generic user interface control document that may be used by mission planners as an aid in assessing the suitability of the ASRG for specific applications. The top-level system requirements are summarized in Table I. Table II contains current best estimates for the performance of a flight system based on the current ASRG design.

TABLE I
ASRG REQUIREMENTS SUMMARY

Requirement	Value/Description
System Operating Life	3 yrs storage + 14 yrs mission
Power (at nominal temperatures and fuel loading)	$\geq$ 140 W_e (BOM) $\geq$ 126 W_e (EOM)
System Mass	$\leq$ 22 kg
Overall Dimensions	Less than 76.2 cm length (Z axis) by 45.7 cm height (Y axis) by 39.4 cm width (X axis)
Mechanical Disturbance	<35 N-m at 1 m moment arm
DC Magnetic Field Emissions	Meet Standard 461E and $\leq$ 25 nT at 1 meter
AC Magnetic Field Emissions	$\leq$ 80 dBpT at 1 m from the geometric center
Spacecraft Bus	22 - 36 V_{DC}, capacitive or battery-dominated energy storage
Total Ionizing Dose	Survive space natural TID = 50 kRads behind 60-mil Al, plus radiation from GPHS modules
Planetary Surface Landing Load	Withstand effects of a 40 g static load
Random Vibration	Withstand effects of EELV launch environments

TABLE II
PROJECTED FLIGHT SYSTEM PERFORMANCE

Parameter	Current Best Estimate
Power (at nominal temperatures and fuel loading)	143 W_e (BOM) 127 W_e (EOM)
System Mass	20.24 kg + 1.23 kg if optional spacecraft adapter is used
Overall Dimensions	Less than 76.2 cm length (Z axis) by 45.7 cm height (Y axis) by 39.4 cm width (X axis)
Specific Power	7.0 We/kg without spacecraft adapter
System Efficiency	28.6%

ENGINEERING UNIT TEST PLAN

Assembly of the ASRG EU is scheduled for completion in December, 2007. From January through April, 2008 it will undergo a series of system-level tests to demonstrate its conformance to requirements and readiness to proceed toward flight qualification. The goal of this testing is to achieve TRL 6, defined by NASA as "system/subsystem model or prototyping demonstration in a relevant end-to-end environment [2]." In order to accomplish this, the EU system will be subjected to qualification-level testing and to expected mission environmental conditions where possible. The EU controller will be connected electrically to the ASRG during all tests and its conformance to functional requirements will be thoroughly demonstrated. However, the EU controller, unlike its flight equivalent, will include commercial-grade electronic components. As such, it will be excluded from the environmental test portion of the program. A mass model will be placed on the ASRG to simulate the controller during these tests. The responses of electronic components to mission environments are better understood than those of the other ASRG subsystems, so this demonstration was not considered necessary for the first set of system tests. Further subsystem testing of the controller may be conducted before qualification if this is later determined to be necessary. Table III summarizes the known differences between the EU ASRG and an ASRG in its expected flight configuration.

TABLE III
COMPARISON OF ASRG ENGINEERING AND FLIGHT CONFIGURATIONS

Parameter	Flight Unit	Engineering Unit
Heat Source	2 General Purpose Heat Source modules, containing $Pu^{238}O_2$	2 Electric Heat Sources, designed to simulate thermal and mass properties of GPHS
Controller	Uses space-rated parts. Mounted on ASRG housing	Uses commercial parts. Connected to ASRG electrically while a mass model is mounted on housing.
Insulation	Aerogel produced by JPL	Microtherm HT
Housing End Enclosure	Beryllium	Aluminum with connectors and vent for ground instrumentation and processing

Before any environmental testing is conducted, the generator will undergo vacuum bake-out processing and a pressure decay test to assure that the housing is properly sealed. The ASRG will also be integrated with the controller for a series of functional electrical tests to demonstrate conformance to requirements and to establish a baseline for later ASRG health tests.

The EU will undergo environmental testing in a thermal vacuum chamber and will later be subjected to random vibration and simulated pyroshock tests. The mechanical disturbance and electromagnetic interference generated by the ASRG will also be measured. Table IV summarizes the planned EU testing.

SUMMARY

The ASRG offers significant performance improvements over RTGs, and is potentially only a few years from flight readiness. To reach this point will require qualification of a radioisotope-fueled, flight-fidelity system, built in accordance with quality assurance practices for nuclear systems and tested in flight-like environments. The reliability modeling and testing efforts must also continue in parallel, so that system reliability can be established with confidence by the time such a system is considered for flight use.

Once the EU testing is complete, two divergent options exist for any continuation of the project. The path selected will depend primarily on NASA mission projections and budgetary considerations, and no decisions have yet been made. The shortest duration to reach flight readiness would be to fuel and qualify the existing ASRG design to achieve the predicted flight performance described earlier in this paper. However, Stirling conversion technology has continued to advance over the course of the ASRG project to date. Should NASA decide that the generator is not required for a near-term mission, these advances could be incorporated into the generator to further improve efficiency and specific power. The extent of such improvements will depend on other requirements decisions, as the greatest improvement opportunities are for vacuum-only systems that could not meet the multi-mission requirements for planetary surfaces. An improved system may require fabrication and testing of an updated EU before proceeding to qualification, which would delay flight readiness by at least two years.

REFERENCES

[1] J.G. Wood, et al., "Advanced Stirling Convertor (ASC) Phase III Progress Update," Proc. Space Technology Applications International Forum, February 2007.

[2] J. Mankins, "Technology Readiness Levels: A White Paper," NASA, Office of Space Access and Technology, Advanced Concepts Office, April 1995.

TABLE IV
PLANNED ENGINEERING UNIT TESTS

Test Type	Purpose	Facility/Level
Thermal Balance	Validate thermal models	Thermal vacuum chamber. Will use lowest achievable temperature and extrapolate to flight conditions.
Thermal Performance	Verify margin/workmanship by imposing temperatures beyond those that would naturally occur.	Thermal vacuum chamber. Includes cycling to impose stresses and plateaus for performance testing.
Mechanical Disturbance	Characterize the dynamics (forces and frequencies) caused by operation of the generator, as measured at the spacecraft interface.	Ambient environment.
Sine Transient	Verify ASRG response within acceptable limits.	Ambient environment.
Random Vibration	Demonstrate that ASRG can withstand launch vibration environment (EELV) without performance degradation.	Ambient environment. Testing to acceptance and qualification level.
Simulated Pyrotechnic Shock	Demonstrate that ASRG can withstand pyrotechnic shock environment without performance degradation.	Ambient environment. Testing on an impact plate.
Electromagnetic Interference (EMI)	Characterize the AC and DC magnetic emissions. Demonstrate conformance to requirements.	AC: shielded anechoic chamber DC: low varying DC magnetic field environment with minimal ferrous materials in the vicinity