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FLEXURE ISOTOPE STIRLING CONVERTOR (FISC) DEVELOPMENT PROGRESS

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The AMSC Stirling development team (formerly Infinia Corporation) is developing an advanced Stirling convertor, designated as the Flexure Isotope Stirling Convertor (FISC), for high efficiency Radioisotope Power Systems (RPS). After a successful Phase I FISC design, a Phase II fabrication and test contract with NASA Glenn Research Center (GRC) is about 30% complete at this writing in late 2018. Two FISC demonstration units will be thoroughly evaluated in Phase 2, then delivered to GRC for a wide range of Phase 3 performance assessments and flight qualification tests. FISC is a direct derivative of Infinia's Technology Demonstration Convertor (TDC) and Stirling Radioisotope Generator (SRG) development contract with DOE/GRC between the mid-1990's and 2005. All four TDC units assigned to long-term testing at GRC demonstrated exceptional life and reliability in excess of 12 years with no maintenance or degradation. FISC uses the same basic topology as the already robust TDC. Some changes were required to address significantly higher operating temperature environments, and additional changes will further improve design margins, robustness and efficiency.

I. INTRODUCTION AND TDC OVERVIEW

The FISC development effort is directed toward meeting or exceeding the objectives set forth in ROSES Solicitation C.22 DYNAMIC POWER CONVERTORS FOR RADIOISOTOPE POWER SYSTEMS. These aggressive goals include 20 years of continuous operation at full power, rigorous launch vibration and static acceleration specifications, efficiency >25% at full power and >20% at half power with ≥ 100 °C cold end temperature, cold end operational capability up to 175 °C, and the ability to withstand 10 seconds of extreme overstroke operation in the event of temporary loss of load. ROSES C.22 also includes numerous other detailed specifications such as operating in a wide range of space environments.

The former Infinia Corporation successor is Qnergy in Ogden Utah, which is commercializing their PowerGen Free-Piston Stirling (FPS) remote power generator. The Infinia Technology Corporation subsidiary of Qnergy, established to develop FPS cryocoolers and conduct contract R&D, was acquired last year by AMSC and continues operations as part of AMSC in their same Richland, WA facility. All of the key personnel who developed the TDC are currently on staff at AMSC or Qnergy, except for Dr. Songgang Qiu at West Virginia University, who still routinely collaborates with AMSC. AMSC is the prime contractor for FISC, with Qnergy as a subcontractor. While the FISC contract is focused on Stirling convertor development, the FISC team also includes Teledyne Energy Systems, Inc. (TESI) who provides system integration and space qualification expertise that will enable the first two FISC demonstration units to closely represent future flight units. All AMSC and Qnergy FPS machines utilize the same basic flexure bearings with clearance seals to support the reciprocating piston and displacer. It is the proprietary implementation of this topology that enables the unprecedented maintenance-free life and reliability exhibited by all these machines.

The external configuration of a TDC is shown in Figure 1, where the linear alternator pressure vessel is at the left of the bolted flange, the heater head heat acceptor is at the far right, and the conductive flange to transfer reject heat is the large diameter central disk. Integration of two TDC's into an SRG generator by Lockheed Martin is illustrated in Figure 2. The alternator pressure vessels are coaxially placed end-to-end and the linear alternator outputs are coupled to synchronize the pistons and balance virtually all of the vibration. The exterior finned structure radiates reject heat to space. Figure 3 shows a typical balanced pair of TDC's in a laboratory test configuration with the hot ends adjacent. The external rods that connect pressure vessel flanges symmetrically and rigidly couple the units to virtually cancel vibration when the linear alternators are synchronized at 180° out of phase.

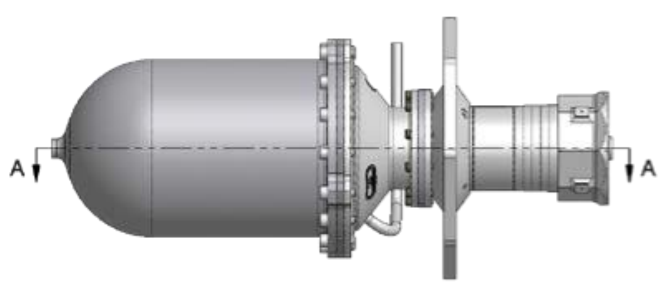

Fig. 1. Configuration of TDC flight version.

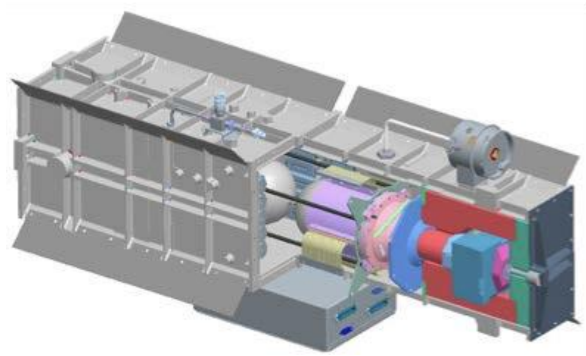

Fig. 2. SRG-110 flight system concept that includes two central TDC flight units with a General Purpose Heat Source (GPHS) near each end.

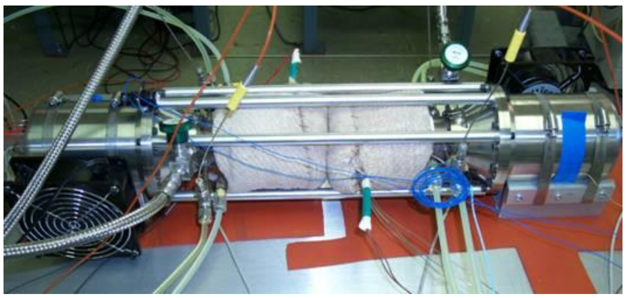

Fig. 3. Balanced pair of TDC's with hot ends adjacent.

Recent TDC endurance testing updates were described in a paper and presentation by NASA GRC[1]. As of November 2018, TDC units 15 and 16 continue testing at GRC with 12.0 years of operation and unit 13 continues with 13.0 years (a world record for dynamic conversion systems), all with no maintenance and no degradation in performance. Unit 14 was shut down for disassembly and inspection after 12.1 years of operation. Preliminary results indicated no degradation despite being subjected to out-of-spec overstroke operation and operating for an extended period in a non-hermetic condition where significant amounts of oxygen were transferred into the helium working fluid. Subsequent more extensive disassembly showed that the hottest ~20% of the regenerator fibers had experienced some structural damage due to oxidation, but that had not affected performance. Based on this observation alternative regenerator materials are planned for FISC, even though new operating procedures should eliminate virtually all oxygen. Other TDC testing successfully implemented at GRC in the early 2000's included random vibration, EMI emissions and all other flight qualification requirements.

II. FISC DEVELOPMENT STATUS

The internal AMSC FISC development team includes three of the key people responsible for TDC/SRG development, with two more at Qnergy. Qnergy has provided a significant support role for FISC, as has a group at TESI with extensive experience in flight qualified space power system hardware. The guiding design principle was to maximize retention of the proven TDC design, but to also make improvements where 1) they were required to meet new NASA program objectives or 2) there was a consensus conclusion by the design team that high-confidence changes could be made to materially improve robustness, design margins or efficiency. A secondary category of potential improvements was also considered to address goals such as size or weight reduction, better generator system interface potential and improved manufacturability.

II.A. Phase 1 Design

There were two areas where TDC design changes were clearly required. Several materials changes were needed to meet the new nominal heat rejection temperature of 100 °C, with operational capability up to 175 °C. In addition, the TDC moving iron linear alternator topology that was designed in the mid-1990's has been replaced by moving magnet alternators for all subsequent AMSC/Qnergy FPS machines. It was therefore intended from the beginning to design a new alternator. This change also enables meeting the new FISC efficiency goals with confidence rather than marginally, since the alternator efficiency will increase from the low-to-mid 80% range to the 90% range.

The AMSC FISC design team rigorously evaluated many candidate design changes that addressed many of the improvement categories described above. The use of modern design tools also enabled more rigorous analysis of stress levels, linear alternator performance and thermal profiles. Even though the focus of the FISC contract is on Stirling convertor development, significant effort was also employed to assess future system integration issues. While TESI supported several Phase 1 tasks, they took the lead on the system integration effort. Options evaluated covered a wide range of possibilities, even considering power output scope changes to evaluate potential benefits for changing from one convertor interfacing with one GPHS to either one convertor for two GPHS units or two convertors for one GPHS. In the final analysis, the one-to-one relationship was maintained. Thermal interfaces of the convertor with both the heat source and heat sink were a key focus. Several alternative packaging approaches and redundancy levels were evaluated. For example, 100% convertor redundancy uses twice as many convertors that operate at half-power unless there is a failure. This offers a major increment in mission reliability, but clearly entails a significant mass penalty. The final conclusion is that the FISC design will offer a wide range of mission customization options for future flight systems.

The Phase 1 design effort also included risk assessments, reliability analyses, alternative hot end temperature evaluations, a robustness assessment, coupled structural/thermal modeling, a performance verification plan, vibration analyses and development of a FMECA. The results of the Phase 1 effort were presented to NASA at an interim Technical Interchange Meeting and a final Phase 1 Design Review. The Phase 1 FISC design was positively received and the Phase II contract was awarded. A comparison of the TDC and FISC envelope geometries in Figure 4 illustrates their overall similarity. The major change is in the linear alternator. Several other subtle but substantive improvements directly address primary contract objectives of developing a robust and reliable Stirling convertor for future RPS flight missions.

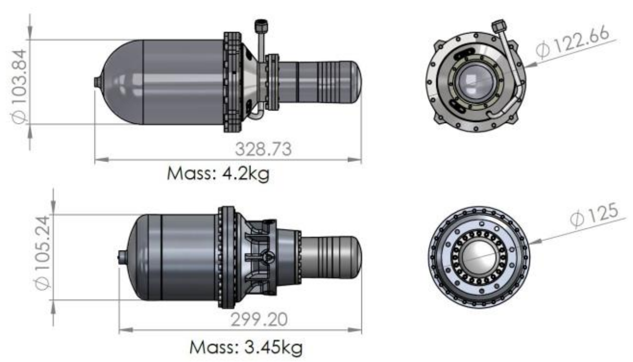

Fig. 4. TDC (top) and FISC (bottom) comparisons.

II.B. Phase 2 Status Update

The FISC Phase 2 work plan is straightforward. Action items from the Phase 1 final review have been addressed and manufacturing drawings and specifications are nearly complete. FISC hardware fabrication of two demonstration units and test stand development are underway. The demonstration units will be assembled and begin operational testing by early summer of 2019. Shakedown testing of new FPS designs normally entails a period of fine tuning to ensure that the free piston and free displacer, which are coupled only by a pressure wave, both operate with full stroke and the proper phase angle. Once proper operation is achieved, extensive operational characterization and performance mapping over a wide range of simulated environmental and off-nominal-design conditions will be conducted. It is anticipated that this full range of testing will be completed before the end of 2019.

A schematic of the basic FISC test configuration and instrumentation is shown in Figure 5. Highlights include piston position sensor, displacer position sensor, heater tape around the linear alternator pressure vessel to provide the ability to control the alternator housing temperature for specific environmental condition simulation, dynamic pressure transducers in the compression space and buffer space, a range of temperature measurements, a pumped loop heating/cooling chiller to set the rejection temperature to any desired level, a controlled heater head electrical input level, and electrical measurement parameters from the linear alternator output.

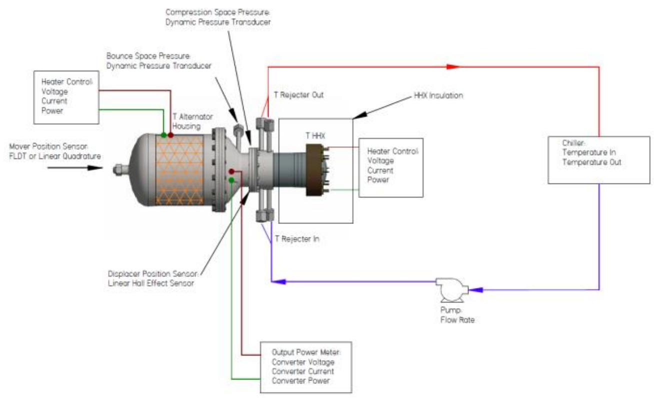

Fig. 5. FISC laboratory testing schematic.

III. CONCLUSIONS

The AMSC FISC team has conducted a comprehensive update of the proven TDC design to address revised NASA specifications and to further improve robustness, design margins and efficiency. An intensive collaborative approach by all team members, with additional review and feedback from NASA and a multi-agency Reliability Informed Lifecycle Testing (RILT) team, have resulted in a high-confidence design that will meet or surpass all contract objectives. Hardware procurement for two FISC demonstration units is underway, with initial testing planned for early summer 2019. Following extensive testing and evaluation of the two demonstration units at AMSC, they will be delivered to GRC by the end of 2019 for their performance evaluations and flight qualification categories of testing.

ACKNOWLEDGMENTS

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