Oral Presentation/Viewgraph Summary:

The U.S. Department of Energy (DOE), Lockheed Martin Space Company (LMSC), Sunpower Inc., and NASA Glenn Research Center (GRC) have been developing an Advanced Stirling Radioisotope Generator (ASRG) for use as a power system on space science missions. This generator will make use of free-piston Stirling convertors to achieve higher conversion efficiency than currently available alternatives. NASA GRC's support of ASRG development includes extended operation testing of Advanced Stirling Convertors (ASCs) developed by Sunpower Inc. In the past year, NASA GRC has been building a test facility to support extended operation of a pair of engineering level ASCs. Operation of the convertors in the test facility provides convertor performance data over an extended period of time. Mechanical support hardware, data acquisition software, and an instrumentation rack were developed to prepare the pair of convertors for continuous extended operation. Short-term tests were performed to gather baseline performance data before extended operation was initiated. These tests included workmanship vibration, insulation thermal loss characterization, low-temperature checkout, and full-power operation. Hardware and software features are implemented to ensure reliability of support systems. This paper discusses the mechanical support hardware, instrumentation rack, data acquisition software, short-term tests, and safety features designed to support continuous unattended operation of a pair of ASCs.

International Energy Conversion Engineering Conference

Test Rack Development for Extended Operation of Advanced Stirling Convertors at NASA Glenn Research Center

10:30 A.M.

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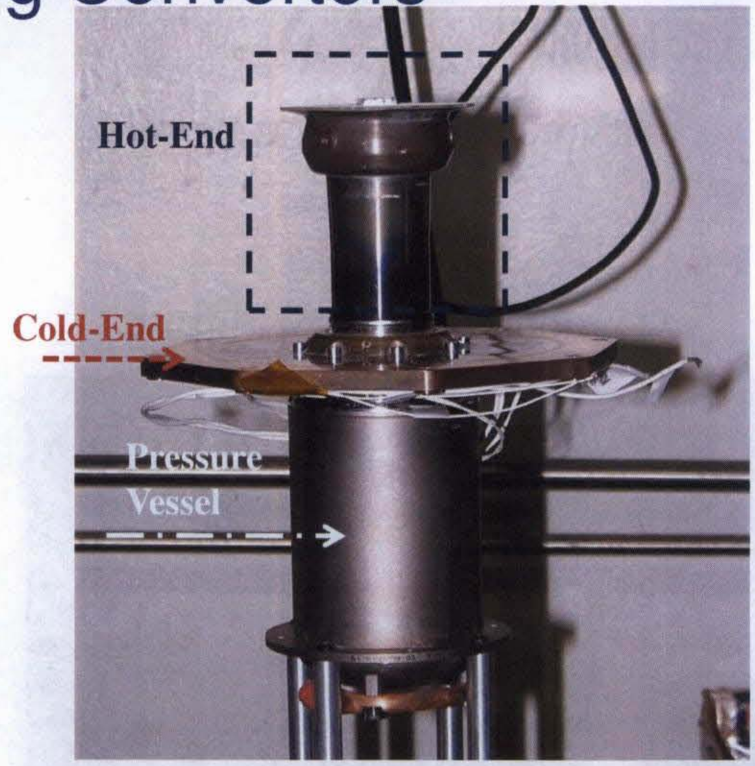
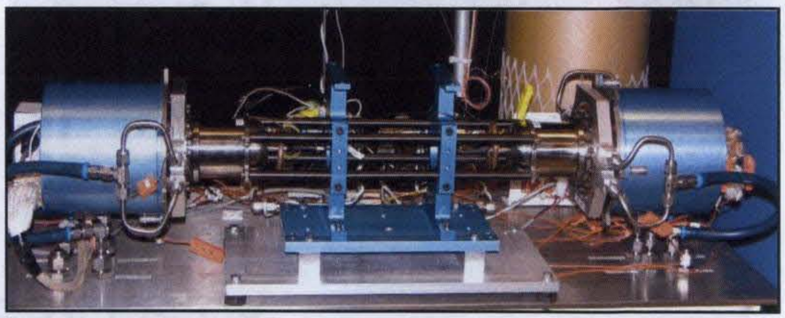
Outline

- Background
  - Stirling convertors & test racks
- Standard Advanced Stirling Convertor (ASC)Test Rack
  - Data acquisition, control systems, measurement & interface
- Advanced Stirling Radioisotope Generator- Engineering Unit (ASRG-EU) Test Rack
  - Data acquisition, control systems, & measurement
- ASC-E2 (second level engineering design convertor) Test Rack
  - Measurement & documentation
- Safety
  - Data acquisition & circuitry
- Conclusion

Background – Stirling Convertors

- The ASC consists of a free-piston Stirling engine integrated with a linear alternator.
  - ASC-0 and ASC-1 convertors: 25 V, 3 A
  - ASC-E and ASC-E2 convertors: 11 V, 8 A
- Extended operation of convertors since 2003.
  - Continuous, unattended operation over thousands of hours
- Hot-end: 650-850 °C
- Cold-end: 60-90 °C
- Frequency: 102.2-104 Hz
- Power: 160 W
- Piston Amplitude: 4.25-4.5 mm





Dual-Opposed Operation

Background – Test Rack

- Test rack provides:
  - Measurement
  - Data collection
  - Stirling convertor control
    - Cold-end temperature
    - Hot-end temperature
    - Piston amplitude (output voltage)
  - Safe operation
- Test rack allows adjustment of:
  - Hot-end and cold-end temperatures
  - Piston amplitude
- Measurements:
  - Alternator voltage, current, and power
  - Operating frequency
  - Piston Amplitude
  - Hot-end and rejection temperatures

Test Rack

Stirling Research Laboratory

Background: Test Racks

- Test racks differ primarily in:
  - Instrumentation used to accomplish measurements.
  - Implementation of safe operation
  - Means to control the convertor, hot-end and rejection temperature.
- Three test rack designs:
  - Standard ASC
    - AC bus control
    - Constant temperature control
  - ASRG-EU
    - AC bus or ASC control unit (ACU) control
    - Constant temperature or fixed heat input control
  - ASC-E2
    - AC bus control
    - Designed to improve quality of the test rack

Standard ASC Test Rack: Data Acquisition

- National Instruments's LabVIEW-based data acquisition (DAQ) hardware and software.
- The DAQ software, which was developed to operate in unattended mode, can control the support systems without user intervention.
- Provides safety to the convertors.

Standard ASC Test Rack: Data Acquisition

- Displays and records data on a computer
  - Heater voltage and current
  - Heat-source temperature
  - Hot-end temperature
  - Cold-end temperature
  - Cold-end coolant inlet and outlet temperatures
  - Ambient temperature
  - Cold-end coolant flow rates
  - Pressure vessel temperature
  - Alternator root mean square (RMS) voltage, RMS current, and power
  - Piston amplitudes
  - Operating frequency
  - AC bus controller voltage and current

Standard ASC Test Rack: Data Acquisition

- Collects and saves data in various time frames
  - Maintains a buffer of data recorded over the last 24 hours at a 2-second scan rate.
  - Records an average of the data over the last 5 minutes of every hour, and allows these data to be stored manually as needed for detailed analysis.
- Calculates parameters with received data
  - Heater resistance and power
  - System efficiency
  - Power factor
  - Average hot-end temperature
  - Cold-end temperature
  - Piston amplitude
  - Net heat input
  - Alternator motor constant

Standard ASC Test Rack: Convertor Control

- Convertor control
  - Performed by an AC bus that simulates the convertors being connected to an AC grid.
  - Controls piston amplitude by varying the AC voltage and, therefore, the load on the convertors.
    - Increasing the AC voltage increases the piston amplitudes.
  - The controller dissipates power generated by the convertors in a load resistor, which is connected across the alternator output.
    - Sized for the maximum power output of the convertor.
  - Low-voltage, high-current alternators, have a transformer between the AC power supply output and the load resistor to enable the use of a more standard power supply.
  - Alternator is connected to tuning capacitors that compensate for the alternator inductance.

Standard ASC Test Rack: Hot-End Temperature Control

- Controlled with a heat-source controller
  - Regulates the power into the cartridge heaters that provide heat to the heat collectors of the convertors.
  - Two independent heat-source controllers are capable of sourcing between 0 and 400 W.
  - Regulates electrical power to the heaters by means of two proportional integral derivative (PID) temperature controllers.
    - Programmed to limit the rate of change in power to 1 °C/sec.
    - Programmable direct-current (DC) power supplies are driven by the PID controllers.

Standard ASC Test Rack: Measurement - Transducers

- Transducers
  - Two sets of transducers are mounted in the test rack.
    - One panel measures heater voltage and current as well as AC bus controller voltage and current.
    - Second panel measures alternator voltage, current, and power.
  - Provide output signals ranging from 0 to 5 V to the DAQ system.

Standard ASC Test Rack: Measurement - Piston Signal

- Piston signal processors
  - A Fast Linear Displacement Transducer (FLDT) integrated in the convertor senses piston position.
    - Consists of a single coil and an aluminum core
      - As the core moves in and out of the coil, the coil inductance changes with position.
    - The processor is calibrated with the FLDT and measures the FLDT signal.
    - It processes and scales the signal into a usable form for the DAQ and safety interfaces in the test rack.

Standard ASC Test Rack: Measurement - Accelerometers

- Accelerometer processors
  - An accelerometer measures the level of vibration created by the convertors during operation.
    - This information can be used to estimate net dynamic forces generated by the convertor pair and to monitor changes over time.
  - Accelerometer signals connected to an amplifier provide a means to collect data from the accelerometer.
    - These data are collected every 1,000 hours of operation through a separate data system.

Standard ASC Test Rack: Measurement- Thermocouples

- Thermocouples
  - Ambient temperature
  - Heater-head
  - Cold-side adapter flange
  - Pressure vessel
  - Heat source
  - Coolant
- Thermocouples are monitored by the DAQ and are used to trigger a shutdown of the convertors.

Standard ASC Test Rack: Measurement Verification

- Two steps are taken to verify measurements collected by the data system:
  - Calibration
    - Measurement instruments such as transducers, flow rate and pressure sensors, and the DAQ system are calibrated yearly.
    - Data are collected and analyzed on a regular basis to determine convertor perfor-mance, making the calibration of the equipment necessary to ensure accurate data.
  - Testing
    - A test procedure is used to verify the measurements received by the DAQ system from instrumentation in the rack: transducer, piston, and pressure signals.
    - This procedure is also executed when instrumentation that has been removed from the rack for calibration is reinstalled.

Standard ASC Test Rack: Interface

- Power panel
  - Serves as an interface for the AC power flow.
  - Tuning capacitors, alternator output, convertor controller, and transducers interface to this panel.
- Pressure panel
  - Serves as an interface for pressure and position signals to the DAQ and protection devices.
- Load panel
  - Interfaces the electrical load, transformer, and AC bus controller.

Standard ASC Test Rack: Interface

- Flow meter signal conditioner panel
  - Provides power to the flow meters.
    - The flow meter signal is received and processed by LabVIEW.
    - The flow meter signal conditioner is mounted and connected to allow for removal while the convertors are operating.
      - The flow meter signal conditioner must be removed from the test rack for calibration.

ASRG-EU Test Rack: Data Acquisition

- The ACU provides data through analog and serial telemetry:
  - DC bus voltage and current
  - Analog piston position
  - Analog alternator current
- The ASRG–EU is instrumented with additional temperature-detection devices, including resistance temperature detectors (RTDs) and thermistors.
- The DAQ performs the following calculations:
  - Controller efficiency
  - Generator system efficiency
  - Generator power
  - Average housing temperature
  - FLDT temperature
  - Alternator current
  - Piston amplitude

ASRG-EU Test Rack: Data Acquisition

- The ASRG–EU is air-cooled, whereas the standard ASC test setups provide cooling with a water/glycol mixture.
- Cooled air is circulated through the protective cover by fans.
- Additional parameters are measured for cooling system monitoring:
  - ASRG–EU housing temperatures
  - Fan speed
  - Upstream and downstream fan air temperatures
  - Protective cover temperatures

ASRG-EU Test Rack: Control Systems

- The test rack provides two hot-end temperature-control systems with only one control system being used at a time
- Constant heater temperature
  - Used when the convertor is operating with the AC bus controller
  - Constant-temperature operation is more straightforward to implement, but it may not be representative of the flight operation.
- Fixed-heat input for temperature control
  - Used when the convertor is operating with the ACU
  - Fixed-heat input mimics operation with the General Purpose Heat Source (GPHS) module.
  - Fixed-heat input is implemented with a microcontroller, with two independent heat-source controllers that are capable of sourcing between 0 and 300 W by regulating electrical power to the heaters.

ASRG-EU Test Rack: Control Systems

- The test rack provides two convertor-control systems with only one being used at a time:
  - AC bus control
    - Dissipates power in resistors.
  - ACU control
    - Relies on a DC electronic load to sink power.
    - The ASRG–EU output voltage is between 22.0 and 34.0 V_{dc} and is determined by the end user.
      - The ACU will track to this voltage, providing power as a constant-power source, and will sense a bus overvoltage condition.

ASRG-EU Test Rack: Control Systems

- The ACU will:
  - Provide constant power as long as the end user is in the required voltage range
  - Internally shunt power and disconnect itself from the bus if the voltage range is exceeded.
    - Shunt resistors sized for maximum output power of the convertors are mounted on the load panel in the test rack for this purpose.
- The bus is connected to a capacitor bank for transient energy storage.
  - This capacitor needs to be in the range of 10,000 to 100,000 μF.

ASRG-EU Test Rack: Measurement

- The test rack allows for three measurements that were not available on the standard ASC test rack:
  - Thermistors
    - Four thermistors measure pressure vessel and cold-end temperature
  - RTDs for temperature measurement
    - Six RTDs measure hot-end temperature
  - Load Cells

ASRG-EU Test Rack: Measurement

- Load cells for force measurement
  - Four load cells measure the vertical, horizontal, and lateral loads at the interface between the test stand and the mechanical hardware.
  - The signal is processed through an amplifier to allow data to be collected with a spectrum analyzer.
  - The load cell readings are summed into single readings of force in the *x*, *y*, and *z* directions.
  - The DAQ system monitors the load cell signal in the *z* direction; this signal is also monitored by safety protection devices

ASC-E2 Test Rack: Measurement

- Currently, two measurement techniques that are different from the standard ASC and ASRG–EU test racks will be implemented on the ASC-–E2 test rack.
  - Existing test racks at GRC measure alternator and heater voltage, current, and power with transducers
    - A power meter was selected that would improve the accuracy of and simplify the rack wiring and calibration process.
  - External current sensors will be used to measure current
    - Minimize the line resistance in the power path of the convertors, which affects the operation of high-current, low-voltage convertors.

ASC-E2 Test Rack: Documentation

- Several goals were set for improving the documentation of the ASC–E2 racks
  - First to improve the quality of the schematics. In the past, schematics were drawn in OrCAD and were not as detailed as should be used for test equipment for flightlike hardware.
    - Control the configuration by adding details such as parts lists, references, notes, wire sizes, lengths, and colors to the schematics.
  - Second to create schematics of circuits that were previously not documented

ASC-E2 Test Rack: Documentation

- Third goal is to have all OrCAD schematics drawn in AutoCAD and filed in the Glenn Adept System.
  - The quality of the test rack will be further improved through a design review with NASA senior engineers from outside of the organization.
- Fourth goal is to write a procedure to guide the assembly and checkout of the test racks to ensure that each rack is identical.
  - This procedure will include:
    - Steps needed to test each interface, control system, and measurement device
    - Order for installing each panel
    - Wire length and routing for interfaces between the instrumentation and the convertors

Safety: Data Acquisition System

- The user may specify upper and lower bounds for any parameter monitored by the DAQ system.
- The DAQ software will safely shut down operation of the test article when an out-of-bound condition is sensed.
- Parameters that trigger the shutdown of a standard ASC include:
  - Low or high hot-end temperatures
  - Low or high rejection temperatures
  - High pressure-vessel temperature
  - High piston amplitude
  - Loss of building power

Safety: Data Acquisition System

- If a shutdown is initiate:
  - The DAQ commands the hot-end temperature to 10 °C and
  - Circulator temperature is set to 25 °C
  - Heater power supplies and AC bus controller are turned off
  - A shutdown is initiated for loss of building power after 5 minutes of operating on an uninterruptible power supply (UPS) system.

Safety: Data Acquisition System

- Parameters that trigger a shutdown of the ASRG–EU or ASC–E2 include:
  - Low or high hot-end temperatures
  - High rejection temperatures
  - High pressure-vessel temperature
  - High piston amplitude
  - Loss of building power
  - High housing temperature
- Both thermistors and thermocouples are used to detect shutdown conditions.

Safety: Data Acquisition System

- If a shutdown is initiated, the DAQ commands:
  - Hot-end temperature to 10 °C
  - Circulator temperature is set to 25 °C
  - Turns off the heater power supplies
  - The convertors continue to be motored with the AC bus controller until the average hot-end temperature reaches 575 °C, with the nominal hot-end temperature being 625 °C.
    - During the shutdown of a standard ASC, the piston motion is stopped, which prevents the transfer of heat.
    - The change to continue to motor the convertor was implemented to allow the convertor to cool down more quickly.

Safety: Data Acquisition System

- Another safety feature in the software notifies the end user when a shutdown occurs, logs the fault via the DAQ, and records the data.
  - The end user is notified by a cell phone text message that indicates the fault code of the shutdown.
- The DAQ shutdown functionality is tested via an unattended DAQ test rack checkout, which verifies that the sequence of each shutdown is correct.
  - The shutdown scenarios are simulated with either a thermocouple calibrator or voltage reference.

Safety: Circuitry

- Three hard-wired protection devices installed in the operations rack function independently of the software-based protection:
  - Temperature limit
  - Protection circuit
  - Emergency push button

Safety: Circuitry – Temperature Limit

- Three panels and a DC power supply are used to initiate the temperature limit shutdown.
  - The fault panel serves as an interlock for the heater power supplies.
    - If a fault is registered by the temperature limit device, the DAQ, or an optional third source, the heater power supplies are disabled and a fault is indicated by a light-emitting diode (LED).
  - A temperature panel houses the PID temperature controller and the temperature limit device.
  - A thermocouple interface is provided between the DAQ and the temperature control panel.
    - Feedback is provided to both the PID and the temperature limit device by two individual hot-end thermocouples.
    - If the hot-end temperature of either convertor exceeds the user-defined limit, the limit controller removes the heater power from both convertors via a relay.

Safety: Circuitry – Protection Circuit

- A failsafe protection circuit (FPC) was implemented to prevent piston overstroke and can monitor up to four input signals
  - Each input has an associated, user-adjustable setpoint.
  - When any signal exceeds its setpoint, the convertor controller is disconnected, and an emergency load is applied across both alternators and a signal is sent to the DAQ.
  - Piston-position sensor signals are the primary input on the standard ASC test rack
  - The ASRG–EU test rack has an additional input from the load cells.
    - This input was added because it is independent of the piston signal from the ASRG–EU controller.
    - If the controller fails, the piston position signal would no longer be available to trigger a shutdown.
    - The increased vibration from an overstroke of the piston would increase the load cell signal and trigger a shutdown.

Safety: Circuitry – Protection Circuit

- A protection circuit interface panel provides:
  - Means for the user to be notified via LEDs when a piston amplitude limit is exceeded.
  - Means for the user to reset the protection circuit after the fault and can stall the convertors by flipping a switch on this panel.
  - The user also can disconnect the protection circuit and select between AC bus control and an external controller.

Safety: Circuitry – Emergency Push Button

- Several steps are required in the event of an emergency shutdown during convertor operation, these include:
  - Removing power from the heaters
  - Loading the convertor
  - Turning off the controller
- An emergency shutdown button was created to simplify this process.
  - This button initiates all of these steps with one action.
  - This safety feature is being considered for integration in the ASC–E2 test rack; it is not available on either the ASC or ASRG–EU test rack.

Conclusion

Standard ASC	ASRG–EU	ASC–E2
Measurement instrumentation		
Thermocouples Transducers Fast linear displacement transducer (FLDT) processor Accelerometers	Thermistors Resistance temperature devices (RTDs) Thermocouples Transducers FLDT processor Accelerometers Load cells	Thermocouples Power Meter Accelerometers
Convertor control		
Alternating-current (AC) bus power supply	AC bus power supply ACU	AC bus power supply
Temperature control		
Constant temperature Water/glycol bath	Fixed-heat input Constant temperature Air-cooled	Constant temperature Water/glycol bath
Miscellaneous		
	Line resistance Direct-current (DC) bus	Line resistance Documentation
Safety		
Piston overstroke LabVIEW Hot-end temperature	Load cells Piston overstroke LabVIEW Hot-end temperature	Emergency shutdown button Piston overstroke LabVIEW Hot-end temperature