NASA/TM—2004-213388 AIAA–2004–5508

Extended Operation of Stirling Convertors

Mary Ellen Roth, Jeffrey G. Schreiber, and Stephen V. Pepper
Glenn Research Center, Cleveland, Ohio

November 2004

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2004-213388 AIAA–2004–5508

Extended Operation of Stirling Convertors

Mary Ellen Roth, Jeffrey G. Schreiber, and Stephen V. Pepper
Glenn Research Center, Cleveland, Ohio

Prepared for the
Second International Energy Conversion Engineering Conference
sponsored by the American Institute of Aeronautics and Astronautics
Providence, Rhode Island, August 16–19, 2004

National Aeronautics and
Space Administration

Glenn Research Center

November 2004

Acknowledgments

The work described in this paper was performed for NASA's Science and Aeronautics Mission Offices, both of which provided funding for these efforts.

This report contains preliminary findings, subject to revision as analysis proceeds.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Extended Operation of Stirling Convertors

Mary Ellen Roth, Jeffrey G. Schreiber, and Stephen V. Pepper
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

A high-efficiency 110 W Stirling Radioisotope Generator 110 (SRG110) is being developed for potential NASA exploration missions. The SRG could provide spacecraft electrical power for a variety of applications, including deep space missions and unmanned surface rovers. The SRG system efficiency is greater than 20%, making it an attractive candidate power system. The Department of Energy SRG110 Project team consists of the System Integrator, Lockheed Martin (LM), Stirling Technology Company (STC), and NASA Glenn Research Center (GRC). LM is to deliver multiple SRG110 generators under this contract. STC has designed and built 16 Stirling Technology Demonstration Convertors (TDC) and continues to develop this technology in support of this project. One of the GRC roles is to provide Independent Verification and Validation of the Stirling TDC's. At the request of LM, a part of this effort includes the Extended Operation of the TDC's in the dynamically balanced dual-opposed configuration. Some potential applications for the SRG110 would involve long duration missions, ranging from three to fourteen years. Performance data of Stirling Convertors over time is required to demonstrate that an SRG110 can meet long-duration mission requirements. A test plan and test system were developed to evaluate TDC's #13 and #14 steady-state performance for a minimum of 5000 hours. Hardware, software and TDC preparation processes were developed to support this test. These included bakeout of the TDC's for the reduction of water vapor and other contaminants, development and fabrication of a Helium charging system for gas analysis and TDC fill operations, development of detailed procedures and test plans, modifications to an existing test stand and control rack, and the development of new control software and high speed protection circuitry to insure safe, round-the-clock operation of the TDC's. This paper will discuss the design and development, and status of the Extended Operation Test.

Nomenclature

SRG110	110 W Stirling Radioisotope Generator
DOE	Department of Energy
LM	Lockheed Martin
STC	Stirling Technology Company
GRC	Glenn Research Center
TDC	Technology Demonstration Convertor
GPHS	General Purpose Heat Source
BOM	Beginning of Mission
RGA	Residual Gas Analyzer
FPC	Failsafe Protection Circuit
LDAS	LabView™ Data Acquisition System

I. Introduction

A high-efficiency Stirling Radioisotope Generator 110 (SRG110) is being developed for potential NASA exploration missions. The SRG110 could provide spacecraft electrical power for a variety of applications, including deep space missions and unmanned rovers. The SRG110 system efficiency is projected to be greater than 20%, making it an attractive candidate power system.[1] The Department of Energy (DOE) SRG110 Project team consists of the System Integration Contractor, Lockheed Martin (LM) of Valley Forge, Pennsylvania, Stirling Technology Company (STC) of Kennewick, Washington, and NASA Glenn Research Center (GRC). LM is to deliver multiple SRG units under this contract. STC has designed and built 16 Stirling Technology Demonstration Convertors (TDC's) and continues to develop this technology in support of this project. One of the roles of GRC is to provide

Independent Verification and Validation of the Stirling TDC's for LM. At the request of LM, a part of this effort includes the Extended Operation of TDC's #13 and #14 in the dynamically balanced, dual-opposed configuration. The TDC's #13 and #14 were delivered to GRC on February 13, 2003. Prior to delivery to GRC, the convertors were operated at STC individually and passed the LM Acceptance Test. While at STC, each convertor had accumulated approximately 100 hours of operation. Following delivery to GRC, TDC's #13 and #14 were scheduled to undergo a Vacuum Bakeout, Thermal Loss Characterization Test (Test Plan 55–029), and Demonstration of Full Power Operation (Test Plan 55–030). The TDC's accumulated 38 hours of operation at GRC as of June 2, 2003, prior to the Extended Operation Test.

II. Design and Development of the Extended Operation Test System

TDC's and other Stirling convertors have been operated at GRC since the mid 1970's. TDC's #5 and #6 have been successfully operated as individual units since their arrival at GRC in September of 2000. TDC's #7 and #8 have been operated as a dual-opposed pair since June of 2001.[2] TDC's #7 and #8 had been used to support a variety of controller, convertor and subsystem characterization tests. However, all of these tests were conducted with a test engineer present. Unattended operation of the convertors had only recently been attempted. To meet the 5000+ hour requirement of continuous operation, hardware, software and TDC preparation processes had to be developed. These included vacuum bakeout of the TDC's for the reduction of water vapor and other contaminants, development and fabrication of a helium gas charging system for gas analysis and TDC fill operations, development of detailed procedures and test plans, modifications to an existing test stand and control rack, and the development of new control software and high-speed protection circuitry to insure safe, round-the-clock operation of the TDC's.

A. Technology Demonstration Convertors

The TDC's are free-piston Stirling engines integrated with linear alternators and controllers. The convertors were designed and built by STC under contract to DOE.[3] This design was baselined by DOE for use in the SRG110, which will use two General Purpose Heat Source Modules (GPHS) for heat and produce over 110 W of electric power at the Beginning of Mission (BOM). To date STC has built more than 16 TDC's and two testbed convertors for the SRG110 project. Among these are TDC's #13 through #16 that are referred to as flight prototypes since these were built under the Quality Assurance Program developed by STC for future flight convertors. The TDC's convert thermal energy into alternating current electrical power. The convertor operates by using heat from an external heat source to power a Stirling thermodynamic cycle that is operated by the resonant displacer and piston of the Stirling engine. Power input to the piston from the thermodynamic cycle is converted into electric power in the linear alternator. For laboratory operation, electric heaters are used to heat the hot end of the TDC. For laboratory testing, the temperature of the cold end is maintained by circulating coolant through an external cooling jacket around the cold end of the convertor. Each TDC is equipped with its own electric heater. A cross section of the TDC is shown in figure 1. The TDC's #13 and #14 that are currently undergoing the Extended Operation Test are shown in on the test stand in figure 2. The TDC's were mounted on the test stand with the linear alternators adjacent to one another, and the heater heads outboard. A heat exchanger was installed around the pressure vessel to control the temperature of the linear alternator. This heat exchanger uses fluid supplied by a circulator to control the temperature. A similar circulator is used to maintain the cold-end temperature of the Stirling cycle. The hot end has an array of ten cartridge heaters in a nickel heater ring to simulate the heat supplied by a radioisotope heat source.

The TDC's were designed to produce up to 65 W_e with a net heat input of less than 250 W thermal. The design operating point is with the hot-end temperature at 650 °C, the cold-end temperature at 80 °C, and the pressure vessel around the linear alternator at 45 °C. The design amplitude of the power piston is nominally 6 mm. During the extended operation test, the hot-end temperature has been set with the maximum temperature among five thermocouples in the nickel heater ring at 650 °C. The cold-end temperature has been defined as 7.5 °C above the average of the inlet and outlet temperatures of the circulated coolant. This was selected to result in an average wall temperature of the heat rejection surface to be 80 °C, based on a simplified analysis of the cold-end cooling jacket. Since the test began, a more detailed analysis has been completed that shows that the temperature difference between the fluid inlet and the average wall temperature is far greater, thus, the cold-end of the Stirling is believed to be closer to 90 °C rather than the intended 80 °C. The pressure vessel temperature is defined as the average of the three thermocouples that are mounted on the external surface.

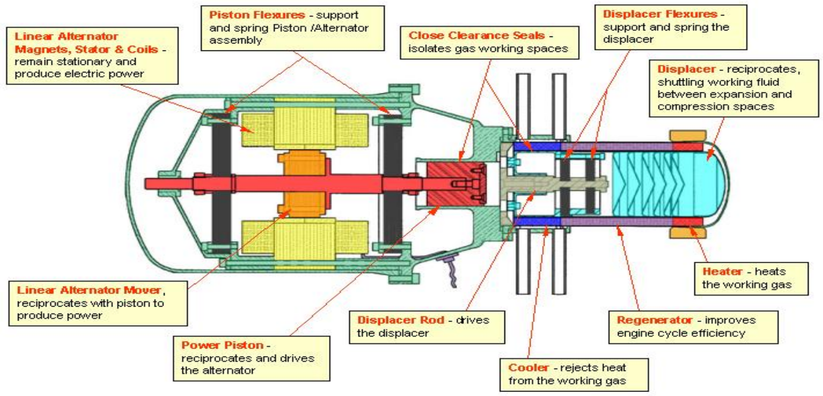

Figure 1.—Cross section of TDC with internal components.

B. Test Stand

The test stand is comprised of three major subsystems; 1) a Data and Control System rack, 2) the test stand, and 3) the cooling system. The TDC's, in the dual-opposed configuration are shown in figure 2. The rack and cooling system circulators are shown in figure 3. An existing test stand that had been used for performance testing of earlier TDC's, along with a Data and Control System, and the system software were modified to support unattended operation of the TDC's. This included more complete limit checking of the signals being monitored, and logic to initiate an appropriate shut down in the event of an out-of-range signal. Two types of shut down were developed; one for an emergency that stops the convertor as soon as possible, and the other providing a more long-term, slower shutdown.

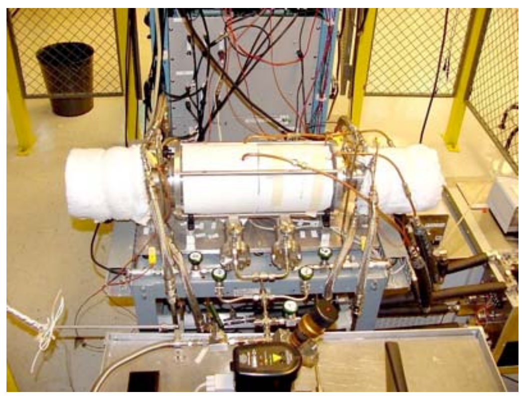

Figure 2.—TDC's #13 and #14 mounted on the test stand for extended operation.

1. Data and Control System

The Data and Control System is a LabView™ based system that monitors, displays and records various operational parameters. Software developed by STC was delivered with the first shipment of TDC's to GRC. That software was modified by GRC engineers and developed into the presently used Data and Control System. This system has been used for operation of TDC's #5 through #8. The system was then updated for unattended operation of the TDC's to include automatic shutdown of the convertors in the event of a failure or detection of out-of-normal range operating condition. Some of the conditions that have been programmed to trigger a shutdown include hot end or pressure vessel over temperature, cold end under temperature, convertor over pressure, piston over stroke, loss of utility power, or loss of coolant.

A special circuit was developed to detect a piston over stroke or excessive TDC vibration, and respond by placing a protective load on the output of the TDC's, and send a signal to the LabView™ Data Acquisition System (LDAS). LabView™ then initiates a shutdown of the system. The protection circuit is described in more detail in Part D of this paper. Two hard-wired protective shutdowns were designed into the Data and Control System rack that do not use the LabView™ software. Over temperature of a specified hot-end thermocouple or loss of coolant flow in cold end automatically shut off the power supplies for the hot-end electric heaters.

Figure 3.—Rack with data and control system, and chillers along side to control coolant temperatures.

In the case of software initiated shutdowns, LabView™ sends commands to turn off the heater power supplies, set the circulator temperature set points to 20 °C, and generate a freeze file of all monitored parameters covering a time period of 10 minutes prior to the shutdown and 5 minutes afterward.

The Data and Control System relies on several transducers for accurate measurement of the operational parameters. Temperature, voltage, current and charge pressure of each TDC are monitored and displayed at all times. Data can be acquired and saved to the hard drive of the data system computer in three different ways that includes a five-minute average data set, a continuous data set that can be recorded at a user defined rate of up to 30 scans per minute, and a user-initiated freeze file. A list of the parameters, transducers, and transducer accuracy are shown in table 1.

Table 1.—Parameters measured and calculated by the data system.

Parameter	Units	Transducer Model	Manufacturer	Uncertainty
Hot End Temperature	°C	KMTSS-040U-12, Type K	Omega	±2.0 °C
Cold End Temperature	°C	KMTSS-062U-6, Type K	Omega	±2.0 °C
Pressure Vessel Temperature	°C	SA1-K, Type K	Omega	±2.0 °C
Piston position	Mm	3515LUA	Allegro	±0.25 mm
Displacer Position	Mm	3515LUA	Allegro	
Heater DC Supply Voltage	Volts, DC	VT7-005X5	Ohio-Semitronics	±0.4 Vdc
Heater DC Supply Current	Amperes, DC	CT7-014X5	Ohio-Semitronics	±0.025 Adc
Alternator RMS Voltage	Volts, RMS	VT8-005X5	Ohio-Semitronics	±0.4 Vrms
Alternator RMS Current	Amperes, RMS	CT8-008X5	Ohio-Semitronics	±0.01 Arms
Alternator AC Power Out	Watts	PC5-106X5	Ohio-Semitronics	±1.25 W
Charge Pressure	Psig	K17M0215F2500	Ashcroft	±5 psig
DC Bridge Voltage	Volts, DC	VT8-004X5	Ohio-Semitronics	±0.4 Vdc
Coolant Flow Rate	Liters/Minute	FTB602-T	Omega	
Calculated Parameters				
Gross Heat In	Watts	Calculated		1.56 W
Net Heat In	Watts	Calculated		
Frequency	Hz	Calculated		

2. *Cooling System*

The TDC's were delivered with an integrated cooling jacket for the cold-end heat exchanger. Special copper cooling jackets were fabricated at GRC for controlling the temperature of the pressure vessels. The cooling system consists of two PolyScience™ Model 9510 circulators. One circulator controls the cold-end temperature of the thermodynamic cycle, and the other controls the temperature of the pressure vessel. Ethylene glycol has been used in both of the circulators and heat exchangers.

3. *Convertor Mounting*

The TDC's are mounted to an aluminum base plate that is attached to the steel test stand with rubber isolation mounts. The TDC's are configured in the dynamically balanced dual-opposed configuration and attached rigidly to the aluminum plate. When operation is dynamically balanced, there is no net vibratory force generated, and the compliance and/or damping of the rubber isolation mounts have no bearing on the dynamics of operation.

C. Gas Charging System

The TDC's operate with helium as the working fluid at an elevated pressure. To ensure stable, long-term operation of the convertors, it is important to provide and maintain the helium environment as pure as possible. A charging system was developed to allow filling of the TDC's with high-purity helium with measured composition, and to allow monitoring of the make-up of working fluid during the test. This capability was developed in response to one of the goals of the Extended Operation Test which was to seek and measure any changes that may occur over time. It was thought that there might be some out-gassing from the organics in the linear alternator. The requirement for the clean initial fill was because impurities in the working fluid may potentially react chemically with other internal components in contact with the gas. These components may suffer damage that could adversely affect convertor performance and life. Impurities may be present due to incomplete removal of the air prior to filling with helium, by out-gassing from internal components during operation at elevated temperature, or by ingress of air by permeation through the elastomer o-rings. The charging system was designed and fabricated to support all of the gas management activities during this test by performing three functions:

1) Evacuation of the TDC’s.
2) Pressurization and top-off of pressure in the TDC’s.
3) Perform analysis of gas samples from the TDC during operation.

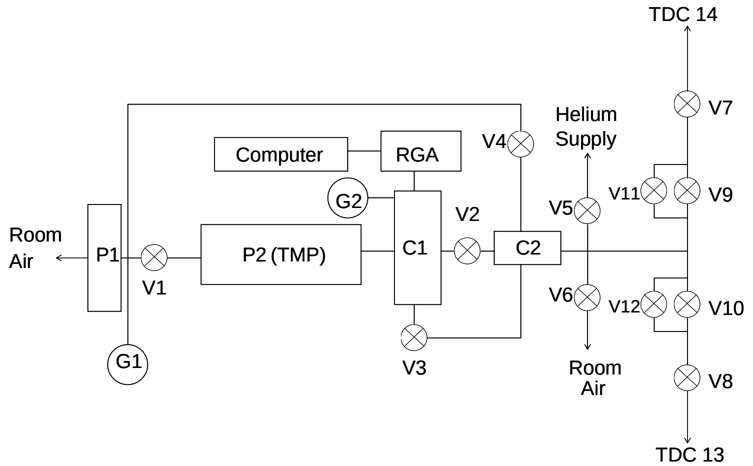

Figure 4.—Plumbing diagram of the final version of charging system.

The configuration of the charging system evolved as the testing continued. Improvements were made to allow for more precise control of gas flow into and out of the TDC’s. A plumbing diagram of the version of the station currently in use is shown in figure 4. A photograph of the system is shown in figure 5. The principal components of the system are a 53 liter/second (N_2) turbomolecular vacuum pump for evacuation of the TDC’s, and a quadruple Residual Gas Analyzer (RGA) for analysis of the molecular components of the gas sampled from the TDC’s. A complete listing of the components can be found in table 2. The plumbing shown in the photograph are standard stainless steel tubing, 0.25” outside diameter, and 0.18” internal diameter. The tube sections are joined with standard Swagelok fittings, although future versions of the manifold will make use of orbital welded connections and fittings more appropriate for ultra high purity gas systems.

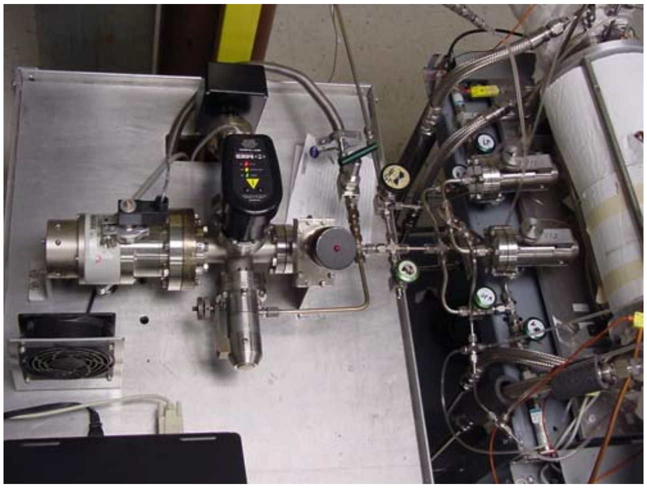
Figure 5.—Charging system for TDC’s #13 and #14.

D. Failsafe Protection Circuit

Most all of the tests that are conducted at GRC involve either extended operation, which is performed without an operator present, or tests that investigate operation under experimental conditions. The experimental conditions could be operation at conditions far from the intended design operating conditions, testing with advanced controllers, or tests to characterize response to transients. Each of these types of tests brings some element of risk to the hardware. A Failsafe Protection Circuit (FPC) was developed to control the convertor in the event of an anomaly. The user interface of the FPC is shown in figure 6. The circuit has five input signals that are compared to reference values or thresholds. The signals that have been used as inputs during dual-opposed operation are the two piston positions and the three signals from the tri-axis accelerometer. If any signal exceeds the threashold set by the operator, the FPC will apply a known load directly to the terminals of the linear alternator. The load is sized to bring the piston amplitude to a safe level; about half the amplitude of full power. The circuit is fast acting so that the load can be applied in less than one-half cycle of operation. One example would be in the case of loss of load during a controller test. A new version of the FPC has a feature that indicates which of the five input signals caused the circuit to trip. The FPC has been incorporated into all test stands at GRC.

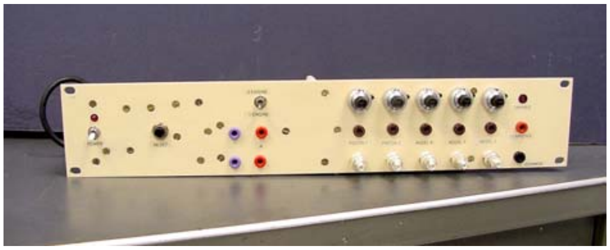
Figure 6.—Failsafe protection circuit user interface.

E. Procedures and Test Plans

All activities performed on TDC's #13 and #14 in support of the Extended Operation Test are governed by either Procedures or Test Plans. Procedures are generally activities that are repeated, or performed as part of the processing and not strictly for taking data. Tests Plans govern activities that are designed for the sole purpose of generating data. In support of the Extended Operation Test of TDC's #13 and #14, procedures were developed for: 1) Proof Pressure Test, 2) Rack Set-Up, 3) TDC Start-Up, 4) TDC Shut-Down, 5) Unattended Operation Set-Up, 6) Failsafe Protection Circuit Set-Up, 7) Unattended Shut-Down, 8) Leak Check, 9) Evacuation and Fill, 10) Gas Analysis, and 11) Bake. Test Plans developed were 1) Thermal Loss Test, 2) Full Power Test, and 3) Extended Operation Test.

Table 2.—Components of charging system.

Designation	Manufacturer & Model	Description
P1	Pfeiffer Duo 2.5A	Backing pump
P2	Pfeiffer TMU 064	Turbomolecular pump
V1	MDC KBFV-075	Butterfly valve
V2	MDC GV1500M	Gate valve
V3	Varian 9515106	Leak valve
V4	Swagelok SS-6BK	Bellows-sealed valve
V5	Swagelok SS-4H	Bellows-sealed valve
V6	Swagelok SS-4H	Bellows-sealed valve
V7	Swagelok SS-4H	Bellows-sealed valve
V8	Swagelok SS-4H	Bellows-sealed valve
V9	Swagelok SS-4H	Bellows-sealed valve
V10	Swagelok SS-4H	Bellows-sealed valve
V11	Varian 9515106	Leak valve
V12	Varian 9515106	Leak valve
C1	MDC 150-5	5-way, 2 ¾" conflat cross
C2	Swagelok SS-400-4	¼" crosses
G1	MKS/HPS 907	Pirani gauge
G2	MKS/HPS 903	Cold cathode gauge
RGA	Ametek/Dycor MA-200M	Quadrupole gas analyzer
Computer	Compaq Armada 1750	Laptop computer

III. Pre-Operation Tests

Prior to the start of extended operation of the convertors, tests and procedures were performed. A summary of these activities is presented in table 3. To accurately calculate efficiency of the convertors, the loss of heat through the heater head insulation had to be measured. A Thermal Insulation Loss Test was performed on both convertors. The method used at GRC called for a low pressure fill with argon, and heat added without the TDC's operating. All of the heat added was either transported from the hot end to the cold end, or was lost through the insulation. The heat transported from the hot end to the cold end was calculated. It was felt that this could be performed more accurately with the low pressure fill of argon with a known conductivity, rather than evacuating the TDC and having heat transported through radiation heat transfer between surfaces for which the optical properties were unknown.

To insure a clean fill of the working fluid throughout the test, the convertors underwent a vacuum bakeout. This was performed to eliminate all contaminants prior to the fill with ultra-pure helium. A vacuum was pulled through the fill lines by the gas charging system previously described. A preferred approach would have been to clean the TDC as it was produced, similar to practices used in Stirling cryocoolers, however these processes had not been developed at STC at the time that TDC's #13 and #14 were built. The vacuum was pulled through the fill lines, and a housing was assembled around the TDC's to keep them at the bakeout temperature. The bakeout lasted 500 hours at which time the pressure measured at the vacuum pump was 4×10^{-8} torr. The major constituent was water with a partial pressure of 1×10^{-8} torr. More detail on this procedure is provided later in this paper. Helium was then added and analyzed through the RGA to begin the test with a known working fluid.

A Full Power Verification Test was performed to document the convertors baseline performance. Data had been taken when the convertors were tested at STC, so this test performed the function of verifying that the TDC's were unaltered in any way during transportation to GRC and during the installation on the GRC test stand. The Full Power Verification Test showed data that were very close to what was reported by STC, with the differences attributed to the error in measurements, and the difference in the mounting configuration used. While at STC, the TDC's had only been tested as single units. At GRC, the test was performed with the convertors in the dual-opposed configuration. In the STC test, the convertors each operated at their own preferred frequency, while at GRC, the convertors operated at a single frequency which was the combination of the two resonant systems.

Table 3.—Pre-operation Schedule.

Activity Description	Date	Notes
Vacuum Bakeout	March 19–April 9, 2003	500 hours at 74 °C
Argon Low Pressure Fill	April 15, 2003	< 10 psig
Thermal Insulation Loss Test #1	April 16–18, 2003	
Evacuation of TDC's	April 18–21, 2003	
Helium Fill #1	April 22, 2003	
Proof Pressure Test of TDC#14	April 22, 2003	
Check out Run #1	April 23, 2003	Heater Wiring failure
Check out Run #2 – post repair #1	May 2, 2003	
Evacuation of TDC's	May 2–4, 2003	
Argon Low Pressure Fill #2	May 5, 2003	<10 psig
Thermal Insulation Loss Test #2	May 6–8, 2003	TDC #13 poor insulation wrap
Both TDC's rewrapped	May 12, 2003	Also replaced charred connectors
Thermal Insulation Loss Test #3	May 13–15, 2003	
Evacuation of TDC's	May 16–18, 2003	
Helium Fill #2 & Checkout Run #3	May 19, 2003	
Full Power Verification Test	May 20, 2003	
Full Power Test Runs	May 21–23, 27, 29–30, 2003	TDC's evacuated after 5/30/03 run
Helium Fill #3 of TDC's	June 2, 2003	TDC's evacuated for 60 hours prior to fill
Start of Extended Operation Test	June 3, 2003	Single shift operation only

A. Vacuum Bakeout

The purpose of the Vacuum Bakeout Procedure was to eliminate contaminants from within the TDC's, which may lead to reduced life. A photograph of the gas charging system and TDC's prior to bakeout is shown in figure 7, and a photograph of the bakeout housing is shown in figure 8. At this stage of the development, the gas charging system lacked leak valves, V11 and V12, and the cold cathode ionization total pressure gauge G2 that appear in figure. 5 and table 2. Instead, the RGA control unit recorded a total pressure reading along with each mass spectrum that was acquired. The RGA control unit had been calibrated using a total pressure gauge that was temporarily installed at the position of V3. This method of obtaining total pressure was not as accurate as using an independent total pressure gauge. Such a gauge has been installed in the current version of this system, however, it should be noted that even a gauge with higher accuracy was not able to assess the true pressure inside of the TDC's. The small diameter of the tubing, as well as the limited size of the port into the TDC, provides a very small conductance from the TDC to the RGA and the vacuum pump. Thus, the pressure within the TDC's was always significantly higher than the pressure recorded by the RGA or any gauge far removed from the source of the gas. In addition to this issue of the pressure difference between the TDC interior and the gauge location, there is also the issue of whether the RGA spectra are providing a true description of the molecular components of the gas within the TDC's.

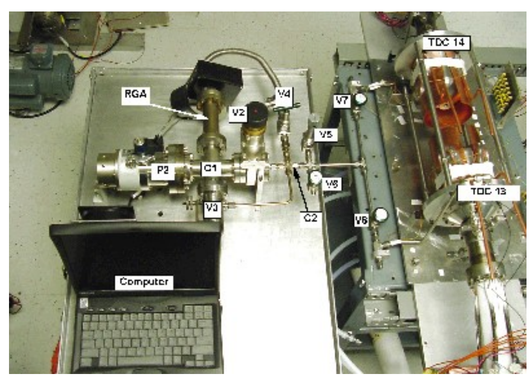

Figure 7.—Gas charging system with TDC's just prior to vacuum bakeout.

Molecules released by the TDC's at elevated temperature (from the organic components, for example) may condense on the interior surfaces of relatively cool tubing before they reach the RGA to be detected, and, thus appear in the mass spectrum. Thus the RGA spectra must be taken provisionally, with the understanding that gas phase molecules present within the TDC may go undetected by a distant RGA.

Prior to the bakeout, the total pressure was 1.03×10^{-5} Torr and H_2O was the major feature in the RGA spectrum. No air leak was observed in either the charging system or the TDC's. The values of the total pressure and partial pressures of water and isopropyl alcohol during the bakeout are shown in figure 9. Isopropyl alcohol was identified from a spectral feature at m/z = 45 and the cracking pattern from the National Institute of Standards and Technology database. This molecule was probably present due to its use as a solvent to clean the hardware of both the TDC's and the gas charging system. It desorbs from the interior surfaces of the system and possibly from porous organic material in the TDC's. After 500 hours of bakeout at 74 °C, the isopropyl alcohol disappeared and the water was reduced by an order of magnitude. After allowing the TDC's to cool to room temperature, the total pressure was 8.96×10^{-8} Torr, a reduction of two orders of magnitude relative to the value prior to bakeout. The dominant feature in the RGA spectrum was still H_2O, along with the CO (m/z = 28) and CO_2 (m/z = 44) usually found in mildly baked vacuum systems. No evidence for decomposition products of organic materials in the TDC's was ever observed.

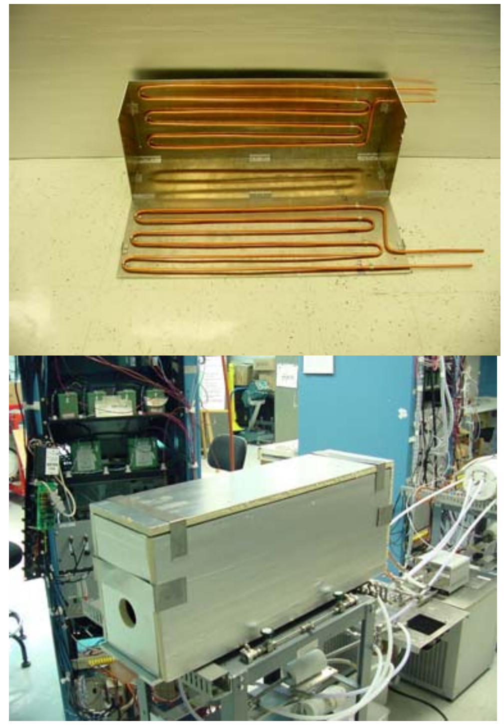

Figure 8.—Bakeout housing interior (above) and on test stand (below).

B. Thermal Insulation Loss Test

The purpose of this test was to characterize the thermal loss through the heater-head insulation over a range of temperatures. This was necessary to permit calculation of the net heat input from the measured gross heat input, to support efficiency calculations for future tests. The convertors were pressurized to an ambient charge pressure of 6.8 psig of argon. To perform this test, it was necessary to know the rate at which heat is conducted and/or radiated from the hot end to the cold end. The low-pressure argon fill was chosen over a commonly used method of evacuating the Stirling convertor for two reasons. First, it was felt that the capability to determine the temperatures of the internal components with the low-pressure fill of argon would be more accurate than with the TDC's evacuated, and radiation heat transfer being used to couple the uncharacterized surfaces. Secondly, it would be difficult to determine the true pressure inside of the internal components, such as the displacer, when a vacuum is pulled through a fill tube and the tortuous internal paths. Argon was selected as the fill gas due to the relatively low conductivity of which would minimize the error associated with calculating the conduction of heat through the gas itself. The range of cold-end temperatures used for this test was from 60 °C to 100 °C, at four different levels of gross heat input of 55 W, 65 W, 75 W and 85 W. The pressure vessel temperature was maintained 45 °C. Some of the heat lost was due to conduction from the hot end to the cold end. This conduction loss was calculated separately.

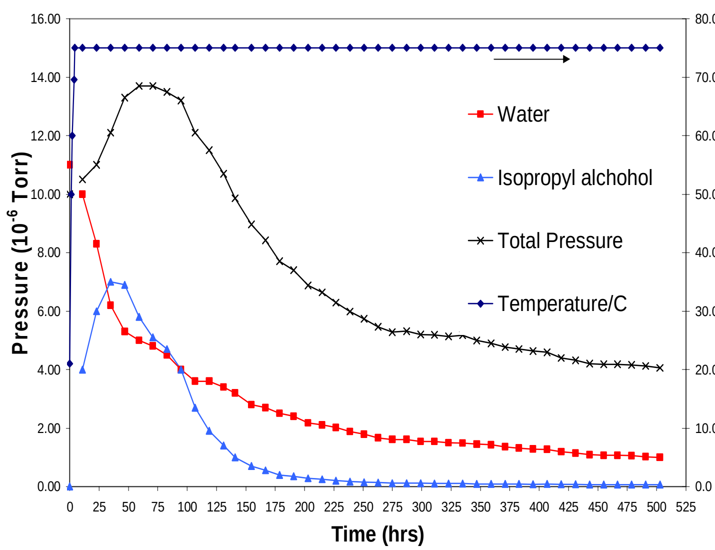

Figure 9.—Partial pressures, total pressure, and temperature during bakeout.

The remaining heat was lost through the insulation to ambient. The insulation loss was characterized as a function of the hot-end and cold-end temperatures, and used in the data system to calculate net heat input.

C. Full Power Verification Test

The purpose of this test was to measure the steady-state performance of convertors #13 and #14 configured as a dual-opposed pair, operating at the nominal design operating conditions of 650 °C hot end, 80 °C cold end and 45 °C pressure vessel temperature, and to compare the GRC data to that taken by STC. The LDAS was configured specifically for TDC's #13 and #14 and was used to acquire and record the data. The STC zener diode controller was used as the controller for this test. The GRC-developed Variable Stroke Control Module was used to vary the amplitude of the piston below the amplitude allowed by the STC fixed zener diode controller. The FPC was connected as a safety load. This test was conducted on May 20, 2003. A summary of the performance is shown in Table 4. The efficiency calculation made use of the results of the Thermal Insulation Loss Test.

Table 4.—Full Power Test Data.

	STC Data		GRC Data	
	TDC #13	**TDC #14**	**TDC #13**	**TDC #14**
Test Configuration	Single	Single	Paired	Paired
Average Hot End Temperature (°C)	647	647	649	650
Average Coolant Temperature (°C)	77.4	77.1	72	72.8
Average Alternator Temperature (°C)	44.6	44.0	45.0	45.4
SCA Heat Input (Watts)	245	255	250	262
AC Power Out (Watts)	68.8	70.5	69.0	70.5
AC RMS Voltage (Volts)	84.5	85.5	85.5	85.7
AC RMS Current (Amperes)	0.92	0.93	0.91	0.92
Piston Amplitude (mm)	5.46	5.94	5.53	5.22
Mean Pressure (MPa)	2.52	2.53	2.52	2.53
Efficiency (%)	28.1	27.6	27.6	26.9

IV. Extended Operation Test

Extended Operation of TDC's #13 and #14 began on June 3, 2003. Operation at this time was limited to single shift operation during work hours. Before unattended operation could be initiated, modifications were necessary to the test stand to meet the requirements of the GRC Safety Office. These included installation of a burst disk in the helium fill line and installation of a security cage around the test area. Unattended operation was initiated on June 23, 2003 following receipt of the Safety Permit. A schedule of events is outlined in table 5. Through the majority of this test, the convertors were operated at the nominal conditions of 650 °C hot-end temperature, 80 °C cold-end temperature, and 45 °C pressure vessel temperature. On December 9–10, 2003, at the request of LM, the operating conditions of the TDC's were varied to evaluate performance of the convertors at BOM and End of Mission conditions.

The convertors were returned to nominal operating conditions on December 10, 2003. Testing was stopped several times at the beginning of the test due to electrical noise in the FPC. These issues were resolved on July 18, 2003. The first significant shutdown occurred on August 14, 2003 due to the power failure of the US power grid servicing the Cleveland area. Operation resumed August 18, 2003. A second shutdown occurred October 15–31, 2003 at which time a test was performed to characterize the permeation of gasses through the TDC o-rings. This test is described in detail later in this paper. A 17 minute shutdown occurred on February 24, 2004 due to a coolant low temperature trip caused by the addition of coolant to the circulator used to maintain the cold-end temperature. The Extended Operation Test continues and has accumulated 8870 hours as of August 9, 2004. The measured performance of the convertors and changes made to the system are detailed in the following sections.

Table 5.—Extended Operation Schedule.

Activity	Date	Notes
Start of Extended Operation Test	June 3–20, 2003	Single shift operation only
Start of Unattended Operation	June 23, 2003	
Heater wiring failure #2	June 24, 2003	
Reduced power operation	June 25–July 1, 2003	Operated at reduced power due to wiring
Test shutdown #1	July 2–14, 2003	Heater wiring replaced
Extended Operation resumed	July 14, 2003	Operation resumed at 3:00 p.m.
Test shutdown #2	August 14–18, 2003	Utility grid failure
Extended Operation resumed	August 18, 2003	Operation resumed at 9:00 a.m.
Test shutdown #3	October 7, 2003	Loose thermocouple wire
Extended Operation resumed	October 7, 2003	Operation resumed at 3:00 p.m.
Permeation Test Part I	October 15–31, 2003	TDC's not operating during this part of test
Operation resumed	October 31, 2003	Temporary operation
Permeation Test Part II	November 3–4, 2003	TDC's operational, but at very low power
Extended Operation resumed	November 5, 2003	Operation resumed at 9:00 a.m.
Initiated argon purge	November 24, 2003	Over heater head and pressure vessel o-rings
Test shutdown #4	November 24, 2004	Nuisance trip, TDC's stopped for 17 minutes
Extended Operation resumed	November 24, 2003	Operation resumed at 4:22 p.m.
EOM and BOM tests	December 9–10, 2003	TDC's operational, not at nominal conditions
Return to nominal conditions	December 10, 2003	5:20 p.m.
Test shutdown #5	February 24, 2004	Coolant temperature trip, 17 minute shutdown
Extended Operation resumed	February 24, 2004	Operation resumed at 8:32 a.m.
Initiated partial helium purge	March 31, 2004	Changed to helium purge on heater head o-rings
Initiated Complete Helium Purge	April 27, 2004	Changed to helium purge on all o-rings
Test shutdown #6	June 9, 2004	Facility electric power lost from local substation
Extended Operation resumed	June 14, 2004	Operation resumed at 9:01 a.m.
Test shutdown #7	June 23, 2004	Nuisance trip, TDC's stopped for 6 hr, 17 minutes
Replace control potentiometer	June 24, 2004	Stopped for 39 minutes to replace pot on controller
Set point adjustment	July 7, 2004	Adjusted set point to track earlier operation
Shutdown #8	July 28, 2004	Lost facility power, stopped for 3 hours, 35 minutes

D. Test Procedure

After the convertors were brought to full power operation, the LDAS was switched to the Unattended Mode and the convertors were left to operate. The LDAS was set-up to record a five-minute average of all the measured performance parameters once each hour. Data were retrieved from the LDAS on a weekly basis. A spreadsheet was developed to report a single data point (around mid-day) each day for the duration of the test. The operational run time, helium top off and system changes were also reported. During the first weeks of the test, it was noted that the TDC's lost about 15 kPa (2.2 psi) of helium pressure each week. The gas charging system was used to increase pressurize (top-off) of the TDC's to their nominal operating pressure of 2.5 MPa (about 365 psi). To top-off the pressure, valve V2 was closed, valve V5 was opened to pressurize the chamber C2 to 2.55 MPa (about 370 psi) and then valve V7 and valve V9 (or valve V8 and valve V10 for TDC #14) were opened to increase the TDC's pressure to 2.5 MPa (about 365 psi). A weekly top-off schedule was initiated. The gas charging system was also used for impurity analysis of the helium working fluid in the TDC's. For this procedure, gas analysis, valve V2 was open and the base pressure in chambers C1 and C2 was evacuated to less than 2×10^{-8} torr. Either valve V11 or valve V12 was opened to establish a dynamic pressure in chambers C1 and C2, such that the partial pressure of helium from a convertor was 3×10^{-5} torr. This was revised to 2×10^{-5} torr after May 7, 2004 to improve accuracy and reduce scatter in the data. A mass spectrum of the working fluid sample was then acquired by the RGA. The concentration of impurities in the gas from a TDC was obtained from the ratio of the intensity of the impurity spectral feature to the helium spectral feature after accounting for the relative sensitivity of the RGA for the particular impurity molecules.

Performance of the convertors was visually checked by test operators at least once each day. Any changes in the operating conditions were reported to the Project Manager and/or the Lead Test Engineer. The overall performance of the convertors was evaluated initially on a weekly basis and reported to LM. This was later changed to reporting on a bi-weekly basis.

E. Extended Operation

Following the initiation of unattended operation, on June 23, 2003, an automatic hard-wired shutdown was triggered by an over-temperature reading in a thermocouple on the TDC #13 heater. The shutdown was discovered on the morning of June 25th. Since the shutdown was triggered by hardware (a meter-relay) and not by software, it was not possible to determine the exact time of the shutdown. A review of the LDAS data indicated that it occurred sometime between 4 p.m. and 5 p.m. on June 24, 2003. The TDC's were restarted on June 25th and returned to the Unattended Operation mode. Analysis of the data revealed an anomaly with the electric heater of TDC #13. Hot-end temperature measurements, and heater voltage and current measurements indicated the possible failure of one of the cartridge heaters, or possibly a wiring failure. Operation was resumed at reduced power while a process was developed for investigating the anomaly. On July 2, 2004, the convertors were shutdown at 8 a.m. to allow for the investigation. The insulation was removed and a failed electrical connection was found on one of the terminals of heater cartridge D. This can be seen in figure 10. Other connections were found that appeared to be suspect. Following discussions with LM, a decision was made to replace all of the heater cartridge electrical connections and to reroute the thermocouples to improve accuracy of the temperature measurement. This effort was performed by technicians from the GRC instrumentation shop.

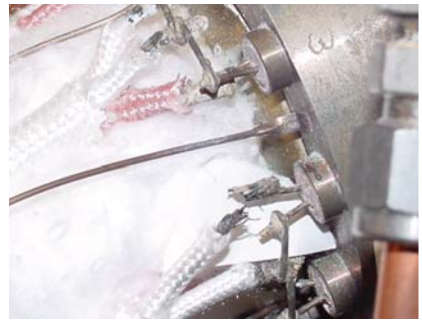

Figure 10.—Broken electrical connection to cartridge heater.

All of the terminals were cleaned and prepped for the new high-temperature nickel wire. Four strands of 24awg Type N thermocouple wire (negative leg) were used as the new wire. This wire was selected because it is 96% nickel. BAg 13 silver braze was then used to secure the connections. The new wiring was completed on July 12, 2003 and is shown in figure 11. The TDC's were brought back into operation on July 14, 2003. The new routing of the thermocouple wires resulted in more uniform temperature readings around the circumference of the heater.

The TDC's remained in continuous operation from July 18 to August 14, 2003, at which time the failure of the power grid servicing the Cleveland area forced a shutdown at 4:24 p.m. GRC remained closed until August 18, 2003. The TDC's were restarted and unattended operation was resumed at 9:41 a.m. on August 18.

An over-temperature shutdown was triggered by a faulty thermocouple wire connection on October 7, 2003. The connection was repaired and operation resumed at 3:00 p.m. that same day. Total down time was 5.6 hours.

Figure 11.—TDC#14 new heater wires attached.

F. Analysis

During the test, data have been continuously recorded for analysis. This includes analysis of the working fluid, and performance of the TDC's. A discussion of some of these data will be presented.

1. Impurity Analysis

The concentration of impurities in the TDC #13 working fluid with run time is shown in figure 12. The results for TDC #14 are entirely similar and are not shown here. Water, carbon dioxide, nitrogen and argon were detected initially. The concentration of carbon dioxide and water remained small and did not increase with time. The initial concentration of argon was attributed to its remaining from the thermal loss test that was previously conducted with argon as the fill gas. Oxygen was never observed as an impurity in the helium working fluid. An increase in the concentration of both argon and nitrogen was observed in the first 2000 hours of operation. The increase in nitrogen and argon was suspected to be due to permeation of air (argon 1% of air) through the rubber o-rings. Oxygen would also permeate into the TDC's, but its absence in the analyzed helium working fluid was believed to be due to its consumption by the TDC's' hot oxydizable internal components. Helium permeation out through the o-rings was thought to account for the loss of helium pressure and the necessity of topping-off process. The outward permeation of helium was confirmed with a helium leak detector and a soap bubble check at the o-rings. To further test this permeation hypothesis, at 2801 hours, the external surfaces of the o-rings were purged with argon to exclude the presence of air. The argon concentration immediately increased more rapidly than before and the nitrogen concentration leveled off, consistent with the replacement of air permeating through with argon. There is thus evidence that the major impurities detected in the helium working fluid were due to permeation through the o-rings. After the concentration of argon had increased to approximately 1000 ppm, the heater head o-ring purge gas was changed from argon to helium at 5837 hours. Although the argon concentration no longer increased, the data became erratic for some unknown reason and it was decided to purge both the heater head o-rings and the pressure vessel o-rings with helium at 6520 hours. Also, at 6847 hours the sampling pressure in the charging system was reduced to 2×10^{-5} torr from 3×10^{-5} torr in an attempt to achieve more stable data. However, even with this scatter in the data, the rapid increase in argon concentration had definitely been halted by the helium purge on the o-rings.

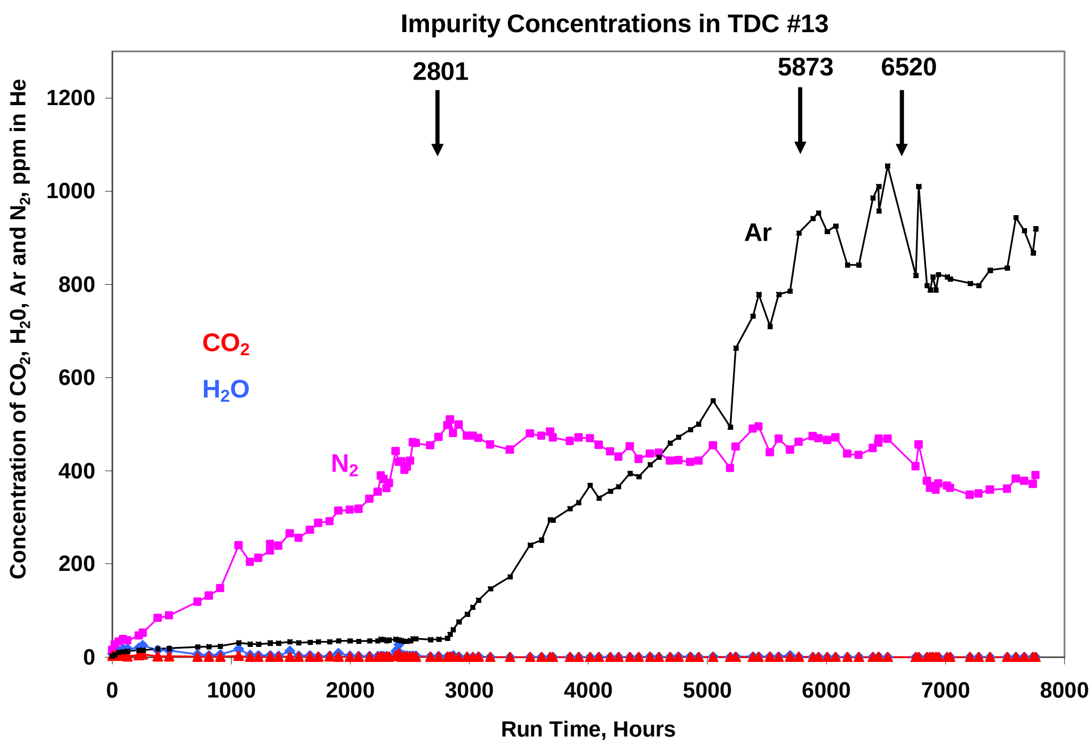

Figure 12.—Concentration of working fluid of TDC #13 during Extended Operation Test.

By this time, a slight degradation in performance of the TDC's had been noted. This will be discussed in a later section of this paper. Gas samples were also showing a steady increase in nitrogen, as shown in figure 12. Air appeared to be entering the TDC's, although no increase in oxygen was observed. Possible points of entry into the TDC's were examined. Helium was detected using both a helium detector and liquid soap at the pressure vessel and heater head flanges. These flanges use Buna-N o-rings to make their seal.

It should be noted that the issue of permeation of atmosphere into the Stirling convertors will not exist in the flight units since the flanges will not contain o-rings to seal the working fluid, rather, they will incorporate hermetic weld seals that eliminate the potential for permeation. This technique has proven successful on virtually all flight cryocoolers.

2. Permeation Tests

Following about 2000 hours of operation, it had been noted that nitrogen was increasing linearly with time and argon appeared to be reaching an asymptote. This was thought to be consistent with an external, unlimited source of nitrogen, and an internal, limited source of argon. A helium leak detector showed that the presence of helium around the two heater head flanges was about equal, and the presence of helium around the two pressure vessel flanges was about equal. The higher temperature heater head o-ring flanges showed more helium than the lower temperature pressure vessel o-ring flanges. This information, along with the observation that both TDC's lost working fluid at the same rate of about 15 kPa (2.2 psi) per week suggested that there was gas was permeating through the o-rings in both directions; outside air permeating inward and helium permeating outward. Calculations based on the partial pressures of helium and nitrogen showed that this was plausible. There was no immediate concern with the amount of nitrogen that had accumulated in the working fluid, rather the lack of oxygen with suggested that the high temperature internal components were oxidizing. Of primary concern were the fibers of the stainless steel regenerator which are not of sufficient thickness to form a protective barrier. Test Plan 55–036 was devised to characterize the phenomenon with three steps.

The TDC's were shut down following 2336 hours of operation. Temperatures were controlled to keep the o-ring flanges at the same temperature as during full-power operation, however the 650 °C heater head temperature was reduced to 80 °C. The TDC's remained at temperature, not operating, and regular gas analysis continued. If permeation were to continue, the gas analysis would now show oxygen since the internal components were not at sufficiently high temperature to oxidize. After nine days at this condition, the nitrogen and argon concentrations remained as before, and no oxygen was detected. The TDC's were then motored to create the internal pressure wave similar to what would occur during full power operation. The heater temperature controller was set to the same temperature as the cold-end of the Stirling so that the heater head was not cooled to low temperatures. With motoring, the pressure wave is nearly the same amplitude as during full power operation, however it is phased as a gas spring would be, rather than being phased by the heating and cooling to produce power. This was performed to determine if the dynamic pressure had some influence on the permeation of gas through the o-rings. Following seven days of motoring, there was once again no change in nitrogen and argon, and no evidence of oxygen. At this point, the only difference between the motored condition and operation at full power was the temperature of the hot end. An attempt was made to have non-operation, with the convertors at the full-power temperatures. The terminals of the alternator were shorted to apply maximum load, and the heater head temperature was increased. As the temperature rose, the piston and displacers began to oscillate at small amplitude. It was found that full temperature could not be achieved without excessive current through the alternator coils, and therefore this part of the test was terminated.

3. Performance Analysis

Data were recorded throughout the test by the LDAS, and analyzed on a regular basis; either weekly or biweekly. Since the most basic objective of the test was to demonstrate long-term operation of the TDC's with no degradation, the data were analyzed to detect any trends that may exist. In the SRG110, the GPHS module will produce heat at a constant rate regardless of temperature. In the test at GRC, the electric heaters used to simulate the radioisotope heat source were controlled to a constant temperature with the gross heat input allowed to vary slightly. With this test configuration, analysis of the data could look at changes in efficiency of each convertor, or the ability to convert the heat supplied into electrical AC power output. Similarly, a change in power output without a change in efficiency would indicate a change in the throughput capability of a convertor. Other parameters, such as vibratory emissions, working fluid composition, and output voltage, were measured in an attempt to detect any changes that may occur.

At the beginning of the Extended Operation Test, the power output from TDC #13 was 66.6 Wac, and for TDC #14 it was 67.7 Wac. The efficiency of TDC #13 was 27.0% from net heat in to AC electric power out, and 26.4% for TDC #14. Due to the slow permeation of helium through the o-rings, the mean operating pressure of each TDC would be decrease by approximately 15 kPa (2.2 psi) each week. The reduction in mean operating pressure would reduce the power output in the recorded data; however, this was not an indication of true degradation, or aging in the TDC. Following the pressure top-off procedure each week, the performance would return to nominal. To eliminate the weekly performance variation due to the change in mean pressure, a correction factor was devised and applied to the data. This was a linear correction proportional to the difference between the measured mean pressure and the design mean pressure. The detailed performance plots show the "Measured" performance and the "Empirically Corrected" data. A correction factor based on first principles contained in the West number[4] was also used and yielded similar results.

A high-level summary of the power output and efficiency is shown in figure 13. These graphs show nearly no change in the power output and efficiency over time. The ordinates of the graphs were expanded in figure 14 to accentuate any variations that may have existed. As can be seen, there was some net reduction in both power output and efficiency during the test. A more detailed examination of the graphs shows that the rates of change seem to fall into three distinct time periods. These three periods correspond the to the three configurations of purge gas used to cover the o-ring flanges of the TDC's.

During the first segment of the test, when there was no purge gas covering the o-ring flanges, the rate of degradation was at its maximum. This was from the beginning of the test through 2807 hours of operation. During this time period, argon content in the working fluid was increasing somewhat, however the concentration of nitrogen was increasing more quickly. If the concentration scale were to be modified, it would show that the argon concentration was asymptotically approaching a final value. It was speculated that the source of argon was the trapped volumes in the TDC's that were able to hold gas throughout the bakeout. The trapped volume in each TDC was estimated to be approximately 1.6 cubic centimeters (0.1 cubic inches). The concentration of argon measured in the working fluid was consistent with theory that argon was trapped during the Thermal Insulation Loss Test and was now slowly being released. Since the argon source was finite, the concentration was moving toward the asymptote. The nitrogen level appeared to be increasing linearly with time. This was believed to be the permeation of air into the working fluid. Oxygen was never detected and was likely consumed by the hot section of the regenerator as it entered the working fluid, thus degrading the performance of the TDC not only by the undesirable characteristics of the relatively heavy molecular weight of the working fluid, but also by altering the physical characteristics of the regenerator matrix through oxidation. During this time period, the rate of power loss in TDC's #13 and #14 was 0.5 W per 1000 hours, and 0.4 W per 1000 hours respectively. The efficiency rate of change for TDC's #13 and #14 were 0.10 percentage points per 1000 hours and 0.05 percentage points per 1000 hours respectively.

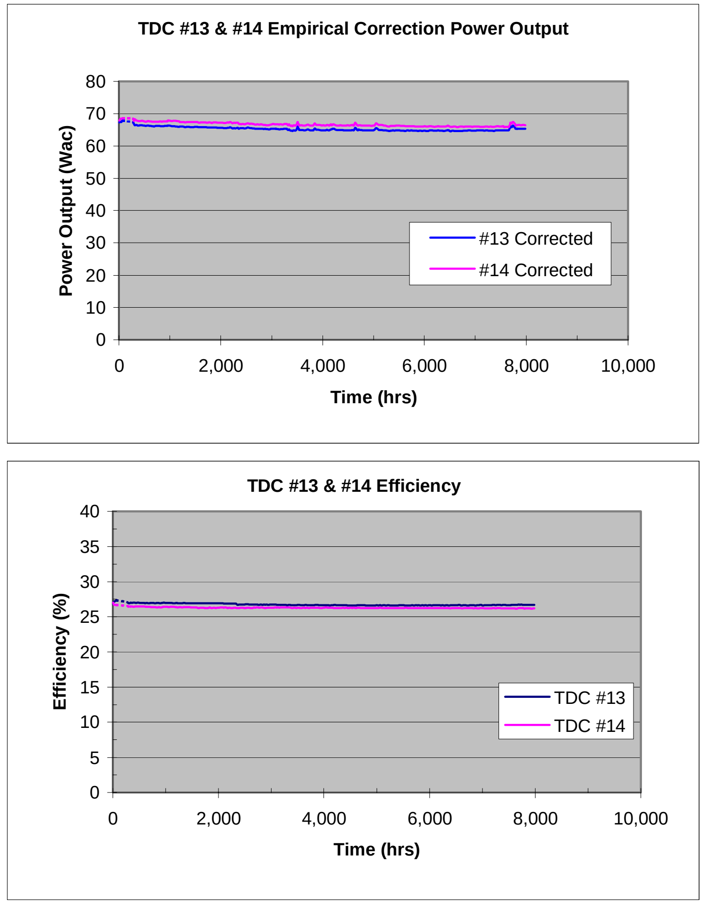

Figure 13.—Overall power and efficiency for TDC #13 and #14.

At 2807 hours of operation, purge rings were installed on the two flanges of each TDC that contained o-ring seals. The purge rings are shown in figure 15. Argon was supplied to each purge ring at a rate of 40 cc/minute to blanket the exterior surface of the flange with an inert gas. A preferred approach would have been to install a ring that would have allowed a vacuum to be pulled around the flanges to remove any exterior environment, however, since the rings were being installed on operational TDC's, an adequate seal could not be achieved. With the argon purge in place, if the source of nitrogen accumulating in the helium working fluid was the ambient air permeating inward, then the working fluid composition would immediately show an increased level of argon, and either a leveled or diminishing concentration of nitrogen. After the purge was initiated, the working fluid composition immediately showed increasing levels of argon and constant levels of nitrogen. During this time, the power output for TDC's #13 and #14 both changed at a rate of 0.1 W per 1000 hours of operation. The efficiency changed 0.02 percentage points per 1000 hours for both TDC #13 and #14. As can be seen in figure 14, the rate of degradation was significantly reduces. The rate of change in performance was believed to be due to the increasing level of argon in the working fluid. Analysis was performed with the Sage™ thermodynamic code to investigate this theory. The performance degradation predicted by Sage was less than that observed in the hardware, however the Sage analysis only considered the impact on the thermodynamic cycle, and not the impact on the dynamics of the moving components.

At 5873 hours of operation, the purge gas used on the heater head o-ring flanges was changed to helium with the pressure vessel o-ring flanges remaining under an argon purge. At 6520 hours of operation the purge gas on all

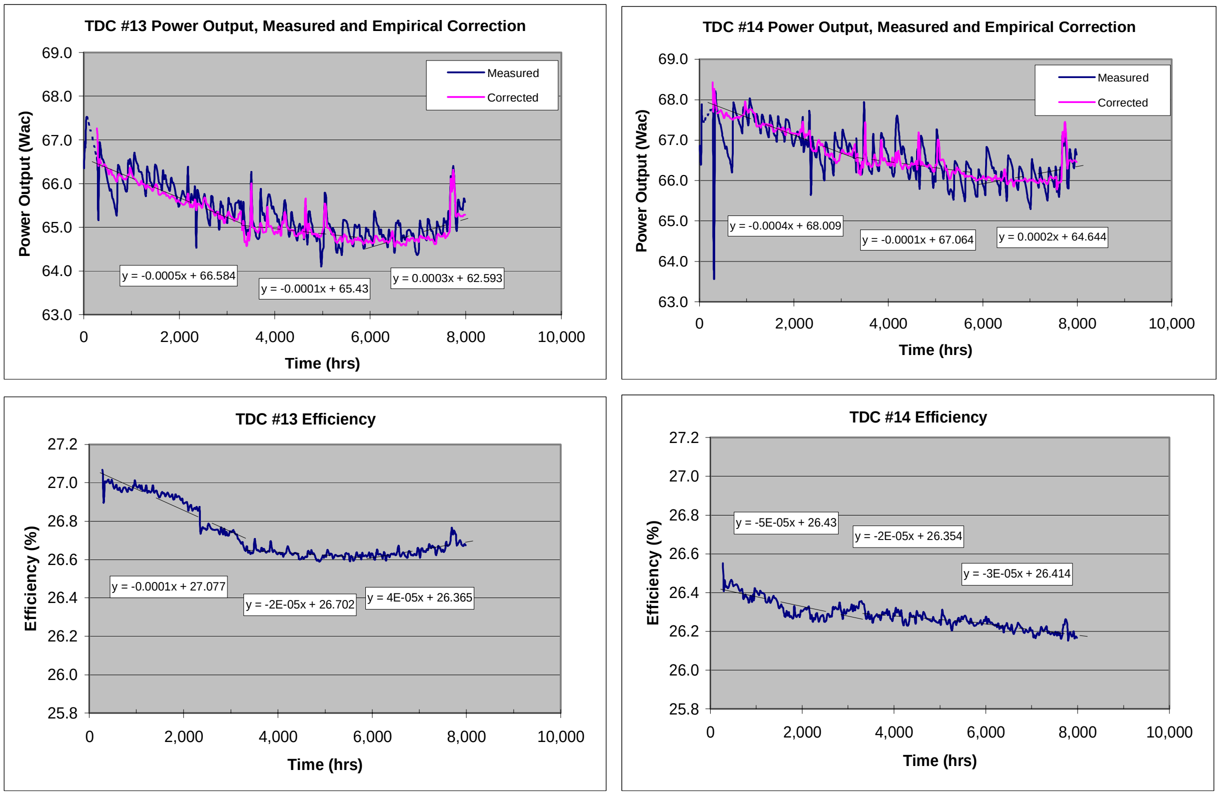

Figure 14.—Performance of TDC's #13 and #14 over 8000 hours of testing.

o-rings was changed to helium. The two-step process was intended to give an indication about the relative permeation of the two o-ring locations. As can be seen in figure 14, the initial results indicate that the performance has been improving since the helium purge was initiated. Curve fits of the data from 5873 hours indicate 0.3 Wac per 1000 hour power improvement for TDC #13, and 0.2 Wac power improvement for TDC #14. Efficiency of TDC #13 is improving at the rate of 0.04 percentage points per 1000 hours; however, the efficiency of TDC #14 continues to lose efficiency at the rate of 0.03 percentage points per 1000 hours.

The continued loss in efficiency for TDC #14 continues to be under investigation. The loss in efficiency is 5×10^{-2} percentage points in efficiency per 1000 hours of operation, and is lessening as the test continues. The likely cause of the minor change in efficiency is the temperature distribution of the heater conduction block. The heater conduction block has 10 cartridge heaters surrounding the TDC heater head. There are five type-K thermocouples evenly spaced around the conduction block used to measure the temperature. These thermocouples are installed into thermal wells. Early in the test, the variation in temperature around the block was less than 5 °C. By the 8000 hour point, the temperature variation around the heater block was slightly over 9 °C. This temperature variation has the ability to reduce efficiency since there would be a slightly different Stirling cycle operating on one side of the heater head compared to a point that is diametrically opposed. The mixing losses in the expansion space could likely account for the slow change in efficiency. Also, since the hot-end temperature is set by limiting the

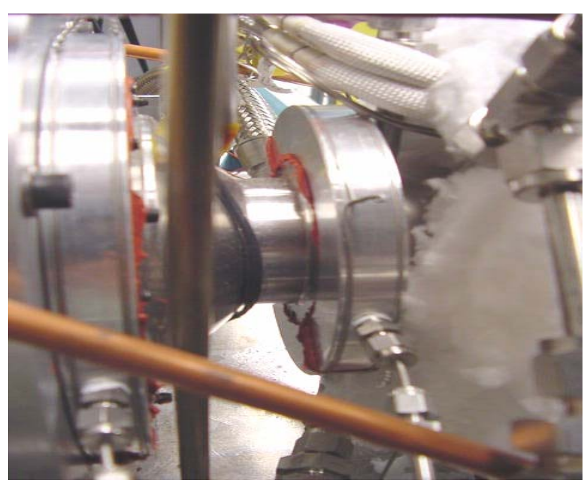

Figure 15.—Purge rings installed over the o-ring flanges of TDC #13.

hottest temperature measured to 650 °C, the average temperature is slowly reducing with time. This would also result in reduced efficiency. It is important to note that both of the effects of the heater temperature distribution are the result of ground test apparatus and a change in the operating point, and not an indication of the Stirling convertor degrading.

In addition to tracking the thermodynamic performance, other parameters have been measured to try to uncover any possible changes in the operating characteristics during the extended test. A tri-axial accelerometer was attached to the mounting flange to measure the vibratory emissions. These could result from the inherent mismatch of the TDC's due to manufacturing tolerances. TDC's #13 and #14 were fabricated by STC to the same specifications, and under the same Quality Assurance system, however there was no attempt to match the units dynamically during fabrication to minimize the residual vibration. Figure 16 shows a graphical summary of the measured signature, including the first three harmonics. As can be seen, the signature appears to have not changed over time, and therefore, the synchronization for dynamic balancing and the tuning of the resonant spring-mass system appears to remains constant.

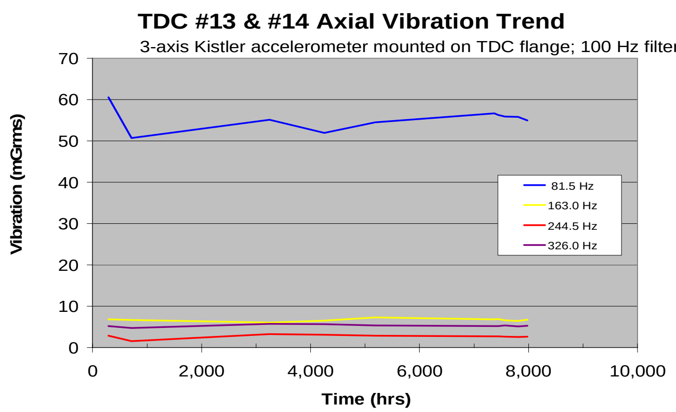

Figure 16.—Measured vibratory emissions including harmonics.

V. Conclusion

An Extended Operation Test with a pair of TDC's in the dual-opposed configuration is currently underway at NASA GRC. Test Plans, Procedures, and some of the supporting hardware were developed specifically for this long-term test. The convertors have accumulated over 8800 hours of operation. Although performance has changed slightly during the test, there appear to be rational explanations for this change. It is important to note that the root cause of the change in performance, being the apparent ingress of air into the convertor, will not be present in a space application. Corrective measures were employed during the test, and the data now appears to be nearly constant.

References

[1]Cockfield, R.D. and Chan, T.S., "Stirling Radioisotope Generator for Mars Surface and Deep Space Missions," Proceedings of the 37th Intersociety Energy Conversion Engineering Conference, Washington, D.C., IECEC 2002 Paper No. 20188, 2002.LM.

[2]Schreiber, J.G., Skupinski, R.C., "Accomplishments of Free-Piston Stirling Tests at NASA GRC" in proceedings of Space Technology and Applications International Forum (STAIF 2002), edited by M. El-Genk, sponsored by the American Institute of Physics, Albuquerque, NM, 2002.

[3]Qiu, S., Augenblick, J.E., White, M.A., Peterson, A.A., Redinger, D.L., and Petersen, S.L., "Developing a Free-Piston Stirling Convertor for Advanced Radioisotope Space Power Systems," in proceedings of Space Technology and Applications International Forum (STAIF 2002), edited by M. El-Genk, AIP Conference Proceedings 608, Melville, New York, 2002, pp. 912-917.STC.

[4]West, C. D., *Principles and Applications of Stirling Engines*, Van Nostrand Reinhold, New York, 1986, Chapter 6, pp. 117.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
November 2004

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Extended Operation of Stirling Convertors

5. FUNDING NUMBERS
WBS–22–972–20–01

6. AUTHOR(S)
Mary Ellen Roth, Jeffrey G. Schreiber, and Stephen V. Pepper

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–14896

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—2004-213388
AIAA–2004–5508

11. SUPPLEMENTARY NOTES
Prepared for the Second International Energy Conversion Engineering Conference sponsored by the American Institute of Aeronautics and Astronautics, Providence, Rhode Island, August 16–19, 2004. Responsible person, Mary Ellen Roth, organization code RPT0, 216–433–6288.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 20 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***
A high-efficiency 110 W Stirling Radioisotope Generator 110 (SRG110) is being developed for potential NASA exploration missions. The SRG system efficiency is greater than 20%, making it an attractive candidate power system for deep space missions and unmanned rovers. The Department of Energy SRG110 Project team consists of the System Integrator, Lockheed Martin (LM), Stirling Technology Company (STC), and NASA Glenn Research Center (GRC). One of the GRC roles is to provide Independent Verification and Validation of the Stirling TDC's. At the request of LM, a part of this effort includes the Extended Operation of the TDC's in the dynamically balanced dual-opposed configuration. Performance data of Stirling Convertors over time is required to demonstrate that an SRG110 can meet long-duration mission requirements. A test plan and test system were developed to evaluate TDC's #13 and #14 steady-state performance for a minimum of 5000 hours. Hardware, software and TDC preparation processes were developed to support this test and insure safe, round-the-clock operation of the TDC's. This paper will discuss the design and development, and status of the Extended Operation Test.

14. SUBJECT TERMS
Closed cycles; Stirling engines

15. NUMBER OF PAGES
22

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	