

Stirling Technology Development at NASA GRC

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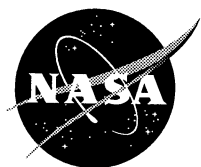
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Prepared for the
Space Technology and Applications International Forum (STAIF-2002)
sponsored by the American Institute of Aeronautics and Astronautics
Albuquerque, New Mexico, February 3–7, 2002

National Aeronautics and
Space Administration

Glenn Research Center

Acknowledgments

The authors would like to acknowledge the Office of Space Science (Code S) and the Office of Aerospace Technology (Code R) at NASA Headquarters for providing funding for this project.

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Document Change History

This printing, numbered as **NASA/TM—2001-211315/REV1, January 2002**, replaces the previous version, **NASA/TM—2001-211315, December 2001**. The callout “IN718 thick sample creep regime” has been inserted in the lower right corner of figure 1.

Stirling Technology Development at NASA Glenn

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Abstract. The Department of Energy, Stirling Technology Company (STC), and NASA Glenn Research Center (NASA Glenn) are developing a free-piston Stirling convertor for a high-efficiency Stirling Radioisotope Generator (SRG) for NASA Space Science missions. The SRG is being developed for multimission use, including providing electric power for unmanned Mars rovers and deep space missions. NASA Glenn is conducting an in-house technology project to assist in developing the convertor for space qualification and mission implementation. Recent testing of 55-We Technology Demonstration Convertors (TDC's) built by STC includes mapping of a second pair of TDC's, single TDC testing, and TDC electromagnetic interference and electromagnetic compatibility characterization on a non-magnetic test stand. Launch environment tests of a single TDC without its pressure vessel to better understand the convertor internal structural dynamics and of dual-opposed TDC's with several engineering mounting structures with different natural frequencies have recently been completed. A preliminary life assessment has been completed for the TDC heater head, and creep testing of the IN718 material to be used for the flight convertors is underway. Long-term magnet aging tests are continuing to characterize any potential aging in the strength or demagnetization resistance of the magnets used in the linear alternator (LA). Evaluations are now beginning on key organic materials used in the LA and piston/rod surface coatings. NASA Glenn is also conducting finite element analyses for the LA, in part to look at the demagnetization margin on the permanent magnets. The world's first known integrated test of a dynamic power system with electric propulsion was achieved at NASA Glenn when a Hall-effect thruster was successfully operated with a free-piston Stirling power source. Cleveland State University is developing a multidimensional Stirling computational fluid dynamics code to significantly improve Stirling loss predictions and assist in identifying convertor areas for further improvements. This paper will update the status and results for these efforts.

INTRODUCTION

The Department of Energy (DOE), Stirling Technology Company (STC), and NASA Glenn Research Center (NASA Glenn) are developing a free-piston Stirling convertor for a high-efficiency Stirling Radioisotope Generator (SRG) for NASA Space Science missions. The SRG is being developed for multimission use, including providing electric power for unmanned Mars rovers and deep space missions. The SRG is being evaluated as a high-efficiency power source alternative to replace Radioisotope Thermoelectric Generators (RTG's). The SRG system efficiency of 20 to 25 percent will reduce the required amount of radioisotope by a factor of 3 or more compared to RTG's. This significantly reduces radioisotope cost, radiological inventory, and system cost and provides efficient use of the scarce domestic supply of radioisotope resources.

STC is developing the Stirling convertor under contract to DOE (White, 2001). Technology Demonstration Convertors (TDC's), operating as single units and in dynamically-balanced opposed pairs, are now being tested by STC and NASA Glenn. Power outputs of 55 to 65 We and efficiencies of 25 to 28 percent have been demonstrated for TDC operating conditions of 650 °C hot-end temperature and cold-end temperatures varying from 80 to 120 °C. Long life has also been demonstrated on a similar STC 10-We radioisotope terrestrial convertor, RG-10, that has been on life test at STC for over 65,000 hours (7.4 years) with no convertor maintenance and no degradation in performance. An assessment of the free-piston Stirling convertor's capability for long life is given by Schreiber (2000). NASA Glenn is providing technical consulting for the TDC development effort under an Interagency Agreement with DOE.

A procurement for a SRG System Integration Contractor is now being conducted by DOE. Three contractors have developed SRG conceptual designs. First SRG's are expected to have a specific power exceeding 4 We/kg. Growth options have been identified to significantly improve the specific power to 6 to 8 We/kg and then to 8 to 10 We/kg.

NASA Glenn is conducting an in-house technology project to assist in developing the convertor for space qualification and mission implementation. This includes independent verification testing of the TDC's, heater head life assessment, NdFeB magnet aging characterization, electromagnetic and thermal analyses of the linear alternator, launch environment characterization testing, electromagnetic interference and electromagnetic compatibility (EMI/EMC) characterization and reduction, and organic materials evaluation. NASA Glenn also supports reliability studies being led by Westinghouse for DOE. NASA Glenn has also initiated efforts to develop advanced Stirling technologies and to evaluate Stirling convertors for further applications. As part of these efforts, a multi-dimensional Stirling computational fluid dynamics (CFD) code is being developed, and a demonstration of an integrated dynamic power system with electric propulsion was accomplished when a Hall-effect thruster was successfully operated with a free-piston Stirling power source. This paper will discuss the status and recent results for this work.

HEATER HEAD LIFE ASSESSMENT

Heater head life is a critical element for achieving the 100,000+ hour life of the convertor. The heater head is a thin-walled pressure vessel fabricated from Inconel 718 (IN718). NASA Glenn materials and structures personnel have developed an approach to characterize the long-term durability of the heater head using relatively short-term extrapolation methods. This approach involves both deterministic and probabilistic methods and uses IN718 material testing, IN718 data from the literature, and heater head structural benchmark tests to calibrate and validate the models.

An initial assessment of the TDC heater head life has been completed (Halford, 2002). These initial analytic studies have indicated that the pressure vessel wall thickness at the hot end of the regenerator will need to be increased over

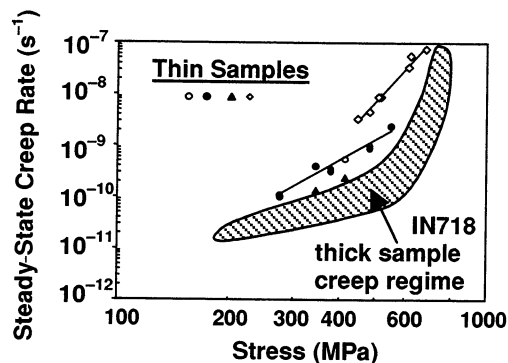


FIGURE 1. Steady-State Creep Rates for Thin (~0.05 cm) IN718 Samples Compared to Typical Values Reported in the Literature for Thick Specimens.

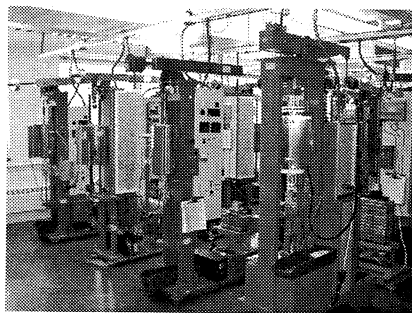


FIGURE 2. IN718 Creep Testing at NASA Glenn.

a relatively short span to achieve the required lifetime. A constant maximum hot-end temperature of 650 °C for very long lifetimes was originally thought to be achievable with the current TDC design, using extrapolated creep-rupture curves for IN718 obtained from handbook information. However, the handbook curves are generally based on data of less than 10,000 hours. Based on an extensive long-term creep and creep-rupture database (up to 87,000 hours) taken on IN718 by the Oak Ridge National Laboratories (ORNL), the rupture life vs. stress relationship for IN718 becomes nonlinear after about 10,000 hours at 650 °C, making extrapolations using short-term data non-conservative. The ORNL data is being used by NASA Glenn to factor in long-term results and also measured statistical variations. In addition, NASA Glenn is now conducting creep testing of the IN718 material that will be used to build the flight convertors. This material differs somewhat from that tested by ORNL in heat treats, grain sizes, slight variations in alloy chemistry, and especially in the thickness of the test specimens. Scaling factors accounting for the differences between the ORNL data and the NASA Glenn data will be established as the NASA Glenn database nears completion. Trade-off assessments are continuing that will determine a recommended pressure vessel wall thickness at the hot end of the regenerator that will provide adequate life (100,000+ hours) with margin based upon probability of survival.

Most published creep data on IN718 has been taken on thick samples; however, thin samples that are relevant to the TDC heater head wall thickness tend to have less creep resistance as shown in figure 1 (Bowman, 2001). The data shown for thin samples include test data taken at NASA Glenn on several heats of material. In thin samples, the number of grains across the thickness is an important parameter. NASA Glenn has completed creep tests to study this effect of wall thickness to grain size ratio and used this data to determine the optimum grain size

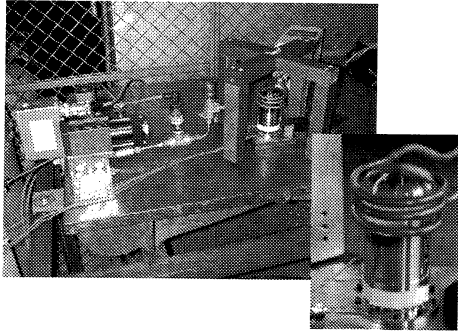


FIGURE 3. Heater Head Structural Benchmark Test Rig.

for the IN718 material that will be used for the flight convertors. NASA Glenn has received this material, and samples are now being used for creep testing at various stress levels. A discussion of these various aspects of assessing IN718 for long-term creep resistance is given by Bowman (2001). Figure 2 shows some of the uniaxial creep frames that are being used for this testing at NASA Glenn. 62,639 total hours of creep testing have been accumulated on 19 samples as of August 31, 2001.

Material creep properties are generally determined from uniaxial creep tests, including both the long-term ORNL data and the data now being taken at NASA Glenn. However, the heater head configuration and pressure loading results in a biaxial stress state. To factor this effect into the life assessment, a structural benchmark test rig, shown in

figure 3 and described by Halford et al. (2002), has been assembled to test prototypical heater heads in accelerated life tests. Elevated pressure and/or temperature will be used to accelerate the testing. Several tests will be run to first assist in the calibration of the life assessment methods and then a longer test run for validation purposes. The test rig has recently completed checkout testing, and heater head testing will be initiated once the heater head design is finalized and sample heater heads have been obtained.

TDC PERFORMANCE AND EMI TESTING

TDC's S/N 5 and 6 were delivered to NASA Glenn in August of 2000. They were tested at full piston stroke and also over a range of reduced strokes while in the dual-opposed configuration (Schreiber, 2002). This configuration leads to dynamically balanced operation that results in very low levels of vibration. An additional set of convertors, known as TDC's S/N 7 and 8, has been delivered to NASA Glenn and has completed acceptance tests. TDC's S/N 7 and 8 are nominally identical to TDC's S/N 5 and 6 and are being tested in the same dual-opposed configuration. During the acceptance test, TDC's S/N 7 and 8 generated 110.1 watts AC of power at the design condition of 650 °C hot-end temperature and 120 °C cold-end temperature. These convertors are presently undergoing variable-stroke performance mapping, and the results are generally the same as those for TDC's S/N 5 and 6. The performance map was not completed in time to include in this report. Current plans call for TDC's S/N 7 and 8 to be tested for approximately 1,000 hours, followed by operation during a vibration test at NASA Glenn to simulate launch. The convertors will then be put on extended test to accumulate another 2,000 hours of operation. This sequence will approximate operation on earth prior to launch, the launch environment, and steady state operation following a launch. The convertors will then be disassembled and carefully inspected to check for any evidence of wear or possible degradation.

Variable-stroke performance mapping of TDC's S/N 5 and 6 has been completed, and they are now used to support a variety of other tests. One facet of this testing is to operate each TDC as a single unit to characterize performance. The fundamental difference in operation as a single convertor stems from the motion of the convertor housing. In the dual-opposed mode of operation, there would be no casing motion if the convertors were identical dynamically

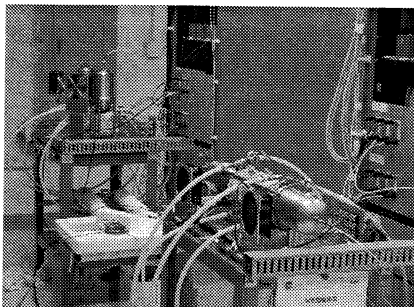


FIGURE 4. TDC's S/N 7 and 8 in Foreground (Dual-Opposed) and S/N 5 and 6 in Distance (Single Units).

and if the connecting structure was perfectly rigid. In this case, the dynamics of the piston and displacer in each convertor would be that of a nonlinear two-body dynamic system. In reality, any connecting structure will have some compliance, and there will be some finite motion of each housing. The single convertor test stand has been designed to approximate the dynamics that may exist in a space power generator. Figure 4 shows TDC's S/N 5 and 6 on the single convertor test stand. Performance data for this configuration was not available for this report.

Performance mapping of the TDC's made use of a laboratory controller that uses control logic with a zener diode to prevent overstroke of the piston. However, it imposes a sharp load twice per cycle and thus introduces a significant content of higher harmonics to the output current and voltage waveforms. To obtain the EMI/EMC levels necessary for most space science missions, it may be preferred that the controller produce little

harmonic content. A controller has been developed at NASA Glenn that uses digital logic to regulate a resistive load on the AC output of the linear alternator. Initial tests with the NASA Glenn controller indicated that the harmonic content was less than 5 percent. TDC's S/N 5 and 6 have been operated with this controller, but full performance mapping has not yet been done. Tests have been performed to characterize the AC magnetic emissions with both controllers. A total of 64 measurements were made over a two-day test. The data is currently being reduced and readied for interpretation. These initial tests will help develop strategies to manage the EMI.

LAUNCH ENVIRONMENT TESTS

Testing and characterization of the TDC's in the NASA Glenn Structural Dynamics Laboratory (SDL) has become a key part of the technology project. The SDL has two capabilities that are utilized. One is a facility known as the Microgravity Emissions Laboratory (MEL), which is used to measure the vibratory emissions that emanate from an operating device. The SDL also has shake tables that are used to perform more typical vibration tests. During 2001, TDC's S/N 5 and 6 have been used in one MEL test and two vibration tests. More details on these tests are given by Schreiber (2001) and Suarez (2002).

The MEL facility is shown in figure 5. The MEL tests were performed on TDC's S/N 5 and 6 operating in the dual-opposed configuration. The purpose of the test was to determine the effect of alignment tolerances on disturbances generated during operation. The MEL fixture was designed to allow the alignment of the converters to be adjusted by lateral offsets and angular misalignments. Also, tests were performed to compare rigidly mounting the converters to using a mounting structure with a resonant frequency either 40 percent below or 40 percent above the TDC operating frequency. The converters were operated at the full piston stroke during all MEL tests and thus were generating their maximum vibratory signature. The results of the test showed the emissions to be distinctly tonal and generally benign.

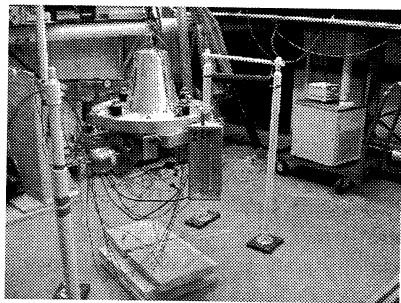


FIGURE 5. The MEL Facility at NASA Glenn.

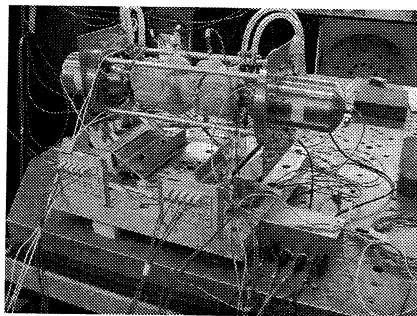


FIGURE 6. TDC's S/N 7 and 8 Mounted in the Engineering Mounting Structure Test Stand.

The TDC was shown to be able to operate at full power and suffer no damage when subjected to high levels of random vibration in previous vibration tests (Goodnight, 2000). The response of the internal components and the remaining margin were not known. To better understand the internal structural dynamics, a test was devised that used a single convertor mounted on the shake table with the pressure vessel removed. A suite of accelerometers, optical probes, and force sensing bolts was developed to measure the response of the key components, primarily the piston rod and linear alternator. The convertor, TDC S/N 6, was motored at the resonant frequency of 73 Hz, which is a lower frequency than for typical operation as a power convertor since it was now being operated at a mean pressure of one atmosphere. Random vibrations were imposed in the axial direction and then in the lateral direction, with the TDC operating at full stroke and half stroke. The level of random vibration used in these tests was 2.17 Grms. This is 25 percent of the flight acceptance level and should allow for sufficiently detailed data that a structural dynamicist could develop an understanding of the structural response. A series of sine sweeps were also performed from 5 Hz to 2000 Hz at levels up to 0.5 G. The tests have been completed, and the data are being analyzed (Suarez, 2002).

Random vibration tests were also conducted with dual-opposed TDC's S/N 5 and 6 mounted in an Engineering Mounting Structure. The purpose of these tests was to study the interaction of dual-opposed Stirling convertors when subject to random vibration through a coupling that may be representative of the structure of the final SRG. Mounting structures were devised with resonant frequencies of 11 Hz, 36 Hz, and 104 Hz. These included structures with resonant frequencies lower and higher than the operating frequency of the convertor. Again, random vibration was

kept to 25 percent of the flight acceptance level. The test fixture with the 11-Hz mounting structure is shown in figure 6. The tests have been completed, but the data have not yet been processed. The TDC's operated in a well

behaved manner, even during sine sweeps when the mounting structure allowed a high degree of motion as the test passed through resonance.

PERMANENT MAGNET AGING CHARACTERIZATION

NdFeB permanent magnets are used in the TDC linear alternators. Long-term magnet aging tests with margin on the magnet operating temperature and in a demagnetizing field are being run on NdFeB magnet samples to quantify any potential magnet degradation with time and temperature. Such degradation, if any, could affect both the remanent magnetization and the demagnetization resistance. The aging tests will be run for up to 12,000 hours at 120 °C and with a DC demagnetizing field of 6 kOe. For a 120 °C convertor cold-end temperature, the magnets are expected to operate at temperatures around 75 °C. The magnet aging test fixture can hold up to 10 magnet samples. Over 4300 hours of testing have been completed as of August 31, 2001. Magnet samples are removed periodically, characterized, and compared to their baseline characterizations completed before the start of testing to determine the rate of aging.

Short-term aging tests were first run on various NdFeB magnet types to assist in selecting the magnets for the long-term tests. Tests were completed for 100 hours on three magnet types at 120 °C and in a 6-kOe demagnetizing field; no measurable changes were found after these tests. 200-hour tests were then run on six magnet types at 150 °C and in a 5-kOe demagnetizing field to see if this higher temperature would produce any measurable aging. These tests showed that, depending on magnet type, remanence losses ranged from 0 to 7 percent and intrinsic coercivity losses varied from about 1 to 4 percent. In general, measurements were resolvable to about 1 percent. In some cases, the coercivity losses were not recoverable by recharging the magnet sample, indicating a structural change of the material. These results are discussed by Niedra (2001).

PERMANENT MAGNET DEMAGNETIZATION MARGIN

NASA Glenn has developed a three-dimensional finite element method (FEM) approach for evaluating linear alternators using Ansoft's Maxwell 3D finite element software. The analyses of the TDC linear alternator was recently extended to include the effects of the load current. The demagnetization margin for the NdFeB permanent magnets was evaluated over the operating cycle and also for several magnet temperatures. The NASA Glenn analysis tools and these results are discussed by Geng (2001). Figure 7 shows the magnetic field strength (H) vs. distance along a pair of magnets attached to one stator leg for the mover positioned at the end of stroke. The model predicts that this is the most severe magnet loading over the entire stroke and that the maximum localized demagnetization field occurs on the inside surface (mover side) of the uncovered magnet.

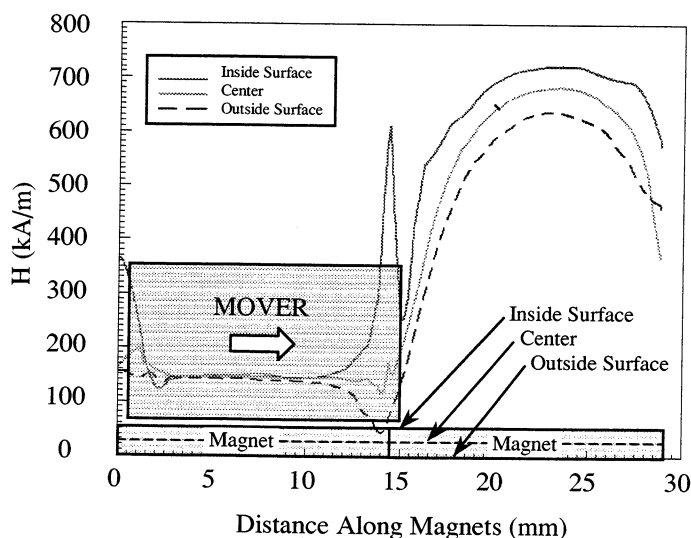


FIGURE 7. Magnetic Field Strength (H) vs. Distance Along Magnets at 75 °C; End of Stroke.

Magnet temperatures were calculated for several convertor cold-end temperatures using a thermal model developed with the ANSYSTM finite element software. For each condition, the maximum localized demagnetization field and the demagnetization field averaged over the magnet volume were determined. These were then compared to the knee of the normal induction curve for the TDC magnets (demagnetization field limit), based on the magnet manufacturer's data, to determine the margin to demagnetization. The results are given in Table 1.

Design margins increase with decreasing convertor cold-end temperature. The final design value of convertor cold-end temperature will be based on system analysis and has not yet been selected. A value for acceptable design margin to demagnetization also remains to be determined. Variations in

individual magnet demagnetization resistance and aging effects, if any, on this demagnetization resistance should be taken into account.

TABLE 1. Magnet Demagnetization Margin for the TDC NdFeB Permanent Magnets.

Convertor Cold-End Temp. (°C)	Ave. Magnet Temp. (°C)	Max. Localized Demag. Field (kA/m)	Demag. Field Ave. Over Magnet Vol. (kA/m)	Demag. Field Limit (kA/m)	Margin Based On Max. Loc. Demag. Field (%)	Margin Based On Ave. Demag. Field (%)
80	53	760	550	1108	31	50
100	62	745	539	1018	27	47
120	75	725	527	884	18	40

EVALUATION OF CONVERTOR ORGANICS

SRG multimission use could include a mission to the environment of Jupiter, such as to the moon Europa. The ionizing radiation around Jupiter is much more severe than that produced by the GPHS radioisotope heat source. The organic materials in the TDC have been replaced, as necessary, with radiation-hard organic materials to meet this need (Golliher, 2001). These organics are used in the piston, displacer, and rod surface coatings; piston bumpers; and alternator adhesives and electrical insulations. These radiation-hard organics were first used on the TDC's that are now on test at NASA Glenn, and these convertors are serving as a test bed for these materials.

In addition, the NASA Glenn Polymers Branch and Tribology and Surface Science Branch are further evaluating two of the key organic materials. Thin-film samples of the Xylan material used in the piston bearing coatings are being subjected to testing in a radiation exposure facility, using X-rays as the radiation source. Both the original material, which was Teflon-based, and the one now being used for radiation hardness, which is based on molybdenum disulphide, MoS₂, are being tested. A one-hour exposure provides a dose of 4 Mrad to the interior of the .005-cm thick film. These thin films will then be "scratch-tested" to evaluate changes in their mechanical properties.

3M™ Scotch-Weld™ 2216 B/A Gray epoxy adhesive is used to bond the NdFeB permanent magnets to the stator laminations in the linear alternator. A series of tests will first be run on test coupons to experimentally quantify this bond strength under various loading modes and as a function of temperature. Pure tension, pure compression, sandwich shear, and single cantilever loads will be included. Fatigue curves will also be generated for the adhesive and interface. Once the general characteristics of the bond have been established, component-scale tests will be conducted to evaluate the performance and lifetime of the bond in the in-service operating environment and under the combined stress states that the bond sees in actual operation. The loading conditions will be based on results of FEM modeling of the linear alternator.

MULTI-DIMENSIONAL CFD PERFORMANCE CODE

A grant has been awarded to Cleveland State University (CSU) to develop a multi-dimensional Stirling computational fluid dynamics (CFD) code to significantly improve Stirling loss predictions and assist in identifying convertor areas for further improvements. The University of Minnesota (UMN) and Gedeon Associates are teamed with CSU for this effort. Key existing one-dimensional Stirling performance and design codes agree reasonably well with each other in terms of overall performance but can differ significantly in the magnitude of specific internal losses. Also, one-dimensional codes do not rigorously model manifolds between heat exchangers and expansion/compression spaces in the convertor. In certain cases, hardware experiences have shown that large performance gains can be made by varying manifolds and heat exchanger designs to improve flow distributions in the heat exchangers. It is expected that this CFD code should give a significant improvement in the understanding of these losses and convertor design areas and, thus, help lead to further performance improvements.

Two CFD codes have been evaluated. The first is a two-dimensional incompressible flow code, CAST, Computer Aided Simulation of Turbulent Flows. CAST was used for initial two-dimensional modeling of “Stirling machine-like” components during the SP-100 program, aimed at eventual development of a Stirling CFD code. CAST was then modified to model compressible, non-acoustic flow (Tew, 2001). The other code under consideration is CFD-ACE+, a commercial CFD code developed by the CFD Research Corporation. CFD-ACE+ can model two- or three-dimensional geometries and includes acoustics. Results from the two codes were compared with test data taken from 1) a gas spring and 2) a single piston/cylinder and annular heat exchanger (Ibrahim, 2001 and Tew, 2001). CFD-ACE+ has now been chosen for proceeding on the development of the Stirling CFD code. This choice was based primarily on CFD-ACE+’s higher state of development, including its ability to model three-dimensional geometries and its sophisticated pre-and post processors. The two codes were similar in their execution time.

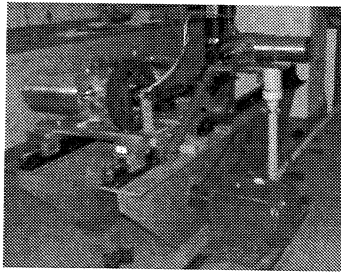


FIGURE 8. Cleveland State University Oscillating Flow Test Rig (photo courtesy of CSU).

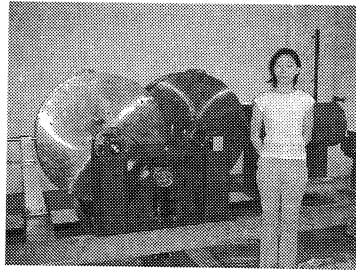


FIGURE 9. University of Minnesota Oscillating Flow Test Rig (photo courtesy of UMN).

It is important to validate the Stirling CFD code as its development continues. The CAST and CFD-ACE+ codes agreed reasonably well with the gas spring test data, but there were some significant differences between the two codes and with the test data in predicting temperatures and heat transfer for the piston cylinder and heat exchanger. Efforts are now underway to obtain further validation test data. Existing test rigs at both CSU and UMN are being modified and tests sections are being designed and

fabricated to look at key areas relative to the multi-dimensional modeling. These include flow area changes such as occur in the manifolding between heat exchangers and the cylinder. Figures 8 and 9 show the CSU and UMN test rigs. The UMN test rig is a large-scale rig that runs at low frequencies, allowing detailed measurements in the flow streams; it relies on achieving dynamic similarity of the key flow parameters. The CSU rig operates at frequencies similar to actual Stirling convertors but is also large enough to allow access for detailed measurements.

INTEGRATED HALL THRUSTER TEST

An important aspect of implementing SRG’s on future missions is the integration of the generator and controller with potential spacecraft loads. Some recent studies have indicated that the combination of SRG’s and electric propulsion devices offer significant trip time and payload fraction benefits for deep space missions (Oleson, 2001). To begin to understand the interactions between Stirling generators and electric thrusters, an electrically-heated STC RG-350 (350-watt output) Stirling convertor was coupled to a 300-watt SPT-50 Hall-effect thruster built for NASA by the Moscow Aviation Institute (RIAME). The RG-350 and the SPT-50, shown in figures 10 and 11, were installed in adjacent vacuum chamber ports at NASA Glenn’s Electric Propulsion Laboratory, Vacuum Facility #8. The Stirling controller interfaced directly with the Hall thruster power processing unit (PPU), both of which were located outside of the vacuum chamber. The PPU accepted the 48-VDC output from the Stirling controller and distributed the power to all the loads of the SPT-50 including the magnets, keeper, heater, and discharge.

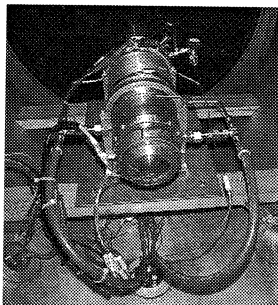


FIGURE 10. RG-350 Stirling Convertor.

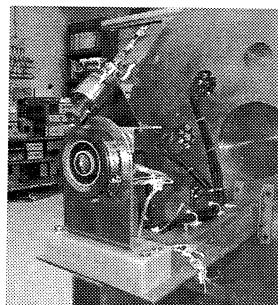


FIGURE 11. SPT-50 Hall-Effect Thruster.

On February 28, 2001, the NASA Glenn test team successfully operated the Hall-effect thruster with the Stirling convertor. This is the world’s first known test of a dynamic power source with electric propulsion. The RG-350 successfully managed the transition from the purely resistive load bank within the Stirling controller to the highly capacitive PPU load. The Stirling convertor was operating at a hot-end temperature of 530 °C and a cold-end temperature of –6 °C. The linear alternator was producing approximately 250 watts at 109 VAC while the PPU was drawing 175 watts at 48 VDC. The majority of power was delivered to the discharge circuit operating at

115 VDC and 0.9 amps. Future testing will examine the possibility of directly driving the Hall thruster discharge circuit using rectified and filtered output from the Stirling alternator.

CONCLUDING REMARKS

The Stirling technology development project at NASA Glenn has produced substantial test results over the last year in the areas of performance validation, IN718 creep testing, NdFeB magnet aging characterization, launch environment testing, and EMI/EMC characterization. These efforts continue as do a heater head life assessment, FEM analysis of the linear alternator, an evaluation of key organic materials, support for DOE reliability assessments, and development of a Stirling multi-dimensional CFD code. This project will continue to provide critical support to the overall DOE efforts to develop the SRG as work moves into the next stage after selection of a Stirling System Integration Contractor. The integrated test of a Stirling convertor driving a Hall thruster indicates a further promising application for Stirling technology.

REFERENCES

- Bowman, R.R., "Long-Term Creep Assessment of a Thin-Walled Inconel 718 Stirling Power-Convertor Heater Head," *Proceedings of the 36th Intersociety Energy Conversion Engineering Conference*, Savannah, GA, 2001 (IECEC2001-CT-33).
- Geng, S.M., Schwarze, G.E., Niedra, J.M., and Regan, T.F., "A 3-D Magnetic Analysis of a Stirling Convertor Linear Alternator Under Load," *Proceedings of the 36th Intersociety Energy Conversion Engineering Conference*, Savannah, GA, 2001 (IECEC2001-CT-34), NASA/TM—2001-211084, July, 2001.
- Golliher, E.L. and Pepper, S.V., "Organic Materials Ionizing Radiation Susceptibility for the Outer Planets/Solar Probe Radioisotope Power Source," *Proceedings of the 35th Intersociety Energy Conversion Engineering Conference*, Las Vegas, NV, 2000 (AIAA-2000-3077), NASA/TM—2001-210245, January, 2001.
- Goodnight, T.W., Hughes, W.O., and McNelis, M.E., "Dynamic Capability Of An Operating Stirling Convertor," *Proceedings of the 35th Intersociety Energy Conversion Engineering Conference*, Las Vegas, NV, 2000 (AIAA-2000-2839), NASA/TM—2000-210527, November, 2000.
- Halford, G.R., Arya, V.K., Krause, D.L., Shah, A., and Bartolotta, P.A., "Structural Analyses of Stirling Power Convertor Heater Head for Long-Term Reliability, Durability, and Performance," in these proceedings, 2002.
- Ibrahim, M.B., Tew, R.C. Jr., Zhang, Z., Gedeon, D., and Simon, T.W., "CFD Modeling of Free-Piston Stirling Engines," Presented at the 36th Intersociety Energy Conversion Engineering Conference, Savannah, GA, 2001 (IECEC2001-CT-38).
- Niedra, J.M., "Short-Term Aging of NdFeB Magnets for Stirling Linear Alternator Applications," NASA/CR—2001-210952, July, 2001.
- Oleson, S., Gefert, L., Patterson, M., Schreiber, J., McAdams, J., and Ostdiek, P., "Outer Planetary Exploration with Advanced Radioisotope Electric Propulsion," to be presented at the 27th International Electric Propulsion Conference, Pasadena, CA, 2001.
- Schreiber, J.G., "Assessment of the Free-Piston Stirling Convertor as a Long Life Power Convertor for Space," *Proceedings of the 35th Intersociety Energy Conversion Engineering Conference*, Las Vegas, NV, 2000 (AIAA-2000-3021).
- Schreiber, J.G. and Thieme, L.G., "Update on the Stirling Convertor Testing and Technology Development at NASA GRC," *Proceedings of the 36th Intersociety Energy Conversion Engineering Conference*, Savannah, GA, 2001 (IECEC2001-CT-26).
- Schreiber, J.G. and Skupinski, R.C., "Accomplishments in Free-Piston Stirling Tests at NASA GRC," in these proceedings, 2002.
- Suarez, V.J., Goodnight, T.W., Hughes, W.O., and Samorezov, S., "Impact Testing of a Stirling Convertor Linear Alternator," in these proceedings, 2002.
- Tew, R.C. Jr. and Ibrahim, M.B., "Study of Two-Dimensional Non-Acoustic Modeling of Stirling Machine Type Components," *Proceedings of the 36th Intersociety Energy Conversion Engineering Conference*, Savannah, GA, 2001 (IECEC2001-CT-27), NASA/TM—2001-211066, July, 2001.
- White, M., Qiu, S., Augenblick, J., Peterson, A., and Faultersack, F., "Status Update of a Free-Piston Stirling Convertor for Radioisotope Space Power Systems," in proceedings of *Space Technology and Applications International Forum (STAIF-2001)*, edited by M. El-Genk, AIP Conference Proceedings 552, New York, 2001, pp. 998-1004.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE January 2002		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE Stirling Technology Development at NASA GRC			5. FUNDING NUMBERS WU-783-82-00-00 and 755-A4-14-00	
6. AUTHOR(S) Lanny G. Thieme, Jeffrey G. Schreiber, and Lee S. Mason				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-13119-1	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2001-211315-REV1	
11. SUPPLEMENTARY NOTES Prepared for the Space Technology and Applications International Forum (STAIF-2002) sponsored by the American Institute of Aeronautics and Astronautics, Albuquerque, New Mexico, February 3-7, 2002. Responsible person, Lanny G. Thieme, organization code 5490, 216-433-6119.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Categories: 20 and 44 Distribution: Nonstandard Available electronically at http://gltrs.grc.nasa.gov/GLTRS This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The Department of Energy, Stirling Technology Company (STC), and NASA Glenn Research Center (NASA Glenn) are developing a free-piston Stirling convertor for a high-efficiency Stirling Radioisotope Generator (SRG) for NASA Space Science missions. The SRG is being developed for multimission use, including providing electric power for unmanned Mars rovers and deep space missions. NASA Glenn is conducting an in-house technology project to assist in developing the convertor for space qualification and mission implementation. Recent testing of 55-We Technology Demonstration Convertors (TDC's) built by STC includes mapping of a second pair of TDC's, single TDC testing, and TDC electromagnetic interference and electromagnetic compatibility characterization on a nonmagnetic test stand. Launch environment tests of a single TDC without its pressure vessel to better understand the convertor internal structural dynamics and of dual-opposed TDC's with several engineering mounting structures with different natural frequencies have recently been completed. A preliminary life assessment has been completed for the TDC heater head, and creep testing of the IN718 material to be used for the flight convertors is underway. Long-term magnet aging tests are continuing to characterize any potential aging in the strength or demagnetization resistance of the magnets used in the linear alternator (LA). Evaluations are now beginning on key organic materials used in the LA and piston/rod surface coatings. NASA Glenn is also conducting finite element analyses for the LA, in part to look at the demagnetization margin on the permanent magnets. The world's first known integrated test of a dynamic power system with electric propulsion was achieved at NASA Glenn when a Hall-effect thruster was successfully operated with a free-piston Stirling power source. Cleveland State University is developing a multidimensional Stirling computational fluid dynamics code to significantly improve Stirling loss predictions and assist in identifying convertor areas for further improvements. This paper will update the status and results for these efforts.				
14. SUBJECT TERMS Stirling engines; Nuclear electric power generation; Deep space; Mars; Roving vehicles; Random vibration; Vibration tests; Electromagnetic interference; Life (durability); Linear alternator; Permanent magnets; Ionizing radiation			15. NUMBER OF PAGES 15	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	