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Update on Stirling Radioisotope Power Systems Development at NASA Glenn Research Center

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NASA Glenn Research Center (GRC) continues to lead the Agency in research and development of Stirling technologies for use in Radioisotope Power Systems (RPS) powered space and terrestrial applications. Today this work continues under the High Efficiency Power Generation Technology (HEP-GT) managed by NASA's RPS Program. Most of this work is conducted in the Stirling Research Laboratory (SRL) at GRC. Ongoing development is aimed at increasing the Technology Readiness Level (TRL) of state-of-the-art Free-Piston Stirling Engines (FPSEs) and various supporting technologies by testing in key environments that further statistically and experimentally validate performance, robustness, and reliability. Recent accomplishments and ongoing work within the SRL are described herein.

I. EXTENDED OPERATION MILESTONES

The design life of a Stirling convertor (a Stirling engine that converts heat into electricity through linear motion of an alternator) is a major design consideration as many missions require long-term power. The design life target has historically been set for 17 years which draws from a requirement of 14 years of active mission duty and 3 years of pre-launch storage. To demonstrate these convertors can produce this level of long-life power, extended operation testing (See Fig. 1.) has been developed by the engineers of the Stirling Research Laboratory (SRL).

Fig. 1. SRSC #1 and #2 in extended operation hardware.

The SRL engineers have successfully implemented hardware and software designs to these convertors and their respective test racks to allow operation without direct engineering supervision, enabling continuous, year-round operation. It is important to note that most long-life testing of hardware implements predictive modeling to be able to forecast failure points and design life without having to physically test to the full-time requirement. Predictive failure modeling and accelerated testing are difficult to utilize for long-life Stirling designs that don't exhibit any degradation beyond the predictable material creep in the hot pressure vessel (PV). Therefore, extended operation within design limits is critically important to support reliability modeling for future potential flight development efforts. As of today, there are three convertors in the SRL that were started in the early 2000s that have achieved this design life requirement of 17 years and others that were started in the late 2000s that continue to progress towards that goal.

Table I. Extended operation hours accumulated on various convertors in the SRL at GRC.

Unit	Hours	Years	Cycles (B)
TDC #13	154,872	17.7	45.4
TDC #14	105,616	12.1	31.0
TDC #15	152,573	17.4	44.9
TDC #16	152,573	17.4	44.9
ASC-0 #3	121,978	13.9	45.8
ASC-L	79,541	9.1	29.3
ASC-E3 #4	59,360	6.8	21.8
ASC-E3 #9	45,404	5.2	16.7
SES #2	47,666	5.4	14.0
SRSC #1	13,903	1.6	5.0
SRSC #2	20,077	2.3	7.2
SRSC #3	17,359	2.0	6.2
SRSC #4	11,278	1.3	4.0
FISC #1	10,058	1.1	3.0
FISC #2	13,163	1.5	3.9

Extended Operation Data as of 10/21/2024

In 2024, the Technology Demonstration Convertor (TDC) #13, #15, and #16 all surpassed 17 years of extended operation and continue to hold world records for the longest running flexure-bearing Free-Piston Stirling Engines (FPSEs). Advanced Stirling Convertor, ASC-0 #3, has almost achieved 14 years of extended operation and continues to hold the world record for the longest running gas-bearing FPSE. Another Advanced Stirling Convertor, ASC-L, has surpassed 9 years of extended operation and is unique compared to the other convertors as it is controlled by the Single Convertor Controller (SSC), instead of on laboratory AC or DC bus load controllers. As seen in Table I, the unique testing capability of the SRL to operate these convertors in extended operation for long durations continues to validate the life and reliability of Stirling convertors and increase their Technology Readiness Levels (TRL) for future mission use.

II. UPDATES AND STATUS OF THE STIRLING GENERATOR TESTBED

One of the main focuses of work within the SRL in recent years has been the design, development, and testing of the Stirling Generator Testbed (See Fig. 2) which is a system-level generator consisting of four Stirling convertors joined together in one housing with a centrally located, radiantly-coupled heat source. This design provides system fault tolerance through multi-convertor redundancy, allowing each pair of convertors to be throttled up or down to meet specific power requirements and has the potential to be 3-4 times more efficient than conventional thermoelectric-based Radioisotope Power Systems (RPS)[1]. This testbed can operate with a range of Stirling convertors from legacy designs to the state-of-the-art Sunpower Robust Stirling Convertor (SRSC) designed and fabricated by Sunpower Inc.

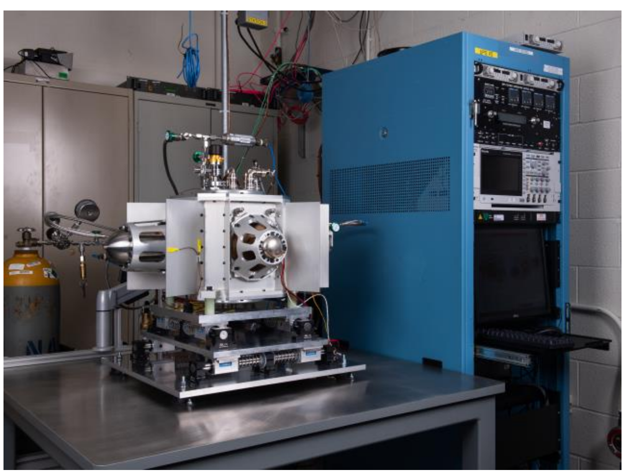

Fig. 2. The Stirling Generator Testbed in the SRL.

This testbed effort started development in 2019 under the Dynamic Radioisotope Power Systems (DRPS) Project and all hardware was received by the end of 2022. While this testbed is capable of a variety of different tests, the aim of the initial testing is focused on baselining performance of four Stirling convertors in one housing with a centrally aligned heat source. Future testing will focus on understanding how much heat is lost from the heat source during operation through the insulation and housing and then moving on to simulating failure of a pair of convertors and demonstration of the ability to throttle the surviving pair up and regulate heat source thermal load[1].

TABLE II. Quasi-steady state baseline operation point.

Parameter	1A	1B	2A	2B	Units
Avg. Hot-End Temp.	501.5	497.9	496.4	497.4	°C
Avg. CSAF Temp.	62.0	63.4	69.4	68.0	°C
Avg. PV Temp	57.3	55.9	49.7	47.0	°C
Heat Collector Plate Temp.	545.7	-	-	-	°C
Piston Amplitude	2.8	2.9	3.6	3.6	mm
Alt. Power	22.8	23.3	19.2	19.0	W_e
Charge Pressure	-	-	348.8	347	psia
Frequency	101.3		78.4		Hz
Avg. Fin Root Temp.	54.6				°C
Avg. Fin Tip Temp.	48.3				°C
Ambient Temp.	25.5				°C
Avg. Heat Source Temp.	609.4				°C
Heater Power	500.8				W
Total Power Output	84.3				W_e
Gross Efficiency	16.8				%
Housing Pressure	23.3				psia

The first 24-hour operator attended testing successfully took place on May 31, 2023, and the results of that testing are displayed in Table II. The four convertors chosen were two dual-opposed Sunpower Inc. ASC-E3 convertors (1A and 1B), and two dual-opposed Infinia Stirling Radioisotope Generator 110 Engineering Unit Stirling Convertor Assemblies (SES) convertors (2A and 2B). The ASC-E3 convertors are hermetically sealed, gas bearing designs, and the SES convertors are non-hermetic, flexure bearing units. The output power of the heat source was 500 We and the targeted Hot-End temperature of the four convertors were around 500°C with a Piston Amplitude of about 2.8 mm for the ASC-E3 convertors and 3.6 mm on the SES convertors, respectively[2].

Despite not being optimized for efficiency, the first operation of the testbed demonstrated a conversion efficiency of 16.8%, significantly better than the 6.3% efficiency of current radioisotope thermoelectric generators (RTGs).

III. CONTINUED VALIDATION & VERIFICATION TESTING

Most current robustness testing that is conducted in the SRL follows the Verification and Validation (V&V) Plan approved during the DRPS project. This plan outlines 4 tracks (or phases) of testing that comprehensively targets each environmental condition that the convertor could experience during a variety of potential missions[3]. Track 1 is basic performance testing to characterize the overall baseline performance of that convertor prior to any robustness testing. Track 2 focuses on random vibration testing which simulates a prototypical launch sequence. Track 3 consists of centrifugal testing where the convertor experiences static acceleration equivalent to launch loads, reentry into a planetary atmosphere, and spin stabilization during cruise. Finally, track 4 focuses on thermal cycling of the convertor using qualification level hot and cold temperatures during on and off conditions, validating geometric stability of convertor internal interfaces. In the past year, the newest SRSC to arrive at GRC (SRSC #4) has undergone all 4 tracks of testing and has completed them all without any signs of permanent degradation. Having surpassed 10,000 hours in extended operation, SRSC #4 will continue through 20,000 hours before it is used in controller and system development.

III.A. Track 2 Random Vibration Testing of SRSC #4

After going through initial acceptance testing and performance mapping from January to April of 2023, SRSC #4 entered track 2 testing and was shipped to the Structural Dynamics Laboratory (SDL) at GRC. For this phase of testing, it saw qualification-level launch vibrations in three orthogonal orientations at the beginning-of-mission (BOM) operating condition. The peak load of 7.7 Grms was calculated based on the assumption of a 75 kg generator mass. Table III shows the vibration power spectral density profile it experienced.

Table III. Qualification-level vibration profile based on GEVS, GSFC-STD-70008 Section 2.4.2.6, assuming generator mass of 75 kg.

Frequency (Hz)	PSD (g2/Hz)
20	0.0078
50	0.0484
800	0.0484
2000	0.0078
Overall grms:	7.77

The first orientation tested with the SRSC #4 was the lateral orientation Z-axis as shown in Fig. 3. It survived the full-level random vibration exposure of 7.7 g_{rms} with only a minor temporary change in performance throughout the testing sequence before returning to nominal performance.

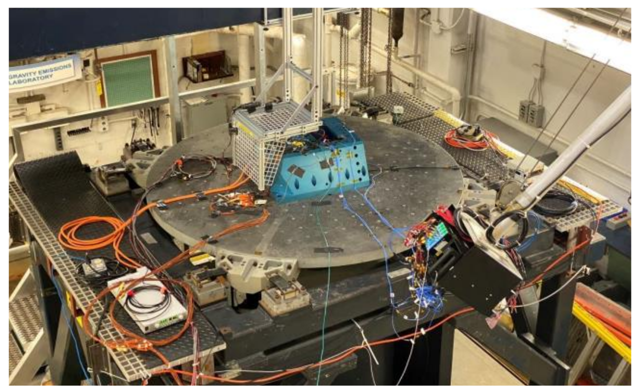

Fig. 3. SRSC #4 in the vibration test fixture and other support hardware configured for Z-axis vibration testing.

Fig. 4. shows the low-level random vibration before, during, and after the full-level vibration and power output of SRSC #4. During the full-level vibration, the power fluctuated from about 37.3 W to about 38.1 W before it quickly recovered to nominal after the full-level vibration subsided. The convertor output power was 0.3 W higher after the vibration test than it was before.

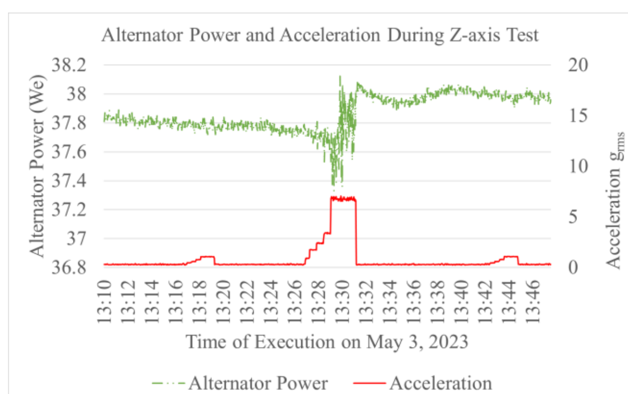

Fig. 4. Alt power and acceleration during z-axis testing.

SRSC #4 was exposed to two more similar vibration tests in the lateral orientation X-axis and axial orientation Y-axis respectively. Alternator Power increased by 0.1 W after the X-axis test and decreased by 0.1 W after the Y-axis test.

SRSC #4 was brought back to the SRL and began extended operation to observe the convertor for any performance changes. Table IV shows SRSC #4 had a permanent change of -1.0 W post-vibration testing as compared to SRSC #3 which had a permanent change of +0.6 W. Changes in power output are within the acceptable success criteria based on measurement uncertainty and the ability to repeat the operating point in the SRL, therefore passing both SRSC #3 and #4 through track 2 vibration testing.

Table IV. Pre-vibration and post-vibration power output comparison of SRSC #3 and #4.

Parameter	Pre-Vibration	Post-Vibration	Difference
SRSC #3 Alternator Power (W)	55.2	55.8	0.6
SRSC #4 Alternator Power (W)	56.3	55.3	-1.0

III.B. Track 3 Static Acceleration Testing of SRSC #4

After finishing all vibration testing, SRSC #4 progressed to track 3 of the V&V Plan in December of 2023 where it underwent Static Acceleration testing at Case Western Reserve University (CWRU) geotechnical centrifuge facility. Here it was exposed to qualification level static acceleration environments to understand the impact they have on convertor operation and long-term performance. Fig. 5. shows the general setup in the centrifuge with the SRSC #4 in the right-hand-side basket and a counterweight in the left-hand-side basket.

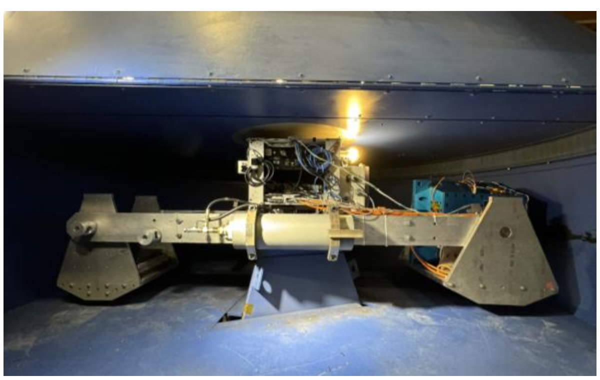

Fig 5. SRSC #4 configured for 6.3g lateral 2 testing on 2023-12-13.

There were two levels of static acceleration exposure that encompassed all qualification-level requirements. The first low-g level includes a dwell of 2 hours at 6.3 g and the second high-g level ramps up to 22.5 g over 90 seconds. The 6.3 g level was tested in four different lateral orientations 90 degrees apart and the 22.5 g level was tested in two lateral and two axial orientations.

Fig. 6. displays the power output of SRSC #4 during the first 6.3 g lateral orientation. The convertor was started and once it reached the target 2 g test condition, the centrifuge started spinning and slowly increased acceleration. The operator would increase the centrifuge by 0.5 g and then allow the convertor to reach steady-state at that level. This continued from the 2 g to the 6.3 g condition. The convertor then dwelled at 6.3 g for 2 hours and then the centrifuge was decelerated back down to 1 g and the convertor was allowed to reach steady-state one final time, completing this testing condition. The visible stable operation for two hours at 6.3 g in this orientation verifies the convertor can survive this level of acceleration even though it shows a temporary reduction in power of < 2 W. After acceleration was stopped, the power output increased back to pre-acceleration levels. The other three 6.3 g conditions had similar results and showed no change to convertor performance.

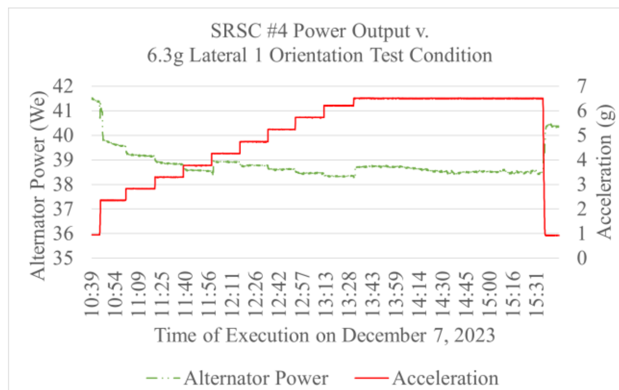

Fig. 6. SRSC #4 power output v. 6.3 g lateral 1 test.

After the four 6.3 g conditions were completed, the fixture was reconfigured for testing in the 22.5 g Axial 1 condition. Similar to low-g testing, the convertor was allowed to reach a test condition, prior to starting the centrifuge. When the centrifuge is initially powered on, a low-g level of 2.5 g is achieved to reach a suitable convertor performance point, which accounts for convective losses while spinning. Once achieving steady-state, the operator quickly ramped the centrifuge up to 22.5 g and maintained this for 5 seconds at which point the convertor was stalled and the centrifuge was decelerated back down to 1 g. The reason for stalling the convertor was to avoid an over-test condition because the centrifuge deceleration time is much longer than the required acceleration profile. After the convertor naturally cooled, it was restarted and was allowed to reach steady-state thus completing this testing condition. Fig. 7. shows this sequence of events. Output power decreased briefly by 0.5 W while ramping up to 22.5 g but then returned to the 2 g level power output well after that. The other axial condition was tested, and the convertor behaved similarly. The last two lateral 22.5 g conditions were the harshest for the SRSC #4 as this orientation had the 22.5 g acting perpendicular to piston motion. During ramp up both showed a decrease in power of about 14 W but returned to normal operation after acceleration ended.

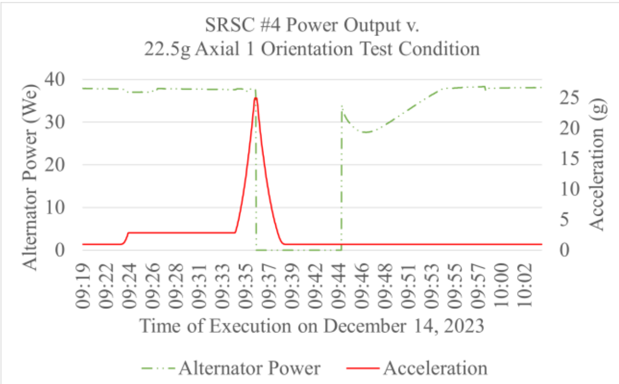

Fig. 7. SRSC #4 power output v. 22.5 g Axial 1 test.

After the acceleration testing at CWRU was completed, the convertor was returned to GRC for extended operation testing. As seen from Table V. SRSC #4 had a permanent change of -0.4 W in Power Output when compared to pre-acceleration testing. This is compared to SRSC #3 which had a change in Power output of +0.2 W after acceleration testing. Changes in power output are within the acceptable success criteria based on measurement uncertainty and the ability to repeat the operating point in the SRL, therefore passing both SRSC #3 and #4 through track 3 static acceleration testing.

Table V. Pre-acceleration and post-acceleration power output comparison of SRSC #3 and #4.

Parameter	Pre-Static Acceration	Post-Static Acceleration	Difference
SRSC #3 Alternator Power (W)	55.5	55.7	0.2
SRSC #4 Alternator Power (W)	55.7	55.3	-0.4

III.C. Track 4 Thermal Cycling of SRSC #4

After SRSC #4 finished all acceleration testing, it entered the last phase of robustness testing which is track 4 of the V&V Plan. Here, it began the thermal cycling phase in April of 2024. The purpose of thermal cycling is to simulate ON/OFF sequences that are anticipated during generator processing. Based on qualification-level requirements, 13 thermal cycles were chosen to be conducted. The following temperature requirements were also given, which contain margin to account for qualification levels.

<u>Hot Test Conditions:</u>
Hot-End Temperature = 720°C*
Cold-End Temperature = 100°C*
Pressure Vessel Temperature = 130°C*

* Condition is nominal full operation temperature + 20°C

<u>Cold Test Conditions:</u>
Hot-End Temperature = 16.5°C**
Cold-End Temperature = 10°C**
Pressure Vessel Temperature = 10°C**

**Condition is nominal full temperature - 15°C

To achieve the cold test conditions in the SRL environment, provisions were needed to insulate the pressure vessel on SRSC #4. Fig. 8. shows insulation surrounding the pressure vessel which is wrapped in cooling loops (not shown).

Fig. 8. SRSC #4 on test stand with thermal cycling hardware installed.

All 13 thermal cycles followed the same ideal temperature profile created from the qualification-level thermal cycling requirements. Fig. 9. shows the dwell times and tolerances to achieve a successful thermal cycle. One thermal cycle required a total of 8 hours to complete not including the overnight non-operating steady-state condition at the cold test condition.

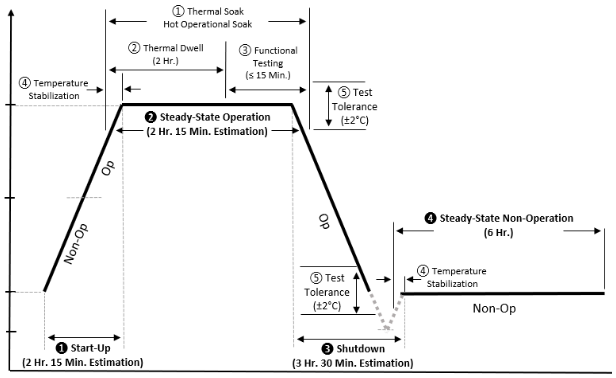

Fig. 9. Ideal thermal cycle temperature profile.

Fig. 10. shows Thermal cycle #7 which was conducted on March 11, 2024. At the beginning of the cycle as the convertor was started, all temperatures and power output increased as normal. Once, the convertor reached the qualification-level hot test temperature, it achieved steady-state and dwelled for at least 2 hours and 15 minutes per the requirements. It was then shutdown, which is shown by the downward slope. There were external chillers attached to the Cold Side Adapter Flange (CSAF) and the PV of the SRSC to assist in the cooling down process. The convertor continued to cool over many hours and dwelled in the cold test temperature profile overnight. Due to the nature of cooling in the SRL environment there needed to be one day in between thermal cycles to achieve the qualification-level cold test dwell of at least 6 hours.

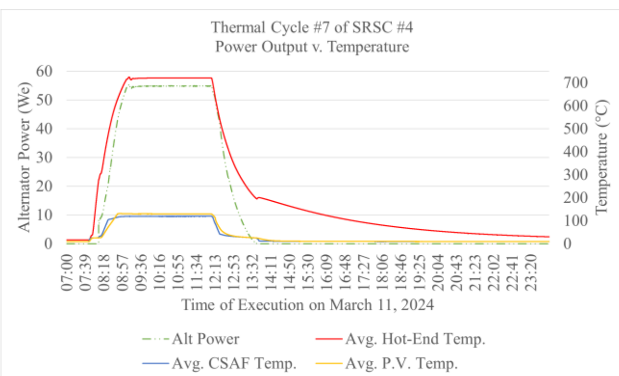

Fig. 10. Thermal cycle #7 of SRSC #4 power output v. temperature.

After this dwell time was completed, the next thermal cycle was conducted. In all, a month of testing was needed to complete all 13 thermal cycles. After the last thermal cycle was completed, the convertor was returned to standard extended operation hardware to compare post-thermal cycle operation to pre-thermal cycle operation for any noticeable performance changes. Table VI. Shows SRSC #4 had a permanent change in power of -0.2 W post-thermal cycling when compared to pre-thermal cycling. Comparing this data to SRSC #3, it can be observed that SRSC #3 had a permanent change in power of +0.1 W. These small changes in power are within the acceptable success criteria based on measurement uncertainty and the ability to repeat the operating point in the SRL, therefore passing both SRSC #3 and #4 through track 4 thermal cycling.

Table VI. Pre-thermal and post-thermal cycling power output comparison of SRSC #3 and #4.

Parameter	Pre-Thermal Cycling	Post-Thermal Cycling	Difference
SRSC #3 Alternator Power (W)	55.8	55.9	0.1
SRSC #4 Alternator Power (W)	55.3	55.1	-0.2

SRSC #4 has successfully completed all 4 tracks of V&V testing and joins SRSC #3 and a handful of other convertors in the SRL that are on long-term extended operation. As the SRL receives future convertors, they will be tested through similar V&V style tests to verify robustness in the pursuit of continuing to increase the overall TRL of the SRSC design.

IV. PRELIMINARY ASSESSMENT OF MEASUREMENT ACCURACY OF SRSC INSTRUMENTATION AND DATA SYSTEMS IN THE SRL

The SRL has been reporting data on convertor performance for decades. There was an assessment of the measurement accuracy of the reported data many years ago. However, changes have been made to the data collection architecture that yields the previous assessment obsolete.

Updated measurement accuracies for 22 parameters including temperature, voltage, current, power, position, pressure, and acceleration were quantified through this effort. The presented measurement accuracies apply to an SRSC data acquisition rack with the convertor operating at the theoretical extended operation baseline condition with nominal instrumentation placement. This initial pass does not consider certain complexities such as sensor drift, noise, condition dependence, sampling rate, etc. for most instruments. The purpose of this effort is to determine which sources generally dominate overall inaccuracy.

It was determined that temperature readings in a modern SRL rack setup carry an accuracy of roughly ± 3 °C. Heater Voltage ± 0.4 V. Heater Current ± 0.02 A. Position ± 0.04 mm Charge Pressure ± 5 psig. Acceleration ± 0.009 g. Convertor electrical power output ± 2.0 W_e.

V. SRSC SENSITIVITY STUDY AROUND NOMINAL EXTENDED OPERATION CONDITION

A sensitivity study was performed to quantify the response of various parameters to controlled perturbations around the nominal extended operation condition using a hermetic SRSC #3. A SAGE model was used to evaluate the magnitude of the perturbations. A total of 39 operating points were obtained, 31 of which are unique. The independently controlled parameters were:

- Piston Amplitude
- Piston Frequency
- Hot-End temperature
- Cold-End temperature
- Pressure Vessel temperature

Once all points were obtained experimentally and computationally, a linear regression was performed to describe the relationship of each perturbed parameter to convertor electrical power output. Fig. 11. shows the comparison between the actual and predicted alternator power for the experimental data. The dashed line represents a 1:1 correlation. The regression equation using experimental data is as follows:

$$P_{alt-exp} = -6650.9790 + (0.0862 \times T_{HE}) - (0.1707 \times T_{CE}) + (0.0840 \times T_{PV}) + (27.5670 \times X_p) + (132.9259 \times Freq) - (0.6738 \times Freq^2)$$

Where:

$P_{alt-exp}$ = predicted alternator power using experimental data
T_{HE} = average Hot-End temperature
T_{CE} = average Cold-End temperature
T_{PV} = average Pressure Vessel temperature
X_p = Piston Amplitude
$Freq$ = Frequency

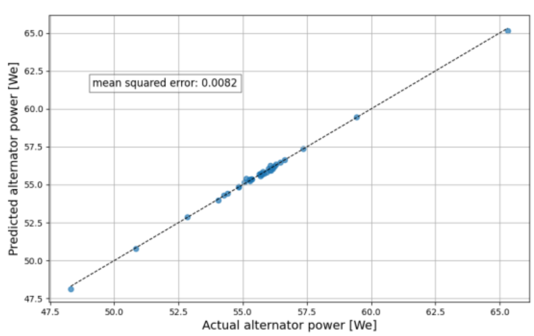

Fig. 11. Comparison of predicted to actual experimental alternator power data.

The regression equation using SAGE model data is as follows:

$$P_{alt-theo} = -6359.6186 + (0.0834 \times T_{HE}) - (0.2256 \times T_{CE}) + (24.1775 \times X_p) + (127.6084 \times Freq) - (0.6469 \times Freq^2)$$

Where:

$P_{alt-theo}$ = predicted alternator power using theoretical data from SAGE

This sensitivity study produced an equation that can be used to predict power around the nominal condition of SRSC #3 in its current state. Adding this equation to the rack software would enable easy comparison between the predicted and actual alternator power. This could make changes in convertor performance more easily identifiable in future testing.

VI. CONCLUSIONS

Ongoing work in the SRL at GRC is aimed at further validating the most state-of-the-art Stirling convertor technologies and has developed a suite of testing capabilities to increase the TRL of these convertors, controllers, and generators. Testing can be tailored to component, subsystems, and systems based on program requirements.

The SRL has successfully completed V&V testing on the flight-like SRSC design, validating robustness in critical environments and operating for thousands of hours to demonstrate steady performance. Continued testing of the Stirling Generator Testbed will further validate this Stirling generator layout for future RPS missions. Such generator concepts will be needed as mission planners look to the future for high efficiency RPS science missions and operations on the lunar surface.

ACKNOWLEDGMENTS AND ENDNOTES

Roles of Co-Authors:

Matthew Stang: *Test Engineer and author of Track 4 Thermal Cycling of the V&V Plan*

Dr. Tyler Steiner: *Test Engineer and author of Track 3 Static Acceleration Testing of the V&V Plan, Measurement Accuracy and Uncertainty Analysis, and the SRSC Sensitivity Study*

Daniel Goodell: *Test Engineer and author of the Track 2 Vibration Testing of the V&V Plan*

Ernestina Wozniak: *Test Engineer and lead designer and engineer for the Stirling Generator Testbed*

Special thank you to the rest of the SRL team who enable the world-class testing capabilities provided by the SRL and who make all this testing possible.

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