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TURBO-BRAYTON CONVERTER FOR RADIOISOTOPE POWER SYSTEMS

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Creare has teamed with Aerojet Rocketdyne, Sest Incorporated (Sest), *and the University of New Mexico Institute for Space and Nuclear Power Studies (UNM-ISNPS) to develop a turbo-Brayton power converter for future NASA missions that use radioisotope heat sources. NASA has considered the closed Brayton cycle attractive for space since the 1960s, and Creare has developed miniature Brayton technology for over 40 years. Key characteristics include high specific power, high efficiency, long-life operation without wear, undetectable vibration, and flexible packaging. Detailed design results indicate a 300 W_e-class converter with a turbine inlet temperature of 730°C will have a thermal-to-electric conversion efficiency of nearly 25% and a specific power greater than 20 W_e/kg.*

I. INTRODUCTION

Future NASA space missions require advanced systems to convert thermal energy into electric power for long durations. Closed-loop Brayton converters are attractive for these applications because they enable high reliability, long life, and high specific power. They also consist of discrete components that can be packaged to fit optimally with other subsystems, and their continuous gas flow can communicate directly with remote heat sources and heat rejection surfaces without heavy conductive links or intermediate flow loops.

Prior closed Brayton cycle work at Creare has focused on cryogenic refrigerators for spaceflight applications. This experience provides critical expertise, which is now being leveraged to develop power converters for space. The resulting technology is readily scalable for power levels from tens of watts to hundreds of kilowatts and beyond. Potential near-term NASA applications include Radioisotope Power System (RPS) devices, "Kilopower" spacecraft, Nuclear Electric Propulsion (NEP), and Surface Power missions.

Creare, Aerojet Rocketdyne, UNM-ISNPS, and Sest form a complementary team. Creare is designing, fabricating, and testing the converter; Rocketdyne specified future generator system details including interfaces with the heat source assembly and the heat rejection assembly; UNM-ISNPS predicted the thermal performance of the heat source assembly; and Sest assessed reliability and robustness. These activities enable a prototype converter that is practical and attractive for future space missions.

II. HERITAGE

The converter builds on proven technology for miniature turbo-Brayton systems Creare has developed for long-duration space missions. These systems have satisfied rigorous NASA and DoD requirements for reliability, endurance, vibration emittance, space launch tolerance, electromagnetic interference and susceptibility, and environmental cycling.[1,2] One such system is a turbo-Brayton cryocooler that operated on the Hubble Space Telescope for over 6.5 years without maintenance or performance degradation while meeting all mission requirements.[3] More recently, Creare made significant improvements in manufacturing readiness level,[4] and is continuing advanced component and system development for several emerging applications.[5,6] Creare began applying turbo-Brayton technology toward the development of miniature power converters for NASA in 2001,[7,8] and this work is continuing today.[9] These projects have demonstrated fundamental technologies required at the sizes, power levels, temperatures, and rotational speeds needed for radioisotope power system converters.

III. TECHNOLOGY DESCRIPTION

Figure 1 is a schematic representation of a closed-loop Brayton converter. In this configuration, the compressor pressurizes the cycle gas and forces it to pass through the system in a continuous loop of steady flow. The temperature of the cycle gas increases as it flows through the recuperator and the hot interface heat exchanger. The hot, high-pressure gas then produces mechanical power as it expands through the turbine. The turbine exhaust stream transfers most of its heat to the high-pressure flow stream via the recuperator. The precooler then transfers waste heat to the heat rejection system before the gas is re-pressurized. The compressor impeller and turbine impeller are attached to a common shaft with a permanent-magnet alternator between them. As a result, the mechanical power produced by the turbine drives the compressor directly, and excess shaft power generates electric power via the alternator. The power conversion electronics transform the high-frequency, three-phase, alternator output into regulated DC power for general use. A heat rejection system transfers waste heat from the precooler, turbomachine housing, and electronics to space via radiator surfaces.

The only moving part in the converter is a miniature turbomachine rotor. Hydrodynamic gas bearings and clearance seals eliminate mechanical contact between moving surfaces. This lack of contact permits high rotational speeds, which is important for high efficiency and specific power; and it also enables extremely long maintenance-free life. Creare has performed several reliability and endurance tests, including a 14-year life test and over 10,000 start/stop cycles with no maintenance, wear, or performance degradation.

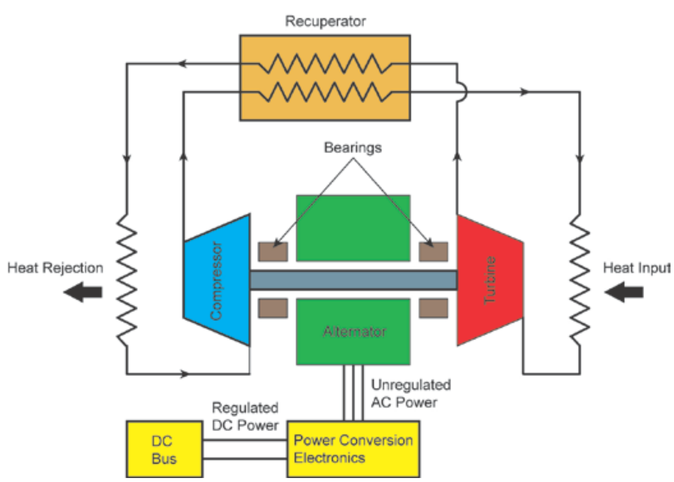

Fig 1. Schematic for closed-loop brayton converter.

IV. TURBOMACHINE

A single turbomachine assembly contains the turbine, alternator, and compressor. It has a hot end and cold end, joined together by relatively thin metal features. These thin features provide adequate structural rigidity for mechanical loads while minimizing conductive heat transfer. The compressor, alternator, and bearings are located at the cold end of the assembly. The rotor shaft extends from the cold end to the hot end, where the turbine is located. The turbine is the only major component at the hot end of the assembly.

The turbomachine includes a small high-speed rotor with a mass of only 39 grams. The rotor has a compressor impeller and a turbine impeller attached to a common shaft, and a permanent magnet is installed inside the hollow shaft to provide the rotating magnetic field for the alternator. The impeller diameters are 19 mm (0.75 inch), and the shaft diameter is 9.53 mm (0.375 inch).

The turbomachine is designed to operate during launch, consistent with RPS program requirements. Prior Creare Brayton systems have completed vibration qualification testing and spaceflight launches. Most notably, the Creare cryocooler on the Hubble Space Telescope endured qualification testing, two launches, and one landing. Several other programs have also conducted vibration tests with Creare turbomachines. However, none of these tests were performed while the turbomachines were operating because none of the applications required operation during launch. Consequently, extensive dynamic CFD analyses have been completed to assess rotordynamic operation during launch, and a risk-reduction test will be performed with a representative rotor assembly to corroborate the results.

V. RECUPERATOR

The recuperator is a micro-tube heat exchanger with counter-current flow. It is an advanced adaptation of traditional shell-and-tube technology commonly used for industrial heat exchangers. The RPS embodiment is significantly lighter and smaller than conventional shell-and-tube heat exchangers and plate-fin units with the same performance characteristics. High performance is achieved by utilizing thousands of very small tubes. Small length scales enable extremely high heat transfer area per unit volume without the need for secondary surfaces (i.e., fins). The result is very high heat transfer density with very low pressure losses. Longitudinal conduction from the hot end to the cold end is also very low, which is important when high thermal effectiveness is desired.

The RPS recuperator is very similar to five units Creare recently built for a turbo-Brayton refrigerator to enable cryogenic propellant storage in space for NASA missions.[10] The cryocooler version passed NASA GEVS launch vibration qualification testing, and analyses indicate the RPS version has greater design margin.

The recuperator is an all-welded stainless-steel assembly. There are no braze joints. The tubes are 304 stainless steel (UNS S30400), and all of the other components are 316L stainless steel (UNS S31603). Stainless steel has acceptable strength and creep resistance for the specified operating conditions. The predicted stress in the micro-tubes is only 8.9 MPa (1,300 psi) due to their small diameter. Stresses in the outer shell and headers are greater because of their larger sizes; however, material thicknesses in these areas have been specified to achieve acceptable creep life with desired reliability.

Creare developed the micro-tube heat exchanger technology and associated manufacturing processes collaboratively with Mezzo Technologies Incorporated and Edare Incorporated. Several units have been built, and the required fabrication processes have been demonstrated. The supply chain, manufacturing process, and quality control are well-established and have demonstrated consistently high quality.

VI. LIFE AND RELIABILITY

Long life with high reliability is critical for spaceflight power systems. Consequently, Sest was recruited to conduct an objective life and reliability assessment with assistance from Creare. The results from this work formed the basis for further independent review currently being conducted by a Risk-Informed Life Testing (RILT) team led by the Johns Hopkins University Applied Physics Laboratory.

Long-life is straightforward to achieve since there is no lubrication or sliding contact during operation, and axisymmetric rotation produces negligible reciprocating forces to initiate fatigue. The life-limiting factor for the converter is centrifugal creep of the turbine rotor. Although high temperature and high speed are desired to maximize efficiency and specific power, both factors are limited to maintain centrifugal creep growth within acceptable limits. Detailed finite element analyses indicate that the RPS life goal of 20 years of operation time (3 years of ground storage and 17 years of operation in space) can be achieved with a turbine inlet temperature of 730°C, using Inconel 718 (UNS N07718) for the turbine impeller. However, creep tests with samples from the selected material lot are recommended to enhance creep-life certainty.

VII. GENERATOR SYSTEM CONCEPT

Creare and Aerojet Rocketdyne worked together to develop a conceptual design for a generator system with a spaceflight configuration. A key requirement is that the assembly must fit within a DOE shipping container with internal dimensions that are 86 cm diameter and 144 cm long. Our design is very similar to the design Aerojet Rocketdyne developed previously for the 500 W_e Dynamic Isotope Power System (DIPS) for the JPL Mariner Mark 2 spacecraft. The current design includes two 337 W_e converters integrated with a common heat source assembly and a common heat rejection assembly. The heat source assembly contains a linear stack of six General Purpose Heat Source (GPHS) Step 2 modules, a containment canister, tubing for the Brayton-cycle working fluid, and thermal insulation. The generator configuration enables both converters to operate at approximately half power, or one converter to operate at full power. The two converters are hermetically isolated from each other with independent gas charges. Each converter consists of discrete components connected by tubing. This feature combined with flexibility of the heat exchanger designs enable custom system configurations that can be designed to fit optimally with other subsystems. Aerojet Rocketdyne has developed preliminary designs for the heat source assembly and the heat rejection assembly.

VIII. STATUS AND PLANS

We have completed detailed design activities for the converter assembly, and we are now fabricating a prototype unit for laboratory testing. Component fabrication is presently under way, and converter assembly is expected to be complete by July 2019. Operation and performance tests will then follow.

IX. CONCLUSIONS

Creare and its partners are developing a turbo-Brayton power converter to support future NASA RPS missions. This converter leverages extensive closed Brayton cycle technology developed at Creare over several decades with emphasis on cryogenic refrigerators for long-life spaceflight applications. This technology is now being adapted to create a converter that is designed to produce 337 W of electric power with a predicted thermal-to-electric conversion efficiency of 24.9% and a predicted specific power of 20.4 W/kg.

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REFERENCES

1. J. J. BREEDLOVE, M. V. ZAGAROLA, G. F. NELLIS, J. A. GIBBON, F. X. DOLAN and W. L. SWIFT, *Life and Reliability Characteristics of Turbo-Brayton Coolers*, pp. 489-498, R. G. ROSS, JR., Ed., Kluwer Academic/Plenum Publishers, New York, NY (2001).

2. F. X. DOLAN, W. L. SWIFT, LT. B. J. TOMLINSON, A. GILBERT and J. BRUNING, *A Single Stage Reverse Brayton Cryocooler: Performance and Endurance Tests on the Engineering Model*, pp. 465-474, Plenum Press, New York (1997).

3. W. L. SWIFT, F. X. DOLAN and M. V. ZAGAROLA, *The NICMOS Cooling System – 5 Years of Successful On-Orbit Operation*, pp. 799-806, Trans Cryogenic Engineering Conference – CEC, **52**, AIP Conference Proceedings, **985** (2008).

4. M. V. ZAGAROLA, J. J. BREEDLOVE, C. S. KIRKCONNELL, J. T. RUSSO and T. CHIANG, *Demonstration of a Two-Stage Turbo-Brayton Cryocooler for Space Applications*, pp. 461-469, S. D. MILLER and R. G. ROSS, JR., ICC Press (2008).

5. J. J. BREEDLOVE, K. J. CRAGIN and M. V. ZAGAROLA, *Testing of a Two-Stage 10 K Turbo-Brayton Cryocooler for Space Applications*, S. D. MILLER and R. G. ROSS, JR., ICC Press (2014).

6. M. V. ZAGAROLA, J. J. BREEDLOVE and K. J. CRAGIN, *Demonstration of a High-Capacity Cryocooler for Zero Boil-Off Cryogen Storage in Space*, International Cryocooler Conference 17, Los Angeles, CA (9-12 July 2012).

7. L. S. MASON, *Realistic Specific Power Expectations for Advanced Radioisotope Power Systems*, 4th International Energy Conversion Engineering

Conference and Exhibit (IECEC), Paper AIAA 2006-4193, San Diego, CA (2006).

8. M. ZAGAROLA, M. G. IZENSON, J. BREEDLOVE, G. M. O'CONNOR, A. C. KETCHUM, R. L. JETLEY and J. K. SIMONS, *An Advanced Turbo-Brayton Converter for Radioisotope Power Systems*, pp. 632-640, Space Technology and Applications International Forum—STAIF 2005, Publ. AIP Conf Proc 746, American Institute of Physics, Melville, NY (2005).
9. J. J. BREEDLOVE, M. V. ZAGAROLA, T. M. CONBOY, A. SHAH, C.-Y. LU, M. EL-GENK and T. SCHRIENER, *Turbo-Brayton Converter for Radioisotope Power Systems*, Nuclear and Engineering Technologies for Space 2018 (NETS-2018), Las Vegas, NV (26 Feb–1 Mar 2018).
10. D. DESERRANNO, M. V. ZAGAROLA, D. CRAIG, R. GAREHAN, T. GIGLIO, J. SMITH, J. K. SANDERS and M. DAY, *Performance Testing of a High Effectiveness Recuperator for High Capacity Turbo-Brayton Cryocoolers*, 19th International Cryocooler Conference (ICC 19), San Diego, CA (2016).