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MATURATION OF DYNAMIC POWER CONVERTORS FOR RADIOISOTOPE POWER SYSTEMS

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Dynamic Radioisotope Power Systems (DRPS) are being developed by NASA's Radioisotope Power Systems (RPS) Program in collaboration with the U.S. Department of Energy (DOE) for space science and exploration missions. A development effort is currently underway to mature dynamic power convertors for infusion into a potential future flight generator. This convertor maturation effort was formulated by the RPS Program at NASA Headquarters based on successful maturation models and utilizes expertise from agency's technology and mission centers to support requirements development and technology assessments. The effort is being executed by Glenn Research Center's (GRC) DRPS Project and the Thermal Energy Conversion Branch. The Dynamic Power Convertor (DPC) contracts consist of three phases to enable design, fabrication, and independent assessment of prototypes after delivery to the government. The contracts are intended to gather data on candidate dynamic conversion technologies to fill knowledge gaps, support assessments of dynamic conversion technologies, and elicit generator requirements. The 110-watt Stirling Radioisotope Generator (SRG-110) and Advanced Stirling Radioisotope Generator (ASRG) flight development projects provided Stirling convertor demonstration units and engineering models to verify and validate convertors against performance specifications and mission requirements. These units utilize temperature resistant materials and non-contacting bearings to demonstrate wear-free, long-life operation. This maturation effort builds on past lessons-learned and new requirements focused on demonstrating convertor robustness to critical environments meant to stress key aspects of each convertor within the margins of the design. This effort seeks to realize the full potential of dynamic power conversion technologies for NASA's space science and exploration missions.

I. CONVERTOR MATURATION MODEL

Development of DRPS for flight is being driven by the integration of two major efforts that would culminate in a DOE flight contract for generator development.[1] These two efforts are 1) the establishment of a Surrogate Mission Team (SMT) that provides clear mission pull and requirements context and 2) the execution of technology maturation operational and evaluation model to sufficiently mature available power conversion technologies to a technology readiness level suitable for flight development. The SMT functions as a surrogate flight mission team until NASA selects an actual flight mission and serves as the requirements and technical authority to the RPS Program. It includes leadership from the NASA RPS Program Office and the DOE, power systems expertise from GRC, and representatives from each of the major robotic mission centers utilized by NASA, specifically, the Johns Hopkins University Applied Physics Laboratory (JHU-APL or APL), NASA Goddard Space Flight Center (GSFC), and the Jet Propulsion Laboratory (JPL). The maturation model being employed for development of DPC technologies, shown in Figure 1, has been tailored based on development of the enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG). It contains two gate reviews, the first allowing passage from phase 1 to phase 2 of the DPC development contracts and the second gate resulting in a recommendation that one or more conversion technologies are mature enough for use in a DOE managed flight development contract.

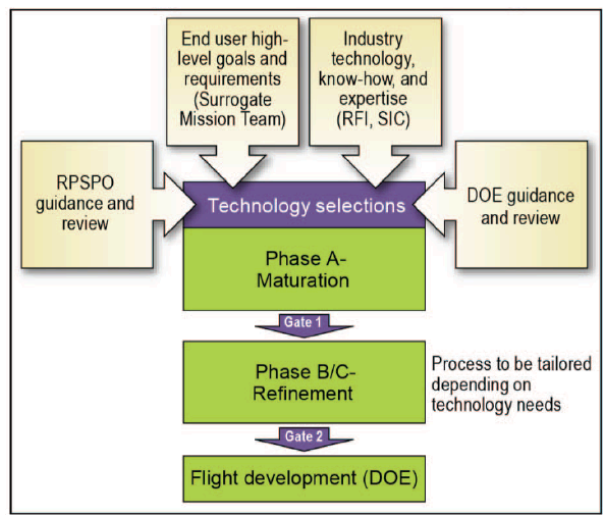

Fig. 1. Dynamic power convertor technology maturation operational and evaluation model.

The model utilizes a cross-organizational team with members from RPS Program, the DOE, and technology and mission centers (APL, GRC, GSFC, and JPL) to enable maturation efforts and perform gate reviews. The maturation model also employs a non-traditional approach for assessment of convertor reliability in place of a traditional lifetime analysis prediction. Depending on what method is chosen for the traditional statistical calculation with a reasonable sample size, the required test durations

turn out to be unreasonably high at millions of hours. To balance the challenge of time and resource limitations, a Risk-Informed Life Testing (RILT) tool has been developed to identify test data gaps and guide risk-reduction activities during convertor maturation.[2] The RILT framework uses test data for parts, components, and assemblies to reduce uncertainty and increase confidence in life model predictions. The RILT approach asserts that the new technology will have a sufficiently high probability and confidence that it will complete its mission successfully if the end of design life performance margins and confidence intervals are at least as large as those quantified for previous successful missions. The RILT effort includes the following primary goals: 1) establish the system lifetime goal, 2) develop physics-based models to analyze the system and determine the probability of meeting that goal and the associated uncertainty or margin, 3) identify data needed to support models and determine sources for data based on in-house, system heritage, or new testing, and 4) analyze data and update probability predictions within the RILT model.

Convertor goals were derived by the SMT with GRC expertise prior to a request for information (RFI) and subsequent request for proposal (RFP) in late 2015. The RFI and RFP were made available using the 2016 Research Opportunities in Space and Earth Sciences (ROSES-16) solicitation program. Proposals were assessed for relevance in 2016 and contracts were awarded the following year to four commercial providers, three of which offered Stirling convertors and one for a Brayton convertor. The 24-month contracts included three phases that would enable design, build, and test support. Designs were reviewed after the 6-month long phase 1 and three of the four contracts were allowed to continue through gate 1. Phase 2 is in progress and will enable convertor production, performance testing, and delivery over an 18-month period, ending in late 2019. Phase 3 of the contract includes 12 months of low-level support for government independent verification and validation (IV&V) testing at GRC.

The majority of dynamic power convertor requirements are shown in Table I. They each address critical aspects and environments of the mission life cycle for a number of different missions. The proposers were asked to designate which RFP goals would be excepted as requirements within their contract so minor differences exist between contracts, depending on functionality of the conversion platform and incoming maturity level. The design life and power requirements enable a long-life, 200-500 We generator with more modest specific power and efficiency requirements compared to past flight efforts. To enable high convertor redundancy in modular building blocks, a partial power requirement was added to ensure the that conversion efficiency was still sufficiently high even if half of the convertors were turned off. The rejection temperature was increased to a challenging 175 °C and the loss of electrical load requirement ensures that convertors can survive collisions between the moving and stationary components without any permanent degradation.

TABLE I. Dynamic Power Convertor Requirements.

Item	Description
Design Life	20 years continuous operation at full power
Power	Suitable for a 200 to 500 W_e generator
Efficiency	≥ 24% at $T_{cold\text{-}end}$ ≥ 100 °C
Specific Power	20 We/kg (convertor only)
Degradation	Output power changes < 0.5 % per year
Partial power	Maintains 20% conversion efficiency at 50% heat input
Atmosphere compatibility	Earth, Mars, Titan, vacuum, Argon
Hot-End Temp	< 1000 °C
Cold-End Temp	Capable of 20 to 175 °C
Random Vibe	Launch spectrum for 1 min in each axis
Static Accel	20 g for 1 minute, 5 g for 5 days
Tolerance to Loss of Load	Survive a loss of electrical load for 10 seconds while at full power
EMI	< 100 nT at 1 m while at full power
Radiation	No degradation after exposure to 300 krad
Autonomy	No external commands needed
Transmitted Forces	Enables generator with less than 10 N transmitted forces to spacecraft
Size	Enables generator for shipping cask

(EMI):electromagnetic interference. Some requirements not shown.

II. DPC CONTRACTS

All four NASA Research Announcement (NRA) contracts were all awarded by October 2017 to commercial engine providers that also produce cryocooler products for terrestrial and flight applications. The contracts were formulated to develop robust, manufacturable, and reliable convertor building blocks that could enable in a 200-500 W_e generator.[3] Contract execution and progress review is monitored on a monthly basis by the contracting officer representatives, project management team, and a multi-disciplinary integrated project team (IPT). The IPT is composed of technical representatives from APL, DOE, GRC, GSFC, and JPL with expertise in dynamic machinery, metallics, organics, safety and mission assurance, risk analysis, system integration, and mission planning. This team is responsible for examining monthly progress of the contracts and providing recommendations and feedback.

II.A. Thermoacoustic Power Convertor (TAPC)

The TAPC was designed by Northrop Grumman Aerospace Systems (NGAS) of Redondo Beach, CA. The convertor consists of a centrally located thermoacoustic heat engine driving a dual-opposed pair of linear alternators. The heat engine amplifies thermodynamic

power using an acoustic wave that travels across the temperature difference created by the cold and hot ends of the engine. Thermodynamic cycle phase is tuned by the acoustic compliance and inertance volumes, designed into the body of the central housing. The thermodynamic power drives the power pistons that are located in the common compression volume of the dual-opposed linear alternators. The piston clearance seals are maintained using flexure bearings that have a high radial stiffness to enable non-contacting, wear-free operation. Electrical power is created by oscillating a moving coil in magnetic field to generate an alternating current. Advantages of this conversion technology include elimination of the displacer moving component found in traditional free-piston Stirling machines. The power pistons can be so well balanced that the exported force from the convertor is estimated to be two orders of magnitude below the requirement. The linear alternator design is based on heritage from flight cryocoolers so the starting Technology Readiness Level (TRL) is considerably high. While the contract did not continue to phase 2 for various reasons, this technology could be further developed for potential use in space environments.

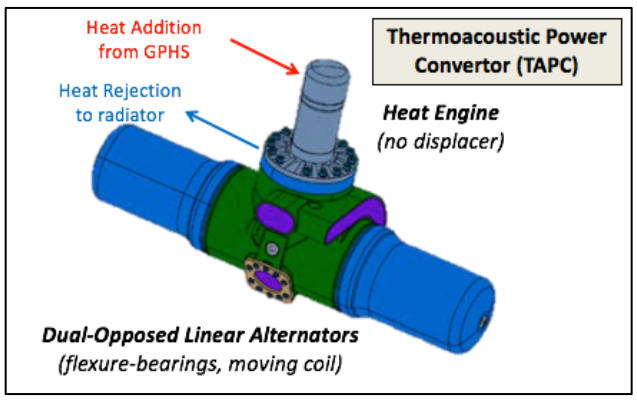

Fig. 2. Thermoacoustic Power Convertor (TAPC).

II.B. Flexure Isotope Stirling Convertor (FISC)

The FISC is being developed by American Superconductor (AMSC) of Richland, WA. The FISC is based on the Technology Demonstration Convertor (TDC), developed under the **SRG-110** flight development project. TDC testing started at GRC in 2000 and four convertors have now accumulated over 430,000 hours (49 years) with TDC #13 exceeding the previous record set at 110,000 hours of operation, making it the longest running Stirling convertor in the world with over 113,500 hours (13 years). The TDC and FISC designs use flexure bearings to maintain running clearances and achieve wear-free long-life operation. The FISC heater head will use Inconel 740H to ensure resistance to creep stress and the alternator design uses temperature-resistant organics to enable operation at 175 °C. The TDC linear alternator design contains a moving-iron design oscillating in a stator containing magnets and coils. To increase specific power and conversion efficiency, the FISC design will use moving-magnet design oscillating in a stationary coil and iron stator. The alternator will be constructed from materials with improved temperature resistance to enable operation at temperatures over 100 °C. New materials include magnets and organics, such as epoxy for magnet bonding and coil wire insulation. The FISC design will ease generator integration by including thermal interfaces that can be connected directly to generator interfaces. The FISC design passed the gate 1 review and the contract is now in the beginning months of Phase 2. This phase includes a few months for design adjustments per the review recommendations, after which hardware fabrication will begin for two prototypes. The units will be non-hermetically sealed to permit later disassembly and inspection during the government assessment testing.

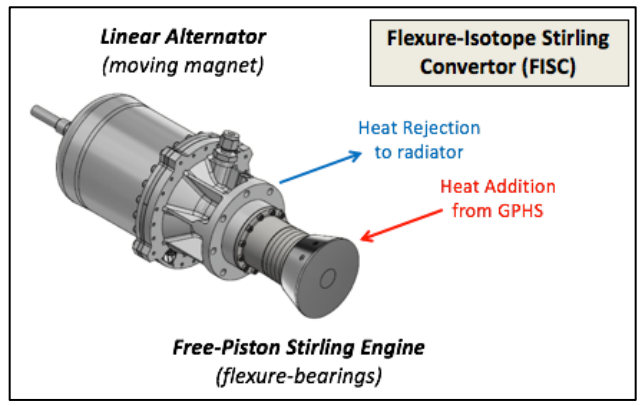

Fig. 3. Flexure Isotope Stirling Convertor (FISC).

II.C. Sunpower Robust Stirling Convertor (SRSC)

The SRSC is being developed by Sunpower Inc. of Athens, OH. The SRSC design is a free-piston Stirling machine based on the Advanced Stirling Convertor (ASC), developed under the ASRG flight development project. ASC testing started at GRC in 2007 and has accumulated over 76,600 hours (8.7 years) on a single unit and over 538,000 hours (61 years) from 39 units, many of which are available for tactical use, some that are acquiring reliability data in extended operation, and some that have experienced a failure to maintain the power output requirement and were subsequently shut down for disassembly and inspection. Such inspections have helped identify root cause and solutions for preventing reoccurrence of the failures. The SRSC has been designed based on lessons-learned and contains features that are expected to eliminate past identified weaknesses. The SRSC design utilizes gas-bearings to maintain running clearances and achieve wear-free long-life operation. The gas bearings are energized by

extracting a portion of the thermodynamic cycle's pressure wave and it provides spring for the power piston while maintaining radial clearances. The power piston and displacer moving components are connected to separate mechanical planar springs, keeping them axially centered and simplifying convertor startup. Other improvements in the SRSC design include high-temperature organics for the 175 °C rejection temperature, a robust magnet can with encapsulated magnets, increased gas bearing capacity, gas bearing supply volume input filter, and robust regenerator designs. The heater head material, Haynes 230, was selected to ensure manufacturability and resistance to creep stress. The SRSC design passed the gate 1 review and the contract is now in the beginning months of Phase 2. This phase includes a few months for design adjustments per the review recommendations, after which hardware fabrication will begin for two prototypes. Similar to other contracts, the units will be non-hermetically sealed to permit later disassembly and inspection during the government assessment testing.

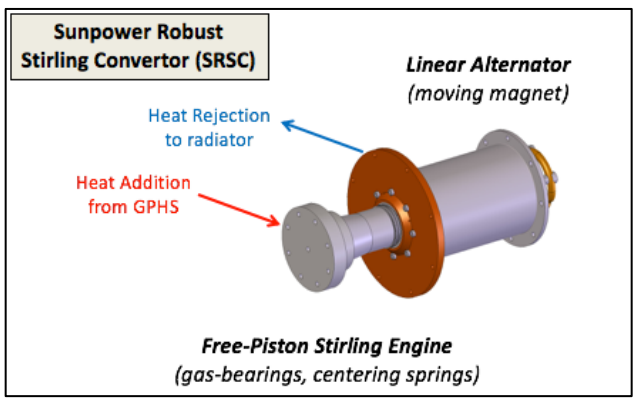

Fig. 4. Sunpower Robust Stirling Convertor (SRSC).

II.D. Turbo-Brayton Convertor (TBC)

The TBC is being developed by Creare Inc. of Hanover, NH. The TBC is a small Brayton-cycle machine and is based on the flight cryocooler that has successfully served on Hubble's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) instrument. The TBC consists of a single rotating shaft with embedded magnet and integral turbine and compressor impellers. The rotary alternator utilizes a rare-earth magnet rotating inside the stationary coil and iron. Non-contacting operation is achieved using hydrodynamic journal bearings and thrust bearings. The conversion process is enabled by unidirectional gas flow through the turbomachine assembly, recuperator, and addition and rejection heat exchangers. The counter-flow recuperator enables high thermodynamic efficiency by pre-warming gas before it flows into the heat source assembly. The TBC has been designed to avoid significant material creep of the turbine impeller at high temperatures. Due to the rotation of the impellor shaft in the alternator, this convertor design could require two counter-rotating units to nullify torque to the spacecraft. The TBC design passed the gate 1 review and the contract is now in the beginning months of Phase 2. This phase includes a few months for design adjustments before hardware fabrication of a single prototype. Similar to other contracts, the unit will be non-hermetically sealed to permit later disassembly and inspection during the government assessment testing.

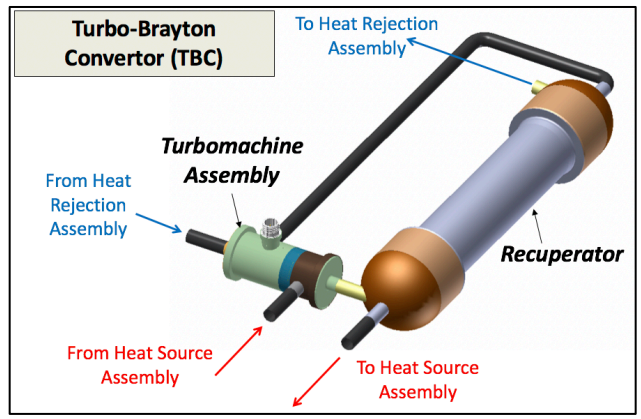

Fig. 5. Turbo-Brayton Convertor (TBC).

III. INDEPENDENT ASSESSMENT

The DPC contracts consist of three phases to enable design, fabrication, and independent assessment after delivery to the government. Prior to delivery, the requirements verification matrix will be reviewed for how well prototypes meet each requirement. Phase 3 of the contract includes 12 months of low-level contractor support for government IV&V testing. The independent assessment serves multiple purposes, including:

- Ensuring delivery and initial quality
- Comparing to contractor measurements
- Verifying prototype to design specification
- Validating prototype to mission requirements
- Assess design durability

The overall objectives for verification and validation activity differs based on what is be proven. Verification provides proof that the prototype complies with design specifications and production documents. Tests are performed to verify that design risks are minimized and to certify readiness for initial validation testing. Validation provides proof that the prototype accomplishes the intended purpose based on stakeholder expectations. Validation testing relates back to the concept of operations and is conducted under realistic conditions (or simulated conditions) with the purpose to determine the viability of the prototype for use in a mission. Both verification and validation may be determined by a combination of

inspection, analysis, demonstration, and test, test being the gold standard.[4]

There are three main categories planned for the IV&V test campaign; inspections, performance, and durability. Each section is shown with more detail in Figure 6 where more detail is provided. The verification and validation plan is currently being formulated.

III.A. Inspection

Inspection activity includes measurement of external surfaces for workmanship and precise measurement of geometry using a coordinate measuring machine. Alternator electrical measurements range from measuring inductance, capacitance, and resistance values to more complex measurements like a high-pot measurement. EMI testing would be carried out to verify compliance to the value shown in the contract requirements. Finally, because the convertors can be partially disassembled due to the presence of bolted flanges, some internal measurements and photographs can be taken before and after testing in critical environments.

III.B. Performance

Performance verification and validation contains the bulk of the testing. Temperature mapping confirms power output and conversion efficiency at each temperature specified in the contract requirements. Low heat input testing captures the 50% heat input point, among others to create a trend of conversion efficiency as the heat input decreases. This will provide inputs to inform generator designs that want to include more convertor spares for redundancy. Horizontal operation is used to simulate ground operations by providing a modest 1 g lateral load to the non-contacting bearings, which have been designed to meet the 5 g requirement shown in Table I. Vertical orientation testing is used to simulate cruise conditions due to the absence of a lateral load on the bearings and it is used to characterize the residual dynamic forces of the balanced pair. Random vibration testing is performed in three orthogonal axes to simulate launch conditions and constant acceleration is also performed in three orthogonal axes to simulate loads during entry, decent and landing on a planetary surface with an atmosphere. In addition to axial heater head outward, another axial orientation is performed with the heater head pointed toward the center of rotation.

III.C. Durability

Durability tests will be used to demonstrate convertor robustness to anticipated events or critical environments that stress key aspects or functions within the margins of the design. Ground testing during fabrication, acceptance, and integration results in a number of stop/start cycles and corresponding thermal cycles. Temporary loss of load will be used to ensure the convertor is robust to undesired, yet possible, errors during ground testing where collisions are possible between moving and stationary components. Finally, elevated piston amplitude is being considered to operate above nominal values near the ends of the design margin in order to accelerate the fatigue life of springs.

Inspection	Performance	Durability
• External Geometry • Alternator Electrical Measurements • Electromagnetic Interference • Internal components	• Temperature Mapping • Low Heat Input • Horizontal & Vertical Orientation • Random Vibration • Constant Acceleration • Shock	• Thermal Cycling • Start/Stop Cycling • Temporary Loss of Electrical Load • Elevated Piston Amplitude

Fig. 6. Independent Assessment Areas of Focus.

II. CONCLUSIONS

Dynamic Radioisotope Power Systems are being developed by NASA's RPS Program in collaboration with the DOE. This development effort builds on past lessons-learned and new requirements focused on demonstration of convertor robustness to anticipated environments. The maturation process has been formulated based on successful RPS maturation model and utilizes expertise from agency's technology and mission centers. A Surrogate Mission Team has led the development of requirements for an RFP and subsequent contracts were awarded to commercial providers of Stirling and Brayton technologies. These contracts consist of design, fabrication, and testing phases which may mature one or more options for a future flight generator. This convertor maturation effort aims to successfully demonstrate robust dynamic power conversion technologies that utilize non-contacting bearings required for wear-free long-life operation.

ACKNOWLEDGMENTS

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