Oral Presentation/Viewgraph Summary:

Under contract to the Department of Energy (DOE), Lockheed Martin Space Systems Company (LMSSC) has been developing the Advanced Stirling Radioisotope Generator (ASRG). The use of Stirling technology introduces a four-fold increase in conversion efficiency over Radioisotope Thermoelectric Generators (RTGs), and thus the ASRG in an attractive power system option for future science missions. In August of 2008, the ASRG engineering unit (EU) was delivered to NASA Glenn Research Center (GRC). The engineering unit design resembles that of a flight unit, with the exception of electrical heating in place of a radioisotope source. Prior to delivery, GRC personnel prepared a test station continuous, unattended operation of the engineering unit. This test station is capable of autonomously monitoring the unit's safe operation and recording . ,.. ,.... performance data. Generator parameters recorded include temperatures, electrical power output, and thelmal power input. Convertor specific parameters are also recorded such as alternator voltage, current, piston amplitude, and frequency. Since November 2008, the ASRG EU has accumulated over 4,000 hours of operation. Initial operation was conducted using the AC bus control method in lieu of the LMSSC active power factor conecting controller. Operation on the LMSSC controller began in February 2009. This paper discusses the entirety of ASRG EU operation thus far, as well as baseline performance data at GRC and LMSSC, and comparison of performance using each control method.

Recent Stirling Conversion Technology Developments and Operational Measurements

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Topics

Advanced Stirling Radioisotope Generator (ASRG) support:

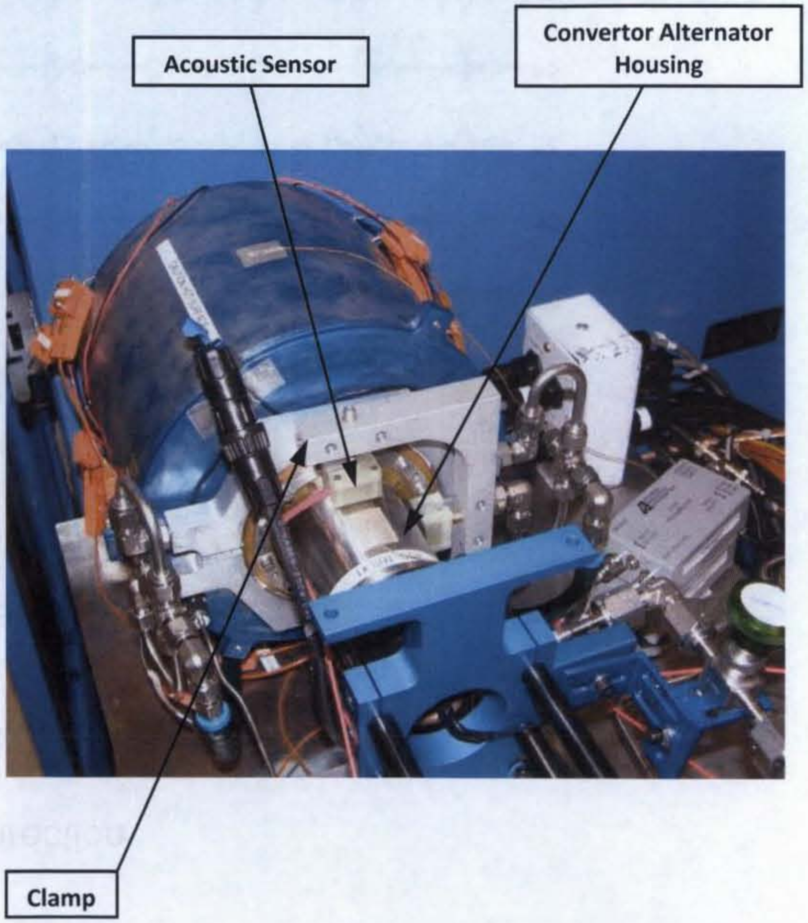
1. Convertor acoustic characterization
   - Develop performance metric for extended operation
2. Electromagnetic interference (EMI) mitigation via bucking coil and permalloy vessel
   - Experimental measurements on a pair of convertors

New Stirling conversion techniques:

3. Multiple-cylinder alpha : Higher power density
   - One of first demonstrations of free-piston in alpha arrangement
4. Thermoacoustic : Eliminates displacer
   - No hot-end moving components, gas shuttled by high amplitude traveling wave

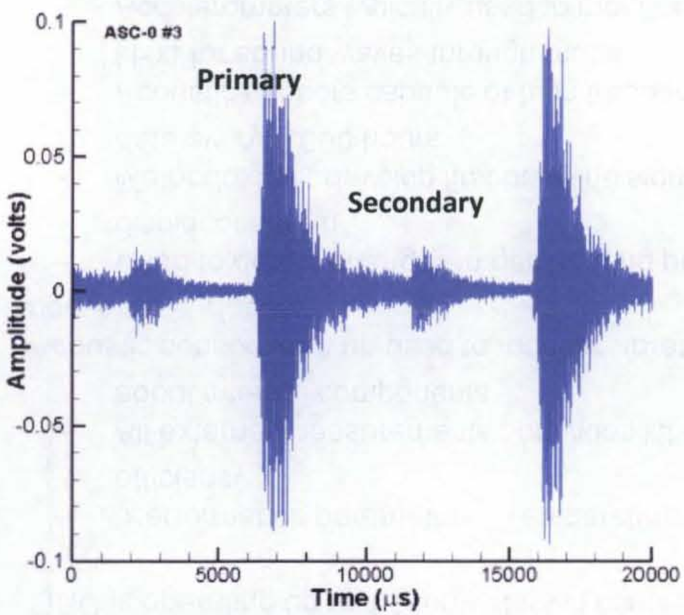
Acoustic Emission Characterization

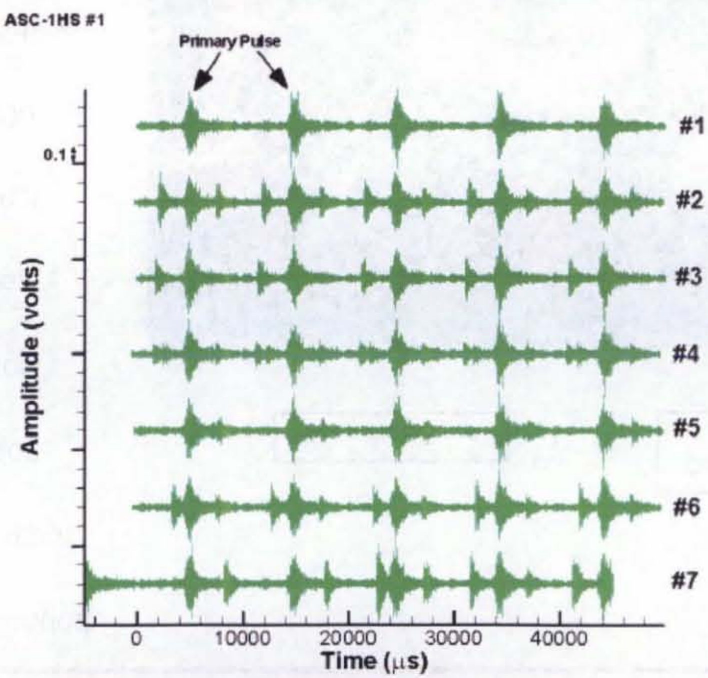
- GRC is operating up to 16 convertors in continuous unattended mode:
  - Performance parameters: Temperatures, power output, efficiency
  - All external measurements : provides little information about internal components
- Acoustic sensors can be used to monitor vibrations through convertor surfaces:
  - Used to detect changes in gas bearing performance, displacer spring
  - Methodology : develop first baseline signature, collect data every 1,000 hours
  - Acoustic sensors capable of high frequency (100-600 kHz) for sound waves through metal
  - Accelerometers typically used to monitor bulk test article motion (~100 Hz)
- Sensors : Physical Acoustics Corp. Micro30S
  - 100 to 600 kHz operating range
  - Loaded onto convertor alternator housing with custom-fabricated clamp for precise preload control
  - Acoustic sensor and piston position signals routed to Yokogawa DL750 oscilloscope
  - Sampled at 1 MHz for periods of 100 ms (10 convertor cycles), capable of storing 100 s of sampled data



Acoustic Emission Characterization

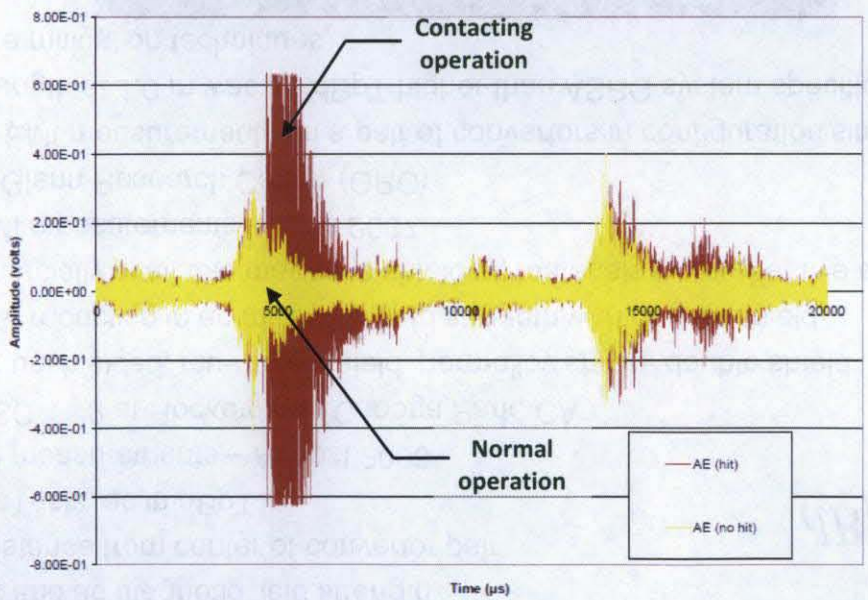
- Majority of measurements taken on Advanced Stirling Convertors (ASC)
- Common pattern found
  - Two pulses : midpoint of piston stroke in each direction
  - At least one secondary pulse
- Some convertor acoustic signatures remained constant , others exhibited variances in some features:
  - Some secondary pulses varied in intensity and phase position
  - Some convertors exhibited multiple secondary pulses





Acoustic Emission Characterization

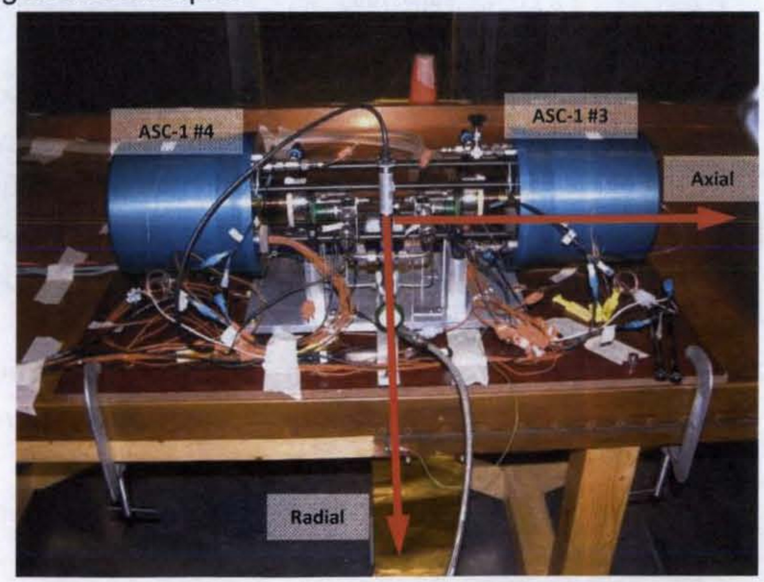
- Observed acoustic emissions during deliberately disrupted convertor operation:
  - Inoperable gas bearings
  - Piston to displacer and planar spring contact
  - Loose planar spring fasteners
- Conclusions:
  1. Gas bearing operability did not change acoustic signature
  2. Contact between piston and displacer or planar spring resulted in sensor saturation
  3. Loose planar spring fasteners also resulted in sensor saturation
  4. Severe convertor disruptions can be detected
  5. For extended operation: baseline signatures can be compared to data collected at regular intervals (1,000 hours)



Electromagnetic Interference (EMI) Mitigation

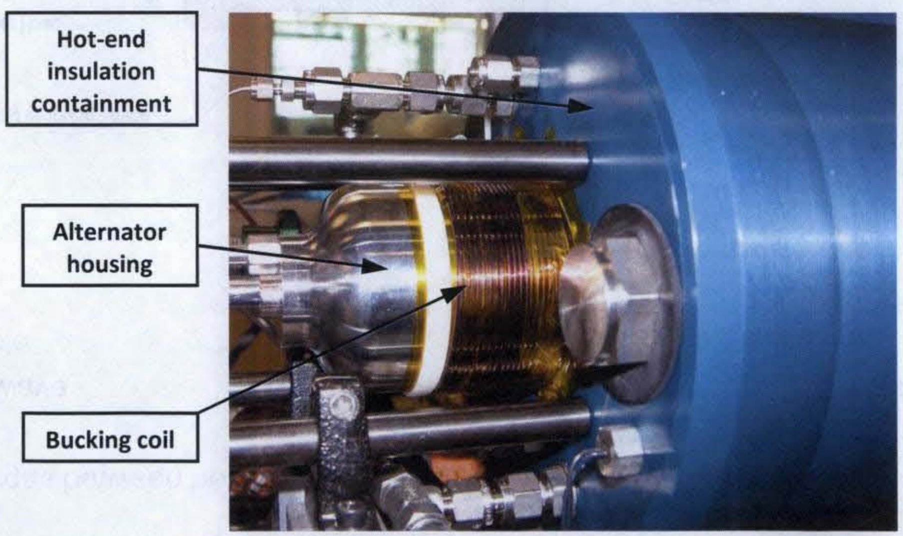
$$dBpT = 20\log\left(\frac{M}{1pT}\right)$$

- ASRG system spec. for dc and ac magnetic field strength
  - Specified at 1.0 m distance from center of convertor pair
  - dc measured in nanoTesla, ac in dBpT
- Initial single convertor EMI measurements – August 2006
  - Single convertor : ASC-1 #2 at Rocketdyne, Canoga Park, CA
  - Four configurations : unshielded, mu-metal shield, permalloy shield, double shield
  - Up to 15 dBpT (83 %) reduction in ac magnetic field strength with double shield
  - **Conclusion** : Commercially available magnetic-shielding materials were effective and attenuating ac magnetic field
- Dual-opposed convertor EMI measurements – June 2007
  - ASC-1 #3 and #4 at Glenn Research Center (GRC)
  - Baseline unshielded EMI measurements on a pair of convertors in configuration similar to ASRG
  - ac magnetic field strength at 1.0 m was 11 dBpT higher than ASRG system specification
  - **Conclusion** : Explore mitigation techniques



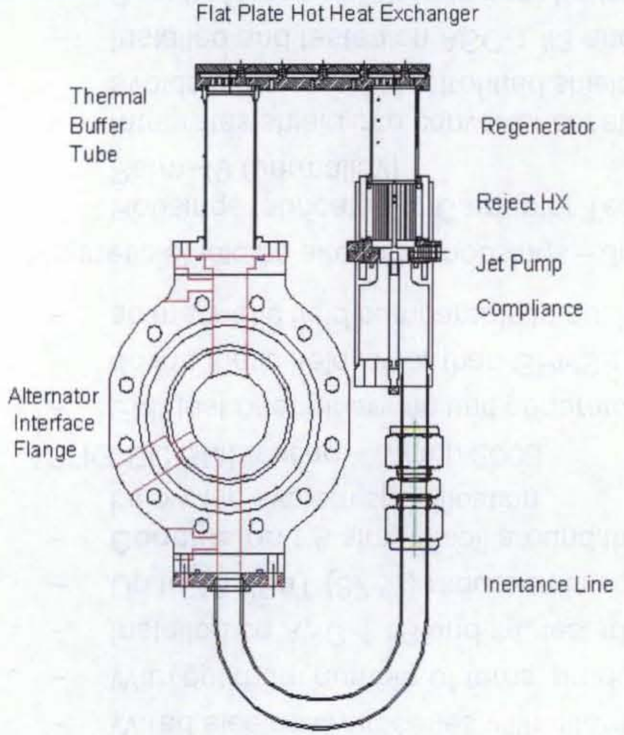
Electromagnetic Interference (EMI) Mitigation

- GRC developed bucking coil investigation – December 2007
  - Coil of magnet wire situated around outer diameter of alternator housing
  - Wired electrically in series with alternator output
  - With optimum number of turns, produced magnetic field that nullifies alternator emission
  - Installed on ASC-1 #3 and #4, tested at GRC
  - Up to 18 dBpT (87 %) reduction in ac magnetic field strength at 1.0 m : well below ASRG system spec.
  - **Conclusion** : A simple coil around the alternator housing was capable of attenuating ac magnetic field emissions below the system specification
- ASRG-EU EMI testing – March 2008
  - EMI test of engineering unit generator at Lockheed Martin
  - dc magnetic field lower than GPHS-RTG
  - ac magnetic field comparable to dual-opposed ASC-1 #3 and #4 measurements
- Magnetic-shielding alternator housings – June 2009
  - Housings fabricated of Carpenter Technology Perm-49 (permalloy)
  - Integrates shield into convertor construction : avoids extra mass of retrofitted shield
  - Installed and tested on ASC-1 #3 and #4
  - Results to be published in near future

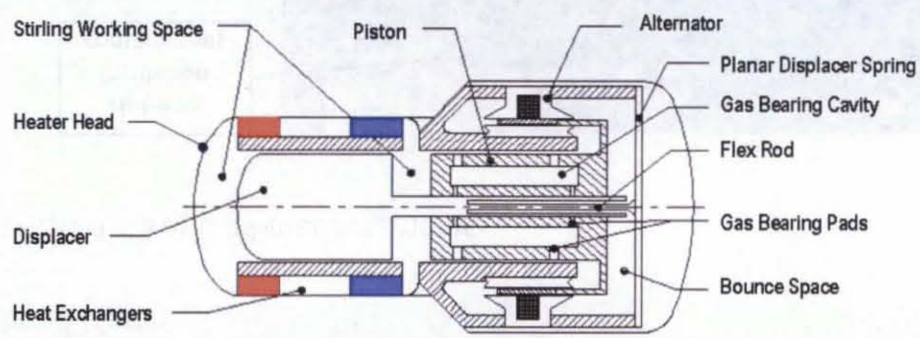


Thermoacoustic Stirling Power Conversion

- Traditional free-piston machine uses displacer to shuttle gas between hot and cold temperatures
- Thermoacoustic eliminates displacer
  - Working gas shuttled by high-amplitude acoustic wave
  - Gas goes through same pressure and volume cycle
  - No hot-end moving components



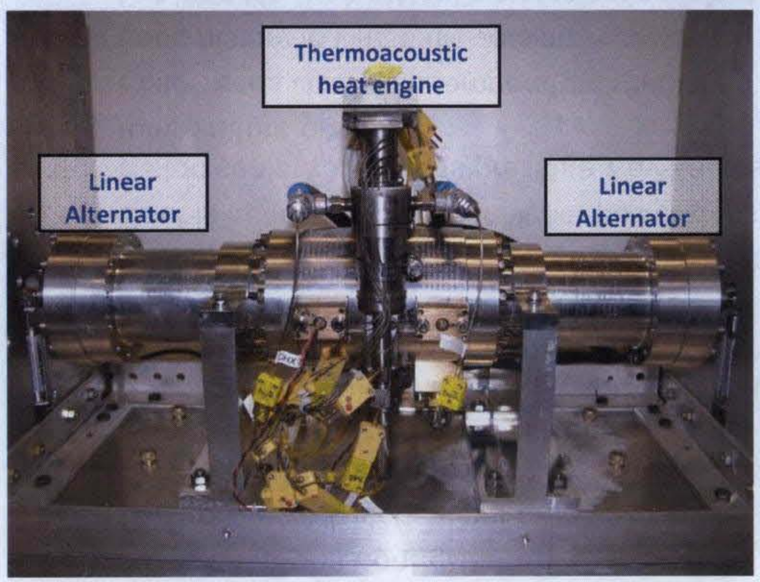
Thermoacoustic configuration
Image courtesy of Northrop Grumman



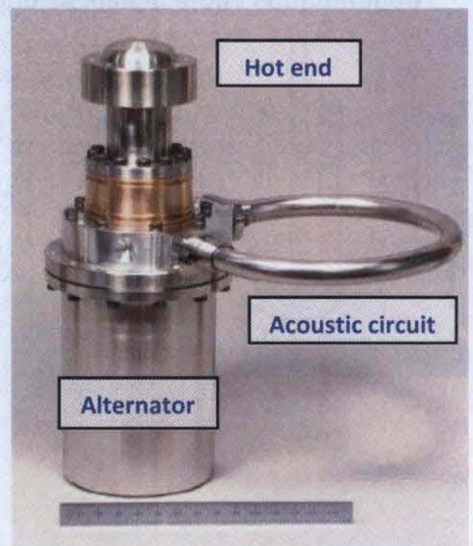
Displacer-based Stirling convertor
Image courtesy of Sunpower

Thermoacoustic Stirling Power Conversion

Research hardware produced by two thermoacoustic Stirling technology development contracts funded by NASA



- Northrup Grumman – 2003
- One heat engine with two dual-opposed pistons sharing working space
- Demonstrated 57 W_e at 17.9 % thermal-to-electric efficiency
- Underwent checkout testing at GRC



- Sunpower – 2008
- Single coaxial thermoacoustic engine with single piston/alternator
- Demonstrated 50 W_e at 17.9 % thermal-to-electric efficiency

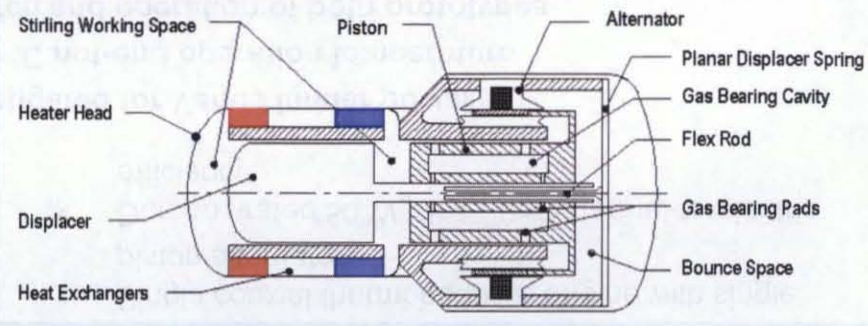
Thermoacoustic Stirling being investigated for Venus lander power

May offer attractive option at up to 200 °C hot-end operation temperature

Facility being prepared at GRC for research and operation of both prototypes

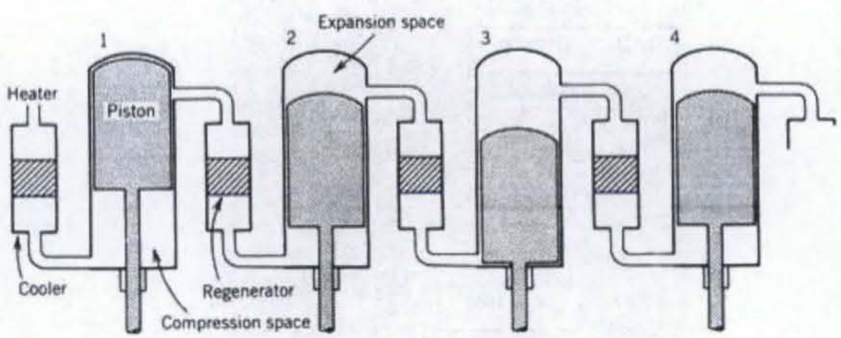
Multiple-cylinder Alpha Stirling

- Most recent free-piston Stirling technology development focused on **beta configuration**
  - Two moving components
  - Coaxial piston and displacer
  - Displacer only moves gas, doesn't seal pressure
  - Piston seals working gas pressure wave from bounce space
  - Piston sees little to no temperature gradient
- Multiple-cylinder **alpha configuration**
  - One moving component per cylinder
  - Expansion space of one cylinder connected to compression space of next cylinder
  - Each piston motion phase difference determined by number of cylinders – 90 ° for 4 cylinder arrangement
  - Pistons move working gas and produce power
  - Double acting pistons offer higher power density
  - Piston seals working gas pressure wave across temperature gradient
  - Piston sees little to no temperature gradient
  - Long history in kinematic version
  - For long life (free-piston) syncronization is not trivial



Beta configuration Stirling convertor

Image courtesy of Sunpower



Multiple-cylinder alpha configuration

Multiple-cylinder Alpha Stirling

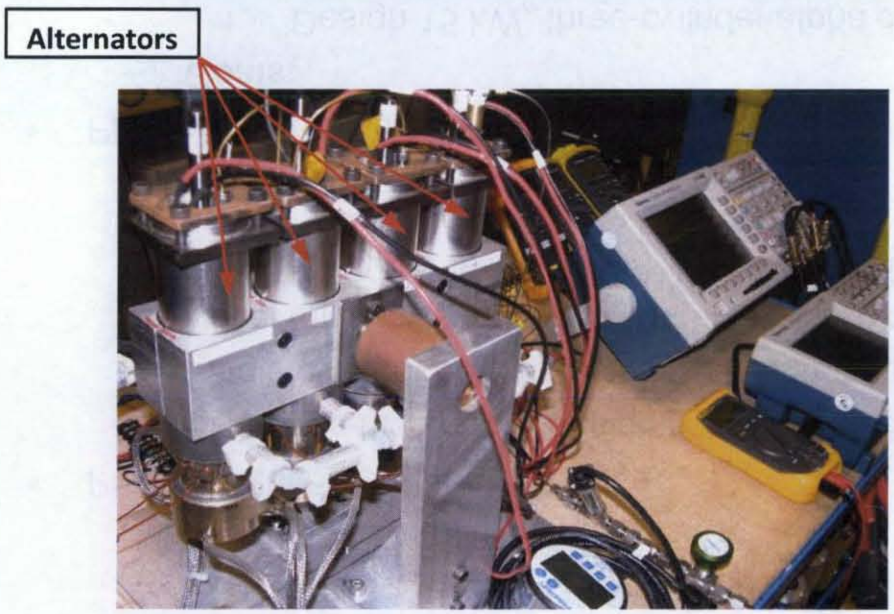
Small Business Innovative Research (SBIR) contract awarded to Sunpower and Global Cooling to investigate multiple-cylinder alpha designs

- Phase I - 2005
  - Evaluated high power design space (5 to 25 kW_e – lunar fission surface power)
  - Single cylinder beta and multiple-cylinder alpha
  - Novel three-cylinder arrangement showed potential for significant improvement over previous high power design from SP-100 project : **40% higher specific power, 34% higher efficiency**

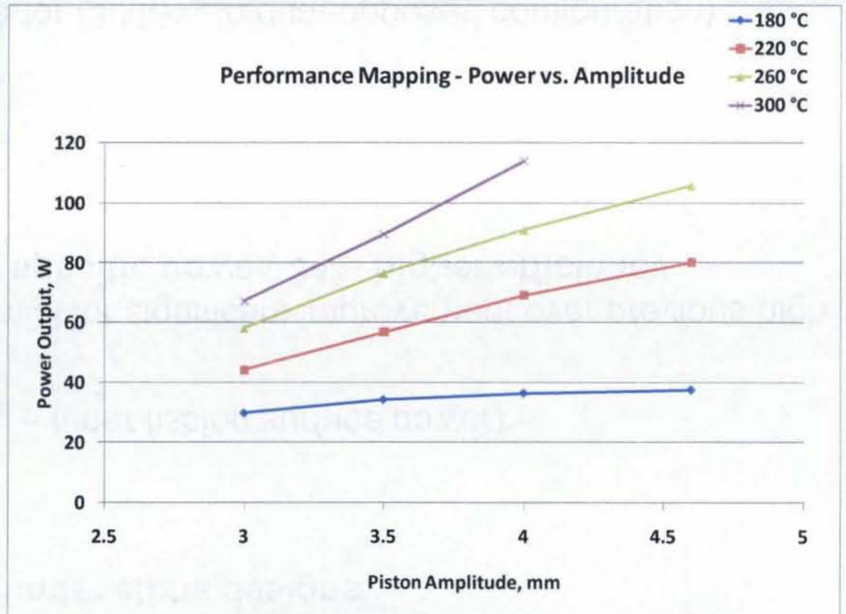
- Phase II – Completed 2008
  - **Goals:**
    1. Design 15 kW_e three-cylinder alpha convertor (30 kW_e in dual-opposed configuration)
    2. Produce 100 W_e-class four-cylinder alpha demonstration convertor for research and code validation
  - Investigate effects specific to alpha configuration – temperature gradient seal loss, cylinder interconect dead volumes, off-resonance pistons
  - Converted existing four-cylinder cooler to convertor
  - Changed hot-end material
  - Installed electric heat source

Multiple-cylinder Alpha Stirling

- Phase II results:
  - Demonstration convertor produced over **135 W** at **290 °C hot-end**, **50 °C cold-end (TR=1.74)**
  - Experimental results agreed well with thermodynamic code prediction
- Delivered to GRC – June 2008
  - Completed low-temperature checkout (180 °C hot-end) and performance mapping
  - Performance mapping : 180 °C to 300 °C hot-end and 75% to full piston amplitude
  - 20 W at low-temperature condition and 115 W_e at full-temperature
  - Demonstrated stable operation – pistons maintained 90 ° phasing with only electrical connectivity



Four-cylinder free piston demonstration convertor at GRC.



GRC performance mapping results at different hot-end temperatures and piston amplitudes

Conclusion

Operational measurements:

1. **Acoustic emission characterization**
   - Baseline acoustic emissions characterized for several convertors undergoing extended operation
   - Methodology developed to monitor convertor operation by comparing periodic acoustic emission data to baseline
2. **EMI mitigation**
   - Baseline magnetic field measurements taken on pair of dual-opposed convertors
   - Bucking coil situated around alternator housing proven capable of reducing ac magnetic field to below ASRG system specification
   - Alternator housings fabricated of permalloy were installed and tested on a pair of convertors

Technology developments:

3. **Thermoacoustic Stirling conversion**
   - NASA contracts produced two operational 100 W-class thermoacoustic research convertors, demonstrating Stirling conversion with no hot-end moving components
   - Facility being built at GRC for further testing
4. **Multiple-cylinder alpha Stirling conversion**
   - NASA SBIR produced operational 100 W-class four-cylinder free-piston demonstration convertor
   - Performance mapping completed

Acknowledgment

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