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Development of Stirling Convertors for Radioisotope and Fission Power Systems

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NASA has been developing free-piston Stirling-cycle power convertors over the past 22 years for use in nuclear power systems that would provide electricity for space science missions to dark, dusty, or distant destinations where solar power is not practical. These nuclear power systems would generate heat from either the radioactive decay of isotopes or fission nuclear reactors. That heat would be converted to usable electricity using highly efficient Stirling convertors for a wide range of power needs needing 10s of watts to 50 kW_e. NASA's Radioisotope Power Systems (RPS) Program is maturing advanced thermoelectric and dynamic conversion technologies that would increase the system efficiency beyond what is currently possible using heritage systems to enable a larger number of robotic missions or higher power missions to solar system bodies of interest. The Dynamic Radioisotope Power Systems (DRPS) Project has matured prototype Stirling convertors to sufficiently increase the technology readiness level for infusion into flight development. Flexure and gas-bearing free-piston Stirling convertors were developed under contract by commercial partners and delivered to enable government evaluation. Gas-bearing designs have met performance and robustness requirements and were selected for flight development. This paper provides the status of SRSC test campaign and maturity level.

I. HIGH EFFICIENCY POWER CONVERSION

Nuclear power systems are under development for potential use in space applications and could be demonstrated on the Lunar surface. These systems would convert heat from a fission reactor or from decaying isotope fuels to usable electricity for spacecraft functions. Highly efficient conversion technologies are desirable because they require less fuel for a desired amount of system power. This could reduce power conversion system mass and heat rejection radiator mass of a fission power system or reduce the isotope fuel inventory and associated waste heat and emitted radiation. For example, heritage thermoelectric power conversion enables system efficiency of 6.5% while state-of-the-art (SOA) Stirling conversion designs are capable of 20% to 28% efficiency. [1,2,3] Of the 2,000 watts thermal energy being converted to electricity for the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), over 1,800 watts thermal energy is rejected to the environment or used to heat critical spacecraft components. Higher efficiency power conversion would lower the amount of waste heat coming from the generator because there is less thermal inventory from the fuel and from cycle heat rejection, which could be important for missions where excess waste heat is a burden, such as missions to the permanently shadowed regions of the Moon, asteroids and comets with volatiles that could be affected by heat. Also, less emitted radiation could be important for robotic life detection missions or when powering human-class rovers where astronauts perform operations in frequent, close proximity to the RPS.

Degradation of power output could limit the utility of a generator for a desired application if the power decreases below a level needed to support critical operations late in the mission life cycle, such as outer planet explorations. The total combined system degradation rate of currently available thermoelectric systems is around 4.5%/yr, when factoring in the 0.8%/yr decay rate of the fuel.[1] To ensure function over the design life of a Stirling or Brayton convertor, sufficient design margin is required for life limiting phenomena, such as creep of hot parts under constant stress and fracture of parts under oscillating stress. Sufficient design margin and robustness comes at the cost of conversion efficiency points. Ultimately, usable spacecraft power must be traded against the amount of fuel that can be made available over time in order to determine how many spacecraft and/or missions can be enabled over that period, assuming limited production rates of any isotope fuel, including but not limited to Plutonium 238 oxide (Pu-238).

II. RADIOISOTOPE POWER SYSTEMS

Radioisotope power systems (RPS) are generators that convert heat made available from the decay of isotopes into usable electricity. The convertor in heritage RPS are thermoelectric couples with no moving parts. These systems require a space qualified fuel source, insulation, conversion technology, and a structure with fins and possibly a shunt. The conversion technology could be constructed from solid metallics that create low voltage when a temperature difference is applied across the length of the thermocouple or a dynamic machine that also requires a temperature difference applied to heat addition and heat rejection points on the engine. Dynamic machines also require an electronic controller to main stability and enable user or autonomous commands. Stirling and Brayton convertors used in terrestrial applications make great candidates for space applications, but modifications are often needed to achieve a desired design life, material margins to survive temperature, radiation, and synergistic compatibility in a hermetic enclosure, and robustness to off-nominal operational conditions.

Free-piston Stirling convertors were developed for specific flight development projects from 2000-2013. The Technology Demonstration Convertor (TDC) is a flexure-bearing free-piston Stirling convertor developed from 2000-2006 during the 110W Stirling Radioisotope Generator (SRG110) flight development project.[4] The project pivoted to higher specific power conversion with the Advanced Stirling Convertor (ASC), a gas-bearing free-piston Stirling convertor developed from 2007-2013 for the Advanced Stirling Radioisotope Generator (ASRG) flight development project. The TDC and ASC designs served as the point of departure for a renewed effort started in 2016.[5]

The latest development effort was formulated by the Radioisotope Power Systems Program and awarded through the ROSES solicitation program. The Dynamic Radioisotope Power Systems (DRPS) Project managed four contractors that started development work in 2017.[6] At this point, all DPC contracts have completed and earlier deliverables have undergone much of the planned government led verification and validation (V&V) test campaign. A total of 7 prototypes were delivered to GRC, including 2 flexure-bearing free-piston Stirling prototypes, 4 gas-bearing free-piston Stirling prototypes, and a one closed Brayton cycle prototype.[7,8] These contracts were used to collect data on candidate dynamic conversion technologies, assess the performance of prototypic units, and explore generator concepts for requirements development. Early system level requirements included a long-life 100-500 W_e generator populated by multiple convertors to enable redundancy and high reliability. The generator power level was later revised to 300 W_e. Requirements introduced in this technology development effort were informed by multi-mission requirements developed by a surrogate mission team with membership from the Applied Physics Laboratory, Jet Propulsion Laboratory, NASA Goddard Space Flight Center and NASA Glenn Research Center. Requirements also included robustness tests that were formulated to overcome weaknesses identified during past programs. New requirements included an increased maximum rejection temperature of 175 °C to enable lunar operations, a constant acceleration load of 5g in 3 orthogonal axes for an extended period, and the ability to survive a temporary loss of electrical load. These requirements ensure future DRPS meet performance, life, and reliability expectations while decreasing risk through implementation of robust designs.

Prototypes are being evaluated under a government led V&V test campaign to ensure initial quality, verify contractor measurements, and validate requirements and robustness. The "Test As You Fly" approach has been applied in order to identify risks and gaps early in the development cycle of a flight system. Key environments include thermal conditions to simulate lunar and Mars environments, launch vibration to simulate rocket lift off, constant acceleration to simulate spin stabilization and entry decent and landing loads, and thermal cycling to simulate on/off cycles and lunar diurnal cycles. There are four main tracks: performance verification, vibration testing, centrifuge testing, and robustness testing. Robustness testing includes a total of 13 on/off thermal cycles and a test to survive a 10-second loss of electrical load to demonstrate survival of an extreme ground user error. This extreme test is performed on SRSCs as part of production prior to deliver so it will be omitted from government testing. In addition, the units will be reconfigured into a dual-opposed assembly to enable measurement of the residual disturbance force between the convertor pair and achieve the target of 18,000 hours of extended operation.

II.A. Gas-Bearing Stirling Designs

The Advanced Stirling Convertor (ASC**)** is a gas-bearing free-piston Stirling convertor was developed for NASA then adopted for the Advanced Stirling Radioisotope Generator (ASRG) flight development project to increase system specific power. A total of 17 ASC prototypes and 20 engineering units were produced between 2007-2015. Two flight units were in production when the ASRG contract was canceled due to cost overruns. Some gas-bearing convertors were selected for continued operation to collect life data for reliability studies. ASC-0 #3 is currently the longest running ASC with over 12.7 years of operation. ASC-L has accumulated over 8.0 years of operation while under control of the Single Convertor Controller (SCC), a fault-tolerant engineering model controller developed by the Applied Physics Laboratory. Continued operation of convertors demonstrates reliability designs and no degradation and is discussed in more detail later.

The SRSC design included changes that improve robustness and ease startup, compared to the ASC. While the ASC and SRSC both use gas bearings to maintain non-contacting running clearances needed for wear-free operation, changes were made to increase the SRSC bearing stiffness for improved robustness during lateral loading. Additionally, the gas bearing system now employs more gas pads for better distribution of the restoring force, a check valve filter to prevent debris from entering the gas bearings, and a redundant check valve to eliminate the single point failure. A passive collision prevention system has also been implemented to meet the loss of load requirement and reduce the risk of damage during unintentional overtest conditions. This requirement is met if the convertor can survive loss of the electrical load that maintains piston amplitude for 10 seconds. The passive collision prevention system works by dissipating thermodynamic cycle energy for a portion of the cycle when the moving components exceed a threshold amplitude. This patented Loss of Load Tolerance (LLT) function was originally intended to prevent damage during ground test errors but could also be useful during piston excursions caused by a high random vibration environment or during a switchover event from the primary to a secondary controller. Sunpower has incorporated the loss of load test into production processes to show it works on all units. As a backup to the LLT, the design also includes bumpers that could eventually be removed to save mass.

Sunpower delivered SRSC #1 and #2 to GRC in October 2020. The first pair of prototypes contain bolted flanges to enable disassembly and inspection. The heavy flanges resulted in nonconforming specific power. Also, bolted flanges invariably leak helium and enable low level oxygen ingress into the convertor, as is the cases with SRSC Pair 1, requiring regular replenishment of the working gas. The convertors were delivered with underperforming pistons which lowered conversion efficiency to 21%-22% for a hot-end and cold-end temperatures of 700 °C and 100 °C, respectively. The efficiency was improved on SRSC Pair 2 to 26%, exceeding the 24% requirement. SRSC #3 and #4 were delivered to GRC in April 2022 and January 2023, respectively.[9] Figure 1 shows both types of SRSC prototypes delivered to GRC. These hermetic convertors were half the mass of the bolted flange design. They exceeded the specific power 20 W/kg requirement by 20%, when excluding the hot shoe and rejection flange which may be further optimized during flight integration. Performance was improved by reducing seal losses, which was made possible from implementation of a new running clearance measurement tool that shows compliance to limits before first operation. This tool made geometric adjustments unnecessary for this unit.

Fig. 1. SRSC prototypes delivered by Sunpower.

Prototypes #1 and #2 have exceeded 10,000 hours of operation. Performance testing was carried out during the first few hundred hours of operation, after which steady baseline data was collected at a single operating point. This baseline data is used as a comparison to after each environmental test to ensure no degradation has taken place. All units experienced 8-10 hours at the maximum rejection temperature of 175 ^{o}C during contractor and government testing. Random vibration testing was completed at GRC's structural dynamics laboratory, as shown in Figure 2.

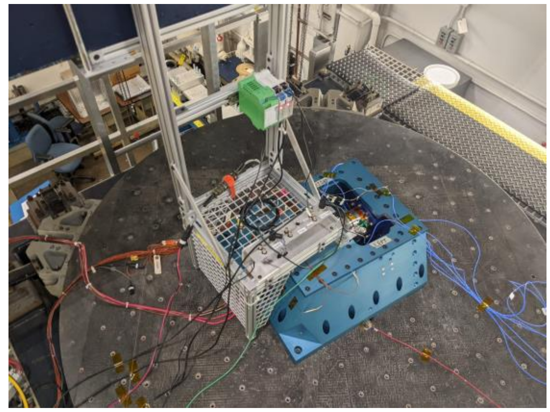

Fig. 2. SRSC prototype installed in the Structural Dynamics Facility at Glenn Research Center.

The data has been flat, with the exception of minor differences in power output after random vibration testing of SRSC #2 and SRSC #3. The positive and negative differences in power output have been around 1 watt (or 1-2% of the total power), when compared to baseline data. To investigate further and to determine root cause, the decision was made to complete a partial disassembly and inspection of SRSC #2. The bolted flange design paid off and made the inspection convenient. The issue ended up being excessive fit up of internal components, resulting in a minor gas leak and loss of conversion power. The test data and inspection results showed this was a performance risk instead of a life and reliability risk. Design revisions were implemented on SRSC #4 to mitigate the performance risk present on the first three units.

An initial CT scan of the key area in the convertor confirms the desired geometry prior to environmental testing. Additional CT scans will be completed after environmental testing to confirm geometric stability. In addition to microfocus CT scans, each hermetic unit is leak tested after delivery and after harsh environmental tests to ensure pressure boundary integrity.

Static load testing was completed on December 15, 2022 using SRSC #3 in a centrifuge facility located at Case Western Reserve University in Cleveland, Ohio. The test subjected the prototype to 6.3g in four lateral orientations. This value contains a 1.25 qualification margin and was used to simulate spin stabilization just after launch, like the New Horizons spacecraft. The tested value included a qualification factor of 1.25 and lasted 2 hours in each orientation. The power output decreased around 1.5 watts while under the 6.3g lateral accelerations, likely due to minor eccentricity in the piston seal as the piston is pushed off center by the lateral load. To simulate launch loads and a Mars entry decent and landing profile, the prototype was subjected to 22.5g for at least 5 seconds in two axial orientations and two lateral orientations. That load value also contained a 1.25 qualification margin. During these higher load tests, the SRSC experienced an expected temporary reduction in power output that recovered after each exposure. When exposed to the 22.5g load in the axial orientations, the convertor experienced a negligible power loss in the outward axial orientation (alternator out) and a 1.5-watt loss in the inward axial orientation (heater head out). For the 22.5g load in the lateral orientations, the convertor experienced a loss in power output from 18-28 watts, due to momentary rubbing of internal components. After completing all static acceleration tests, SRSC #3 was operated in the Stirling Research Lab. The power output was measured to within 0.2 watts compared to baseline data, indicating that the testing did not cause any permanent performance degradation. The centrifuge test facility is shown in Figure 3.

Fig. 3 SRSC #3 prototype installed in the Centrifuge Test Facility located at Case Western Reserve University.

Figure 4 shows SRSC #4 at GRC prior to performance testing. The prototype has completed performance testing and is being operated at the baseline point. Next steps include vibration testing, static load testing, and thermal cycling. The convertor will remain in extended operation and could be utilized in GRC's generator testbed.[2]

Fig. 4. SRSC #4 installed on stand at GRC.

Table I shows the results of SRSC V&V testing, as of May 2023. The SRSC design has passed all requirements so far. Thermal cycling was used to demonstrate geometric stability by simulating the anticipated number of convertor On/Off thermal cycles during future generator qualification testing. Radiation testing has been delayed for now due to budgetary constraints.

TABLE I. Status of SRSC V&V Testing.

Test	Requirement	Status
Performance	Conversion eff.	Passed
Random vibe	Dynamic loading	Passed
Centrifuge	Static loading	Passed
Loss of Load	10 seconds each unit	Passed
Thermal cycling	13 on/off cycles	Ongoing
Extended operation	10,300 hours of 18,000-hour target	Ongoing
Creep test	Temperature, time	Ongoing
High-cycle fatigue test	Piston centering spring endurance limit	Ongoing
Magnet aging	12,000-hour target	Ongoing
Radiation test	Organics & magnets	Delayed

Separate from the convertor development contracts, NASA and DOE awarded a 1-year flight development contract in January 2022 to Aerojet Rocketdyne for delivery of a DRPS design. The Idaho National Laboratory (INL) managed the contract with Aerojet Rocketdyne to design a 300 We generator.[2] The generator, seen in Figure 5, included eight dual-opposed SRSC pairs arranged around a central stack of General Purpose Heat Source (GPHS) Step-2 fuel modules.

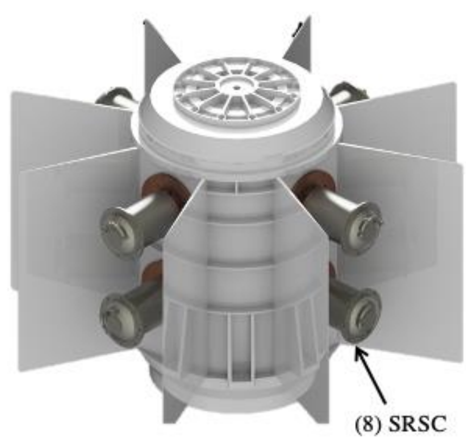

Fig. 5. DRPS design delivered by Aerojet Rocketdyne.

Aerojet Rocketdyne traded two convertors designs before selecting the SRSC as the baseline. In this design, one convertor pair would be disabled in the case of a single convertor failure and the amplitude of the remaining convertors would be increased to maintain generator design power output. The fuel stack and assembly process would utilize existing designs and methods currently used on MMRTG and the convertor heat rejection flange would bolt directly to the generator housing, making subassembly verification and integration straight forward.

Prior to the SRSC and ASC, Sunpower had success in development in higher power units, like the 1 kW EG-1000, and a lower power 35-40 W prototype, called the EE-35.[10] The EE-35 was fabricated and tested under a Phase 2 SBIR that ended in late 2004. The EE-35 was designed to accept half of the heat available from GPHS Step-2 Module so a pair could be arranged on each side of the heat source. The six laboratory units produced for NASA contained heavier housing components, but the lightweight flight version was anticipated to be around 0.44 kg. The serial number B-4 produced 40 watts while at the hot and cold end temperatures of 650 ºC and 80 ºC. The design has an operating frequency of 105 Hz and mean charge pressure of 385 psig. Performance was measured at 55% of Carnot efficiency, 31.7% conversion efficiency, and a specific power of 90 W/kg, assuming the anticipated mass after refinement of the alternator housing. Figure 6 shows the EE-35 prototype and a mass model of the lightweight flight version.

Fig. 6. EE-35 gas-bearing free-piston Stirling prototype (left) and mass model of lightweight flight version (right). *Image courtesy of Sunpower, Inc.*

Commercially available gas-bearing free-piston Stirling designs have been developed for similar applications by Microgen of the Netherlands. Microgen has mass produced 1 kW_e convertors based on Sunpower's P2A design, which was made possible by a licensing agreement between the two companies. Microgen offers units from xxx W_e to xxx W_e. Some designs have been produced in very high volumes, including XX units of the name convertor, YY units of the name convertor, and ZZ units of the name convertor.[11]

II.B. Flexure-Bearing Designs

The TDC served as the point of departure for the Flexure Isotope Stirling Convertor (FISC). A total of sixteen TDC prototypes and two engineering units were produced during the SRG110 flight development contract between 2000-2006. Some flexure-bearing convertors were selected for continued operation to collect life data for reliability studies. TDC #13 is currently the longest running heat engine in the world with over 16.1 years of error-free operation. While the FISC and the TDC use flexure bearings to maintain non-contacting running clearances needed for wear-free operation, some aspects were changed in the FISC design to improve performance, reduce mass, and ease manufacturability. The FISC prototype design and generator concept were developed by American Superconductor (AMSC) and Teledyne Energy Systems, Inc. (TESI).[7,12] AMSC delivered FISC #1 and #2 to GRC in August 2021. Figure 7 shows the prototypes during performance evaluation testing at GRC.

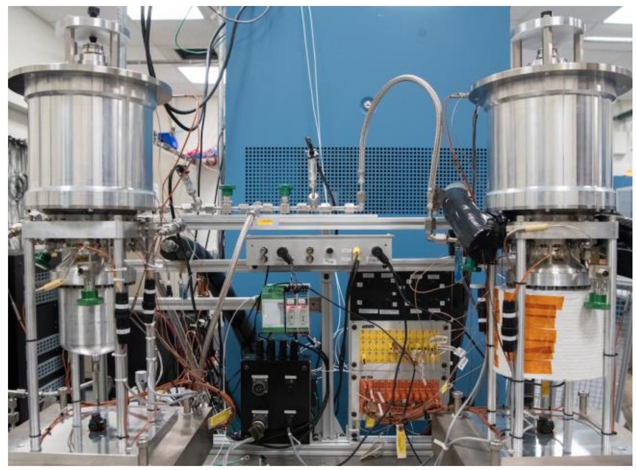

Fig. 7. FISC #1 and #2 on test stand at GRC.

The FISC prototype performance was measured during verification testing and found to exceed the 24% requirement, achieving 58 W_e at 26% efficiency while operating at a hot and cold end temperature of 650 ºC and 100 ºC, respectively. Some requirements were not met, including specific power under by 20%, the maximum rejection temperature under by about 15%, and there was insufficient margin to enable a loss of electrical load test. Random vibration testing of FISC #2 took place in May 2022 and the convertor passed the test with little to no power disruptions. The prototype was subjected to the qualification Grms value of 7.77 dB in three orthogonal axes, a value well below the design value of 10.35 dB. Additional environmental testing was planned for the FISC, but project priorities shifted when the DOE/INL managed flight development contract selected the SRSC as the baseline convertor for their DRPS generator design.

Prior to development of the TDC, Stirling Technology Company (STC) had success with development of several higher power convertors ranging from 350W_e to 3000W_e for cogeneration and remote power applications and also a lower power unit, called the RG-10, for the 10-We RG-10 terrestrial radioisotope convertor.[13] Figure 8 shows the RG-10 generator and electronic controller.

Fig. 8. STC 10-We RG-10 terrestrial radioisotope convertor.

At least one RG-10 convertor was fueled with isotope and field tested. Also, at least one unit accumulated 76,000 hours with no degradation.[14] Those units could have continued to operated but, due to limited publicly available information, the exact number of operational hours is not known.

Commercially available flexure-bearing free-piston Stirling designs have been developed for terrestrial applications, including solar, combined heat and cooling, and remote power generation by Infinia Technology Company and Qnergy. Qnergy offers units from xxx W_e to xxx W_e. Some designs have been produced in moderately high volumes, including XX units of the name convertor, YY units of the name convertor, and ZZ units of the name convertor.[15]

II.C. Life Testing at GRC

Legacy convertors were commissioned during past development efforts to provide performance verification and life and reliability data from high fidelity demonstration units and engineering units. Legacy units utilized temperature resistant materials and non-contacting bearings to demonstrate wear-free, long-life operation and were validated against performance specifications before undergoing extended operation testing. A total of eight Stirling convertors remain on test at GRC in extended operation. Legacy convertors include both gas-bearing and flexure-bearing designs. Many of the units are used to support ongoing controller or generator concept development or to continue extended operation to generate reliability data. Some units have been taken offline due to failure and investigated to identify improvements for future designs. Other units remain in storage, either because they are older deigns and less relevant or designated for tactical testing. Table II shows the recently updated extended operation hours for legacy convertors and new prototypes.

TABLE II. Summary of on-going Stirling convertor testing at NASA GRC.

Test Article	Hours	Years	Cycles (B)	Vibe	Spin	Note
TDC #13	140,611	16.1	41.3			World Record
TDC #15	139,735	16.0	41.1			
TDC #16	140,119	16.0	41.2			
TDC #14	105,616	12.1	31.0			Disassembled
ASC-0 #3	110,447	12.6	41.4	FA		
ASC-L	69,569	7.9	25.6	FA		EM controller
ASC-E3 #4	59,360	6.8	21.8	FA		Eng. Unit
ASC-E3 #9	45,404	5.2	16.7			Eng. Unit
SES #2	33,404	3.8	9.8	FA	FA	Eng. Unit
SRSC #1	9,705	1.1	3.5			Bolted joints
SRSC #2	10,006	1.1	3.6	Qual		Bolted joints
SRSC #3	3,520	0.4	1.2	Qual	Qual	Hermetic
SRSC #4	0	0.0	0.0	Planned	Planned	Hermetic
FISC #2	8,684	1.0	2.6			Bolted joints
FISC #1	5,578	0.6	1.7			Bolted joints

Extended Operation Data as of 2/9/23 *FA: Flight Acceptance*

The key roles of testing at GRC are to provide government verification and validation of convertor performance to design specifications and to build a performance database to support life and reliability estimates. These roles have traditionally been fulfilled through 24/7 unattended operation of convertors and testing performed in relevant environments aimed to simulate the expected mission lifecycle a Stirling convertor would experience in a radioisotope power system. All testing performed at GRC uses electric heat sources to simulate the nuclear fuel in a fueled RPS.

Unattended 24/7 operation is enabled through dedicated test racks which provide software with user controls, data acquisition, automated fault detection and shutdown capability, and hard-wired protections in case the software functions fail. These systems are continuously being improved to provide better data and increased protection to the hardware and data retention. All parameters and calculations are averaged every 2-seconds to create a data point, which is stored in the local database. The database stores a buffer of 96 hours of 2-second data, which is automatically downloaded and saved daily to a remote, backed up data center. This data is also reviewed regularly through automated plotting routines that enable engineers to quickly assess the performance of the convertor and any factors contributing to a change in the performance. In addition, the dynamic signals sampled at a 7 kHz rate are also automatically saved to the data center and can be used to help investigate data further, as needed. An automated text functionality communicates ongoing changes in the test setup to the cognizant engineers responsible for the testing.

III. CONCLUSIONS

NASA has been developing free-piston Stirling-cycle power convertors over the past 22 years for use in space-rated nuclear power systems as a highly-efficient alternative to currently available RPS. Convertor maturation efforts include recently completing multiple convertor technology development contracts and evaluating deliverables under critical environments based on multi-mission requirements developed by a surrogate mission team. Prototypes are evaluated for performance and robustness and then undergo extended operation to demonstrate reliable service. At this point in development, the Sunpower Robust Stirling Convertor (SRSC) has met all necessary requirements that would enable a demonstration on the surface of the Moon. This design has had key accomplishments that increase robustness and maturity level. It has proven tolerant to a loss of electrical load, eliminated the risk of regenerator debris, and all running clearances are documented prior to first operation. It has demonstrated lower production costs and schedule compared to its predecessor. Also, Aerojet Rocketdyne completed a 1-year design of a DRPS with six GPHS modules and eight Stirling convertors for high system reliability through redundancy. This design would produce around 300 W_e at a conversion efficiency of 19.5% and improvements are possible. Glenn Research Center is building a four-convertor DRPS Testbed for demonstration of tolerance to a single convertor fault and other DRPS functions to reduce risk and identify gaps. This maturation campaign ultimately increases the technology readiness level of the convertor to 5 and makes a compelling case for completing a demonstration on the surface of the Moon.

ACKNOWLEDGMENTS

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