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# Extended Operation Testing of Stirling Convertors in Support of Stirling Radioisotope Power System Development

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## Abstract

100 We class Stirling convertors began extended operation testing at NASA Glenn Research Center (GRC) in 2003 with a pair of Technology Demonstration Convertors (TDCs) operating in air. Currently, the number of convertors on extended operation test has grown to 12, including both TDCs and Advanced Stirling Convertors (ASCs) operating both in air and in thermal vacuum. Additional convertors and an electrically heated radioisotope generator will be put on test in the near future. This testing has provided data to support life and reliability estimates and the quality improvements and design changes that have been made to the convertor.

The convertors operated 24/7 at the nominal amplitude and power levels. Performance data were recorded on an hourly basis. Techniques to monitor the convertors for change in internal operation included gas analysis, vibration measurements, and acoustic emission measurements. This data provided a baseline for future comparison.

This paper summarizes the results of over 145,000 hr of TDC testing and 40,000 hr of ASC testing and discusses trends in the data. Data shows the importance of improved materials, hermetic sealing, and quality processes in maintaining convertor performance over long life.

## Introduction

Extended operation testing is a critical element of developing long-life radioisotope power systems. Radioisotope power systems are ideally suited to long-duration missions of 15 years or more. While analytical tools can calculate reliability, and accelerated life tests can significantly shorten testing times in some circumstances, accelerated life tests cannot adequately quantify the extended life characteristics of all components. Further, changes in performance or degradation must be characterized with convertors under nominal operation typical of a mission, not under off-nominal conditions.

An Advanced Stirling Radioisotope Generator (ASRG) is being developed by Lockheed Martin under contract to the Department of Energy (DOE), with Stirling convertors provided by a team of NASA Glenn Research Center (GRC) and Sunpower. GRC, which has been testing Stirling engines and convertors since the 1970s, currently has 12 convertors under extended operation test, and will be adding several more over the next two years, as well as the ASRG Engineering Unit (ASRG-EU). This paper describes the typical extended operation test configuration, details the testing procedures, summarizes test results to date, and lays out future plans.

# Convertors Under Test

From the first pair of TDCs put under extended operation test in June 2003, to the latest ASCs added this year, the convertors on extended operation test represent the progression of convertor development. Table I lists all convertors already part of the extended operation test, plus convertors to become part of the test in the future. These future plans include convertors of the potential flight design.

It is anticipated that all convertors currently under test will continue being tested. While the convertors under test differ from the flight design, they provide data on components and materials shared with the flight design. Further, these convertors under test have accumulated the highest number of hours, and afford the best opportunity to accumulate operating hours comparable to the number of hours required by the mission.

TABLE I.—CURRENT AND FUTURE CONVERTORS IN THE EXTENDED OPERATION TEST

| Convertor | Testing environment | Nominal operating condition (Thot, Tcold) °C | Date extended operation test initiated | Hours to date | Status |
|---|---|---|---|---|---|
| TDC #13 | In air | 650/80 | June 2003 | 38,400 | Ongoing test |
| TDC #14 | In air | 650/80 | June 2003 | 38,400 | Ongoing test |
| TDC #5 | Thermal vacuum | 630/70 | Nov. 2004 | 10,500 | Test ended |
| TDC #6 | Thermal vacuum | 630/70 | Nov. 2004 | 10,400 | Test ended |
| TDC #15 | In air | 650/80 | Mar. 2005 | 24,600 | Ongoing test |
| TDC #16 | In air | 650/80 | Mar. 2005 | 24,600 | Ongoing test |
| ASC-0 #1 | In air and thermal vacuum | 645/72 | Feb. 2007 | 11,000 | Ongoing test |
| ASC-0 #2 | In air and thermal vacuum | 645/72 | Feb. 2007 | 11,000 | Ongoing test |
| ASC-0 #3 | In air; launch simulation | 650/90 | Aug. 2007 | 6,700 | Ongoing test |
| ASC-0 #4 | In air; launch simulation | 650/90 | Aug. 2007 | 6,700 | Ongoing test |
| ASC-1 #3 | In air | 850/90 | May 2007 | 1,800 | Being repaired |
| ASC-1 #4 | In air | 850/90 | May 2007 | 1,800 | Being repaired |
| ASC-1HS #1 | In air and thermal vacuum; launch simulation | 850/90 | Feb. 2008 | 2,200 | Ongoing test |
| ASC-1HS #2 | In air and thermal vacuum; launch simulation | 850/90 | Feb. 2008 | 2,200 | Ongoing test |
| ASRG-EU, with ASC-E #2 and #3 | In air; environmental testing at Lockheed Martin | 640/90 | 4Q 2008 | | Future test |
| ASC-E #1 | In air; launch simulation | 650/90 | 4Q 2008 | | Future test |
| ASC-E #4 | In air; launch simulation | 650/90 | 4Q 2008 | | Future test |
| ASC-E2 #1 | In air; launch simulation | | 2009 | | Future test |
| ASC-E2 #2 | In air; launch simulation | | 2009 | | Future test |
| ASC-E2 #3 | In air; launch simulation | | 2009 | | Future test |
| ASC-E2 #4 | In air; launch simulation | | 2009 | | Future test |
| ASC-E3 #1 | In air; launch simulation | | 2010 | | Future test |
| ASC-E3 #2 | In air; launch simulation | | 2010 | | Future test |

# Test System for Extended Operation Testing

This section summarizes the test system used for extended operation testing at GRC. While test systems for all convertors share many similarities, there are some differences for convertors with higher operating temperatures, in-air versus thermal vacuum testing, and other considerations.

## Mounting

The convertors were mounted horizontally in a dual-opposed configuration, similar to the configuration in the ASRG, to balance out the dynamic forces from the internal oscillating pistons and displacers. The convertors were then attached to an aluminum plate mounted on rubber feet, then secured to a table. An accelerometer secured to the aluminum plate measured vibration of the system. This information can be used to estimate net dynamic forces generated by the convertors as well as monitor for changes over time.

## Heat Source

For in-air testing, electric cartridge heaters, mounted in a nickel block, provide heat to the convertors. The TDC convertors utilize ten heaters configured radially around the heater head in a nickel block brazed adjacent to the heater. For the ASCs, six to eight cartridge heaters are mounted in a nickel block bolted to the ASC heat collector. Securing the nickel block to the heat collector with fasteners that could tolerate the high temperatures without loosing the preload required for good heat transfer through several heat up and cool down cycles proved challenging. For testing convertors in thermal vacuum, Boralectric heaters are used (Refs. 1 and 2). PID controllers adjusted voltage to a variable power supply to maintain a hot-end temperature set point.

The heaters were insulated with a variety of materials. Initial installation and temporary set-ups often use Kaowool fabric insulation. Permanent set-ups and thermal vacuum installations use microporous insulation, a rigid insulation with thermal conductivity an order of magnitude better than Kaowool.

While operating heaters at 650 °C is challenging, the difficulty of maintaining heater temperature long term at 850 °C, which necessitates heat source temperatures even higher, is significantly greater. To reduce heater and heater lead failure due to oxidation, all systems operating above 650 °C include an enclosure which surrounds the heat source and heater head with argon. A gas management system delivers a continuous flow of argon to the enclosure to replenish argon lost through small leaks in the enclosure, maintaining the argon environment.

## Heat Rejection

Fluid circulates near the cold ends of the convertors operating in air, removing heat from the Stirling cycle. Circulators that can both add and remove heat control the fluid temperature. In some experimental configurations with a cold-end temperature of 90 °C, the circulators actually may add some heat to maintain temperature. The system is intended to maintain a constant cold-end temperature over the duration of the test, but some variation does occur over long periods of time due to changes in coolant composition and cooling system performance. Currently the coolant is a concentration of 90 percent ethylene glycol and 10 percent distilled water in an open bath. Previous trials with a 50 percent/50 percent mix resulted in a significant rate of evaporation, which changed the heat transfer properties of the coolant. Baths are checked and topped off on a weekly basis to maintain the nominal 90 percent concentration to minimize variation in heat rejection.

On the TDCs, a copper jacket with copper tubing soldered to it that surrounds the pressure vessel maintains the pressure vessel temperature. Because the TDC alternator is slightly less efficient than the ASC alternator, some heat needs to be removed from this part of the convertor. Pressure vessel temperatures are maintained at a nominal 45 °C.

The ASC pressure vessels are open to atmosphere and reject some heat through natural convection. This set-up causes the ASC charge pressure and thus output power to vary slightly with ambient temperature. If it is determined that the pressure vessel temperature needs to be controlled to a greater degree, a cooling system can be added in the future. Even the TDCs, which have active pressure vessel temperature control, experience charge pressure variation due to ambient temperature changes, probably due to the natural convection from the portion of the pressure vessel next to the cold end exposed to air.

Ambient temperature in the lab changes during the day as well as seasonally throughout the year. Additionally, maintenance and repair on the heating, ventilating, and air conditioning (HVAC) systems as well as periodic HVAC system downtime contribute to temperature variation.

## Controller

The extended operation testing platforms employ two types of convertor controllers: the zener diode controller and the AC bus controller. Both controllers require tuning capacitors to compensate for the alternator inductance. The zener diode controller works by first rectifying the convertor output, turning it into a DC voltage. Resistive loads are switched in and out of the DC bus to maintain the voltage at a constant value. This in turn applies a load to the convertor, controlling the piston amplitude. The dynamics of the two convertors determine the operating frequency, which will change slightly as parameters such as temperature and pressure vary.

The AC bus controller simulates the convertors tied to an AC grid. The controller consists of an AC power supply dumping power into resistors. The alternator output after the tuning capacitor is also connected across this resistor, so the alternator sees the AC voltage and frequency generated by the power supply. The AC bus controller fixes the convertor frequency independent of changes in convertor dynamics, which can be an advantage when looking at trends in data over long periods of time, by eliminating one source of variation. Of course, the operating frequency cannot deviate significantly from the preferred convertor operating frequency. The power factor of each alternator will indicate if the operating frequency deviates significantly from the optimal frequency of each convertor. For convertors with low voltage and high current alternators, a transformer between the AC power supply output and the load resistor enables the use of a higher voltage and lower current power supply.

The AC bus controller controls piston amplitudes by varying the AC voltage and therefore the load on the convertors. Increasing the AC voltage increases the piston amplitudes.

The TDCs are operated using zener diode controllers. The ASC test stations all incorporate AC bus controllers, with the exception of the ASC-0 convertors currently operating in thermal vacuum, which are running on a zener diode controller. This controller will be replaced with an AC bus controller at the next opportunity.

## Instrumentation

The data system utilizes LabVIEW (National Instruments) hardware and software to acquire data and monitor the test. The data system varies somewhat from test to test, but typically the following parameters are monitored:

- Heater voltage, current, and power
- Heat source temperature
- Hot-end temperature
- Cold-end temperature
- Cold-end coolant inlet and outlet temperatures
- Cold-end coolant flow rates
- Pressure vessel temperature
- Alternator RMS voltage, RMS current, and power
- Piston amplitudes
- Helium charge pressure
- Operating frequency

A complete data record of these parameters is stored every hour. In addition, the system maintains a buffer of the last 24 hr of data recorded every two seconds. The LabVIEW system also provides the capability to manually store these data as needed for detailed analysis. From these data numerous parameters are calculated, including net heat input, system efficiency, heater resistance, alternator motor constant, and West number.

To protect the test articles, protection circuits, which can trigger a shutdown in the event of an abnormal condition, monitor the hot-end temperatures and piston amplitudes. The LabVIEW system also monitors critical parameters for potentially unsafe conditions, including high or low charge pressure, high or low hot-end temperature, high pressure vessel temperature, high cold-end temperature, and loss of building power for more than 5 min. If any of these conditions occurs, LabVIEW initiates a controlled shutdown of the system. It creates a data record of two-second data from 10 min prior to the event to 5 min after, to aid in understanding the root cause of the shutdown event.

Additional data taken outside of the LabVIEW system includes gas analysis data, vibration data, and acoustic emissions data. This data is collected every 1000 hr of operation.

## Uninterruptible Power Supply

To address the possibility of loss of facility power, uninterruptible power supplies (UPSs) provide backup power to each test station. This is important, because a sudden loss of facility power could result in an uncontrolled shutdown, potentially damaging the test articles. In the event of a facility power outage, the UPS is connected and a signal is sent to the LabVIEW system. The LabVIEW system monitors the outage, and if it extends beyond 5 min, the LabVIEW system initiates a controlled shutdown. The UPS system can also maintain operation for up to 30 min to perform maintenance on the facility electrical system without needing to shut down the convertors. A 50 kW generator will be installed later this year to provide power in the event of an extended facility power outage.

## Gas Analysis

One of the purposes of extended operation is to monitor the evolution of gasses inside the convertor, especially for organics. Every 1000 hr of operation, a residual gas analyzer (RGA) analyzes a small volume of helium pulled from the convertor through the fill tube.

## Vibration Data

An accelerometer mounted in a position to measure net vibration of the dual-opposed convertor system monitors motion in all three axes. The accelerometer signal is fed into a spectrum analyzer that identifies the most significant frequencies in the vibration signal. These frequencies and the peak grms values are recorded and monitored for significant changes. Typical causes for a change in vibration might include a change in performance due to a change in piston or displacer amplitude or phasing or a change in the dynamic structure of the system.

## Acoustic Emissions Data

The moving parts inside the convertor, such as the displacer spring and the check valve, and the pressure waves from opening and closing of gas ports, and other dynamic events can create an acoustic signature in the body of the convertor. These acoustics do not represent rigid body motion of the convertor, but rather waves within the metal itself. An acoustic emissions (AE) sensor, placed in contact with the convertor with mild clamping force at a location as close as practical to the potential emissions sources, can detect these emissions. This typically is on the pressure vessel near the middle of the convertor (Fig. 1). Currently, Micro30S sensors from Physical Acoustics Corporation with a range of 100 to 600 kHz are used.

AE data are recorded and analyzed in both the time and frequency domain. In the time domain, the relationship between the acoustic pulses relative and events in the Stirling cycle is of interest. The AE data will be monitored over time to look for changes in the acoustic signature of the convertors as an indication of change over time. A typical acoustic emissions profile is shown in Figure 2.

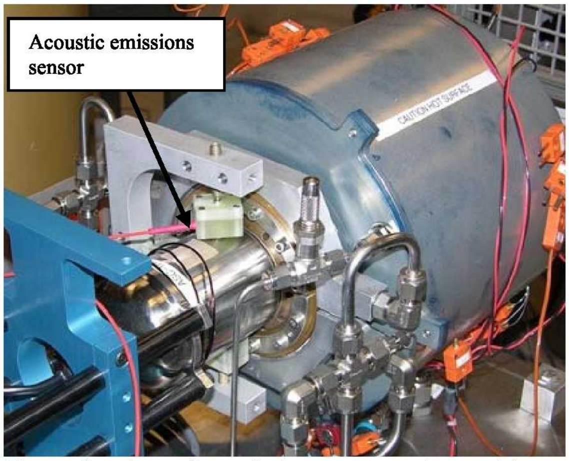



Figure 1.—Acoustic emissions sensor clamped to pressure vessel of convertor.

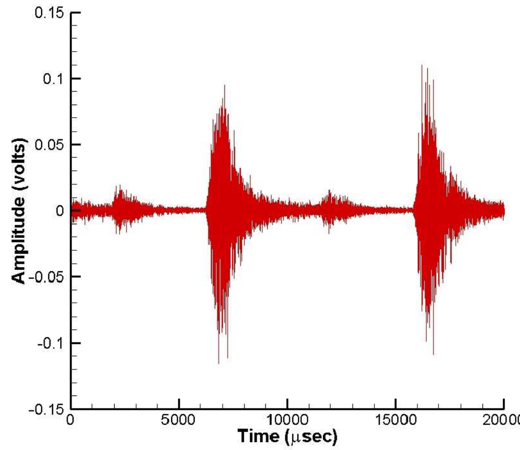



Figure 2.—Typical acoustic emissions signature in the time domain.

## Heater Head Creep Data

Recently the lab has begun taking precise measurements of the heater head diameter along the length of the heater head. Measurements are accurate to the submicron level, with a resolution of 0.05 μm. Measurements will be taken near the beginning of testing, and then repeated at infrequent intervals yet to be determined to quantify the material creep rate.

## Test Sequence

The convertors go through a series of processing steps and initial tests before commencing extended operation. The typical sequence includes:

1. Instrumentation—install thermocouples on the hot end and cold end
2. Installation—add heat source, insulation, and other hardware
3. Bake-out—for non-hermetically sealed convertors, remove contaminants before operation
4. Thermal loss characterization—characterize insulation heat loss to accurately calculate convertor efficiency
5. Low temperature check-out—operate convertors at low temperature to verify sensor signals, piston amplitudes, convertor synchronization, cooling system, and other aspects of the test system
6. Full power demonstration—document full power performance
7. Extended operation
8. Acceptance vibration test and launch simulation vibration exposure
9. Continued extended operation

Previous publications described these steps in detail (Refs. 2 to 7). Some of the TDCs underwent additional tests such as performance mapping prior to extended operation.

The acceptance vibration test and launch simulation vibration exposure merit further discussion. Extended operation seeks to put the convertors through an operational and environmental profile similar to what they will see in an actual mission. To that end, convertors closer to the flight design will be exposed to the expected vibration levels of flight convertors. The flight convertors are expected to go through a workmanship vibration test at the time of manufacture, then an acceptance vibration test. The flight convertors will then begin operation in a fueled generator and after a period of time, go through launch.

Beginning with the ASC-E units, all convertors being manufactured go through a workmanship test. The convertors on extended operation will be put through a simulated launch vibration during one test sequence. After between 5,000 and 10,000 hr, representing the time between generator fueling and launch, the convertors will be removed from the test stand and put through an acceptance vibration test. This will be followed by a launch simulation vibration test, where each convertor is shaken in the X-, Y-, and Z-axes for 1 min in each axis while operating at full power. Each convertor will be tested separately in a fixture that applies the dynamic load through the pressure vessel flange and the cold side adapter flange. The 8.70 grms flight vibration profile from NASA-STD-7001 (Ref. 3) will be used, but may be modified based on recent dynamic testing of the ASRG-EU to more closely represent the vibration profile of the ASC-E when mounted inside the generator. After the acceptance vibration test and launch simulation vibration exposure, the convertors will return to extended operation.

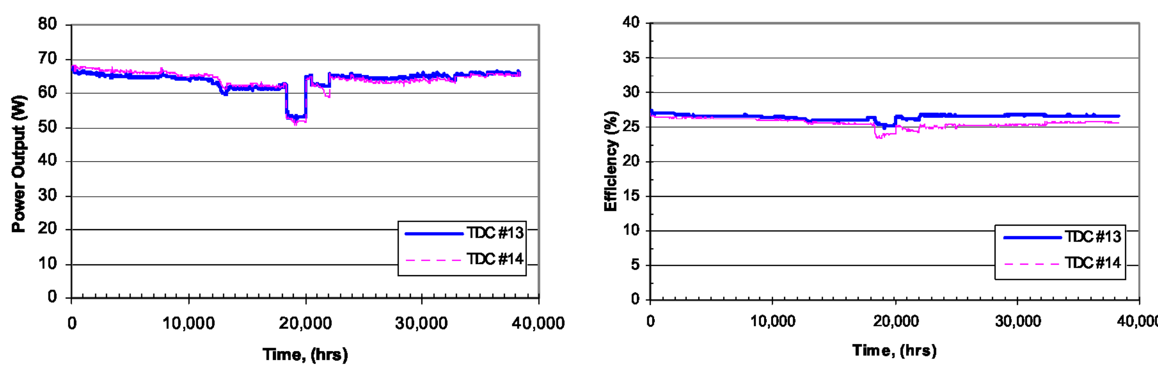
## Extended Operation Test Results to Date

### Extended Operation of TDCs #13 and #14

The test facility and testing of TDCs #13 and #14 are discussed in Reference 4, and a detailed discussion of operation through 2006 in Reference 8. The latter report summarizes the variety of activities associated with convertors to resolve air permeation issues through the o-rings and other details associated with extended operation testing.

TDCs #13 and #14 have operated over 38,400 hr (4.4 years). In September 2007 at 32,199 hr the convertors shut down due to a circulator failure. While they were shut down other needed maintenance on the supporting infrastructure was performed, including equipment inspection, transducer calibration, cooling system maintenance, and flushing of water jackets and fluid lines.

Figure 3 shows output power and net efficiency to date for TDCs #13 and #14. The slight degradation in power and efficiency prior to 19,000 hr is attributed to regenerator oxidation due to oxygen permeation through o-ring seals. Hermetically sealing the flanges at 19,000 hr prevented further oxidation. The convertors operated until about 20,000 hr at a lower power level after hermetic sealing. Shortly after returning to full power operation a number of cartridge heater failures caused a drop in power. The heaters were all replaced at about 22,000 hr, and the convertors have continued to operate with negligible change in performance since then.




(a) Convertor electric power out

(b) Net efficiency, heat in to electric power out

Figure 3.—TDCs #13 and #14 performance data through 38,400 hr of operation.

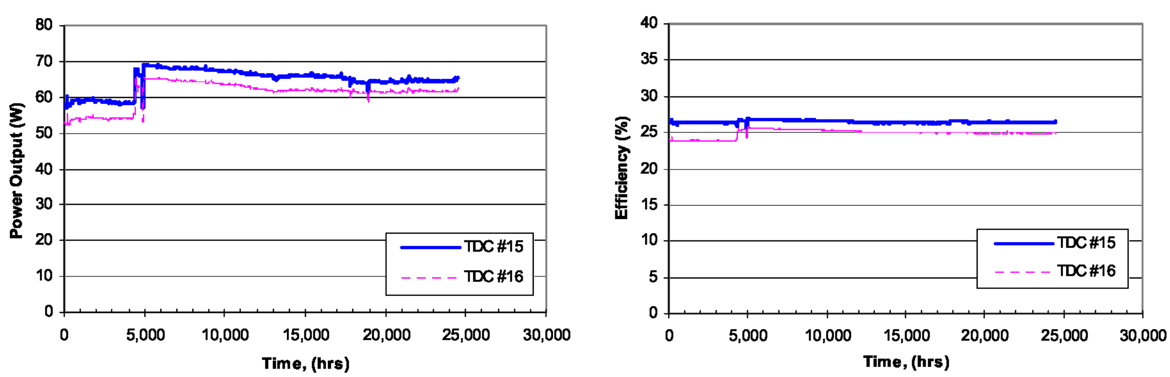
## Extended Operation of TDCs #15 and #16

Two more TDCs were put on extended operation in March 2005. Initial start-up, operation, and hermetic welding through 10,200 hr are discussed in detail in Reference 8. These TDCs have operated over 24,600 hr (2.8 years) to date. In September 2007, the convertors shut down due to an instrumentation issue. While they were shut down other needed maintenance was performed on the supporting laboratory systems, including transducer calibration, cooling system maintenance and flushing of water jackets and fluid lines.

Figure 4 shows test data from TDCs #15 and #16. The convertors operated at a reduced hot-end temperature of 500 °C prior to hermetic sealing at 4,400 hr to prevent internal oxidation. To date, over 24,600 hr of extended operation have been completed on TDCs #15 and #16, with over 19,600 hr since hermetic seal welding. From about 6,000 through 13,000 hr there appears to be a slight decrease in output power, with a small change in efficiency. For the last almost 10,000 hr power and efficiency have been fairly stable.

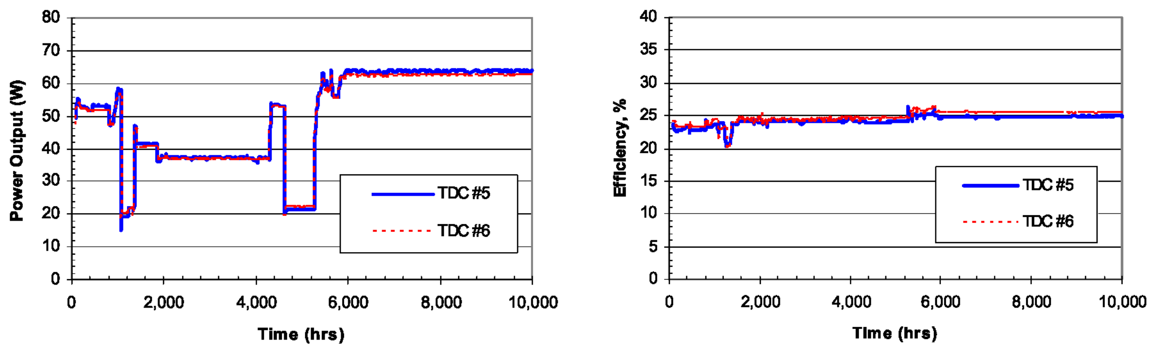
## Extended Operation of TDCs #5 and #6

Extended operation of TDCs #5 and #6 in thermal vacuum began in November 2004 and successfully completed 10,016 hr of operation in August 2006. Since the test objective to demonstrate Stirling convertor operation in a thermal vacuum environment was met, and in order to prepare for testing the ASC-0 #1 and #2, the convertors were shut down and the test ended. Details of this test, including design, set-up, thermal issues, mechanical challenges, and test results can be found in References 1, 2, 8, and 9. Figure 5 summarizes data from the complete test. The net efficiency number is calculated based on a finite element thermal model to estimate heat loss through the insulation. The convertor operating point reached full power after about 6,000 hr, after working through initial start-up and heater issues, implementing hardware improvements, and completing bakeout. Performance data after 6,000 hr shows steady operation and no degradation in performance.




(a) Convertor electric power out (b) Net efficiency, heat in to electric power out

Figure 4.—TDCs #15 and #16 performance data through 24,600 hr of operation.




(a) Convertor electric power out (b) Net efficiency, heat in to electric power out

Figure 5.—TDCs #5 and #6 performance data through all 10,016 hr of thermal vacuum operation.

## Extended Operation of ASC-0 #1 and #2

ASC-0 #1 and #2 were the first ASC convertors put on extended operation at GRC. These convertors utilize Inconel 718 heater heads and therefore operate at a maximum hot-end temperature of 650 °C and a rejection temperature of 90 °C. These convertors are configured to allow both in-air and thermal vacuum operation. The ASC-0 #3 and #4 have been hermetically sealed by welding the flange joints, but access to the fill tube remains via an isolation valve. Reference 5 describes their set-up and initial testing. These convertors operated for 600 hr in air in February and March 2007 and then were configured for thermal vacuum operation in the same facility used for TDCs #5 and #6 testing. Lessons learned from the TDCs #5 and #6 experience benefited ASC testing in thermal vacuum, resulting in a smoother start-up and greater uptime. Thermal vacuum operation began at the end of March 2007 and will continue until ASC-1HS #1 and #2 take their place. ASC-0 #1 and #2 have logged over 11,000 hr of total operation.

Figure 6 shows test data for ASC-0 #1 and #2. During the initial 600 hr of in-air operation the output power showed significant variation with a downward trend. Variation in charge pressure and operating frequency can explain some of this variation, but some of the variation may be due to a change in convertor performance. This pair of ASCs is the only pair operating with a zener diode controller instead of the AC bus controller, which allows the frequency to vary. Since the frequency is determined by balancing the dynamics of both convertors, a change in the dynamics of just one convertor can change the frequency of the system, affecting the performance of the other convertor. Thus the possibility exists that variation in the performance of one convertor could cause variation in the other's performance, or that both convertors' performance could be varying.

After 600 hr of in-air testing the convertors began thermal vacuum operation. By 1700 hr a couple start-up issues were resolved and operation continued at a fixed operating point. The data more clearly shows potential degraded performance from ASC-0 #1, with a gradual decrease in output power through 5,500 hr, followed by more erratic performance. ASC-0 #2's output power also decreases slightly, but this may be due to a change in ASC-0 #1's dynamics causing a change in the operating frequency. Other parameters including gross heat input, alternator current, and piston amplitude show similar trends as the power.

After these convertors are removed from thermal vacuum they will again be operated in air, but this time on an AC bus controller. This will provide additional information on the convertor performance with different test hardware and controller. It should be noted that this behavior was evident from the beginning of convertor operation, and that these convertors were built prior to Sunpower implementing their ISO 9001-based Quality Management System.

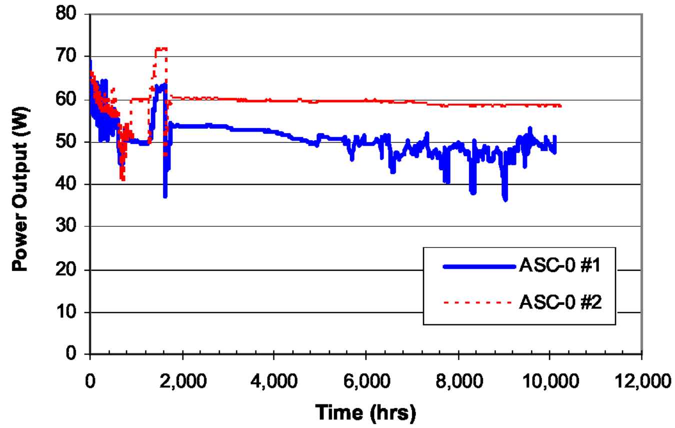
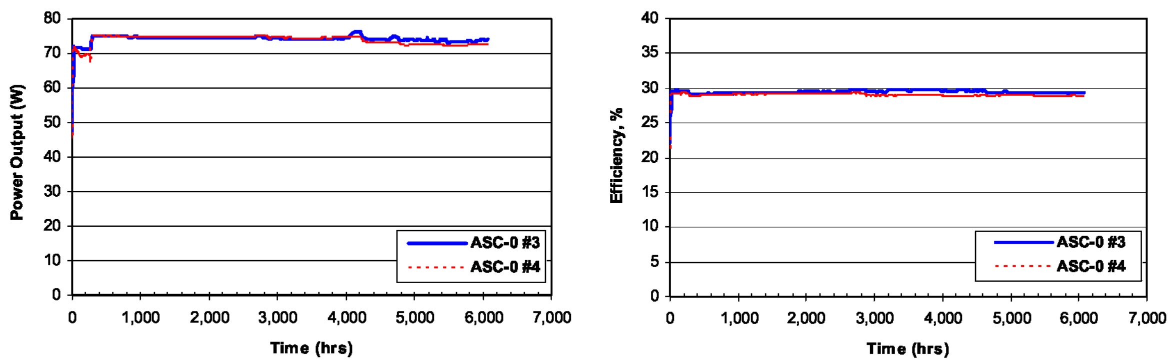



Figure 6.—ASC-0 #1 and #2 electric power output.




(a) Convertor electric power out

(b) Net efficiency, heat in to electric power out

Figure 7.—ASC-0 #3 and #4 performance data through 6,000 hr of operation.

## Extended Operation of ASC-0 #3 and #4

The ASC-0 #3 and #4 convertors began operation at GRC in August 2007 and have reached over 6,700 hr. They are configured similarly to the ASC-0 #1 and #2 convertors, with Inconel 718 heater heads and hermetically sealed flange joints. Their start-up and initial operation is discussed in Reference 7. Figure 7 shows test data through 6,000 hr. Output power remained relatively steady, and efficiency has between 28 and 30 percent over this period.

## Extended Operation of ASC-1 #3 and #4

The ASC-1 #3 and #4 convertors are a product of NASA Research Announcement (NRA) technology development and were not intended for extended operation. However, because they have an 850 °C-capable MarM-247 heater head, they are being tested under extended operation to generate operating experience with that material at higher temperatures. An enclosure surrounds the heater and heater head with argon to minimize heater oxidation at these high temperatures.

The ASC-1 #3 and #4 convertors design included 9 o-ring seals, and as a result they lose helium pressure at a much higher rate than the other convertors. To avoid frequent helium topoffs to maintain pressure, an electronic pressure-regulating system was implemented. This system maintains the helium pressure within a few psi.

The convertors underwent several tests before thermal loss characterization. The thermal loss test unexpectedly damaged the convertors by exposing parts of the convertors to temperatures beyond their design points. The thermal loss characterization was conducted with the convertors under vacuum, to eliminate heat transfer through the gas in the convertor. Subsequent analysis showed that when the hot end of the convertor is brought to full operating temperature while under a vacuum, the heat transfer internal to the convertor is significantly different than when the convertor is fully charged with helium. The cold end of the displacer specifically becomes much hotter. The ASC-1 #3 and #4 displacers were epoxied together, unlike newer convertors. The epoxy joint failed due to the high temperature from the thermal loss test, causing a rub.

When the convertors were opened to investigate the rub, significant oxidation was observed on the displacer dome. The convertor remained fully functional even with this oxidation. Since these convertors can operate at heater head temperatures up to 850 °C, oxidation is more of an issue, and further oxidation needs to be prevented. Oxygen is entering through the o-rings, so a second enclosure is being designed to surround the remaining o-rings in argon or other inert gas, to prevent oxygen from entering.

### Extended Operation of ASC-1HS #1 and #2

ASC-1HS #1 and #2 have recently started, and results of this test will be reported in the future.

## Conclusion

Extended operation of Stirling convertors provides valuable data to understand long life characteristics of these devices. The Stirling convertors at GRC have accumulated over 185,000 hr under extended operation, and as more convertors are put on test, the rate at which hours accumulate will increase. Testing of convertors will continue at GRC, with newer convertors built to flight level quality processes to be put on test in the near future. As Figure 8 shows, the convertors are projected to operate 80,000 total hours in 2008. In 2009, total hours should exceed well over 100,000 hr.

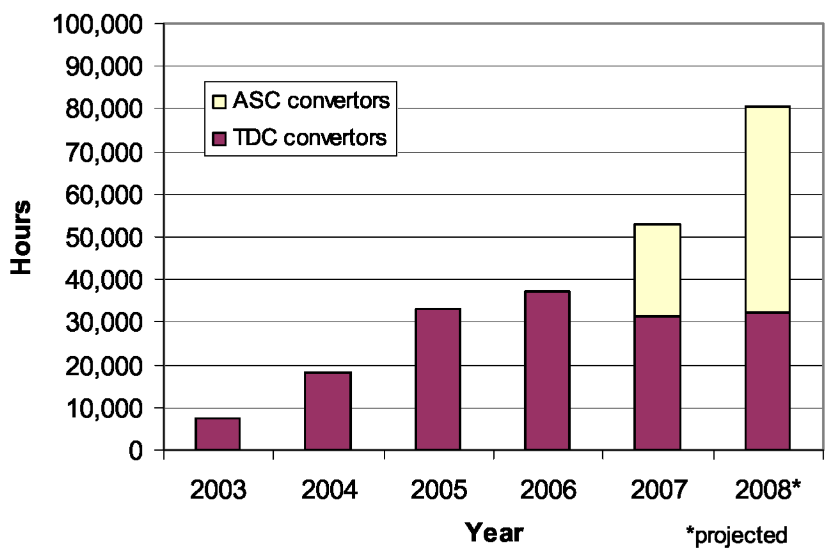



Figure 8.—Total annual extended operation hours.

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| **14. ABSTRACT**<br>100 We class Stirling convertors began extended operation testing at NASA Glenn Research Center (GRC) in 2003 with a pair of Technology Demonstration Convertors (TDCs) operating in air. Currently, the number of convertors on extended operation test has grown to 12, including both TDCs and Advanced Stirling Convertors (ASCs) operating both in air and in thermal vacuum. Additional convertors and an electrically heated radioisotope generator will be put on test in the near future. This testing has provided data to support life and reliability estimates and the quality improvements and design changes that have been made to the convertor. The convertors operated 24/7 at the nominal amplitude and power levels. Performance data were recorded on an hourly basis. Techniques to monitor the convertors for change in internal operation included gas analysis, vibration measurements, and acoustic emission measurements. This data provided a baseline for future comparison. This paper summarizes the results of over 145,000 hr of TDC testing and 40,000 hr of ASC testing and discusses trends in the data. Data shows the importance of improved materials, hermetic sealing, and quality processes in maintaining convertor performance over long life. | | | | | | |
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