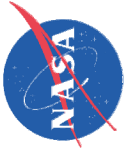


# Summary of Stirling Converter Testing at GRC

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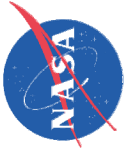
The NASA Glenn Research Center (GRC) has been testing free-piston Stirling converters for potential use in radioisotope power systems. These converters tend to be in the 35 to 80 watt electric power output range. Tests at GRC have accumulated over 80,000 hours of operation. Test articles have been received from Infinia Corporation of Kennewick, WA and from Sunpower of Athens, OH. Infinia designed and built the developmental Stirling Technology Demonstration Convertors (TDC) in addition to the more advanced Test Bed and Engineering Unit convertors. GRC has eight of the TDC's under test including two that operate in a thermal vacuum environment. Sunpower designed and developed the EE-35 and the Advanced Stirling Converter (ASC). GRC has six of the EE-35's and is preparing for testing multiple ASC's. Free-piston Stirling converters for radioisotope power systems make use of non-contacting operation that eliminates wear and is suited for long-term operation. Space missions with radioisotope power systems are often considered that extend from three to 14 years. One of the key capabilities of the GRC test facility is the ability to support continuous, unattended operation. Hardware, software, and procedures for preparing the test articles were developed to support these tests. These included the processing of the converters for minimizing the contaminants in the working fluid, developing a helium charging system for filling and for gas sample analysis, and the development of new control software and a high-speed protection circuit to insure safe, round-the-clock operation. Performance data of Stirling converters over time is required to demonstrate that a radioisotope power system is capable of providing reliable power for multi-year missions. This paper will discuss the status of Stirling converter testing at GRC.



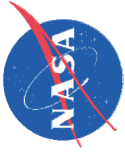
# Summary of Stirling Converter Testing at GRC

presented at the  
2006 International Energy Conversion Engineering Conference  
San Diego, CA

by  
Jeff Schreiber  
NASA Glenn Research Center  
Cleveland, OH

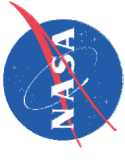


**This work was enabled through the Department of Energy (DOE) Stirling Radioisotope Generator (SRG110) program and through NASA Science Mission Directorate Funding. Any opinions, findings, and conclusions or recommendations expressed in this presentation are those of the presenter and do not necessarily reflect the views of the National Aeronautics and Space Administration.**



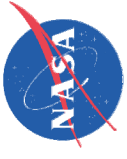
## Stirling Engine and Converter Testing at GRC

- Historical perspective, testing from 1975 through 1998
  - Kinematic engine tests
    - Research, heat exchangers, cycle data for code validation
      - GPU-3
      - Advenco
    - Automotive Stirling engine project
      - P-40
      - Mod I, Mod IA
  - Free-piston engine & converter tests
    - Research, cycle data, dynamics, understanding the operation
      - Type 10
      - RE-1000
      - HP-1000
      - Hydraulic output engine
      - Space Power Research Engine
- One of the motivations for the early kinematic research was looking into the future for space power



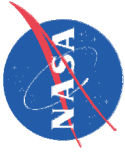
## Stirling Converter Testing at GRC

- Activities under the radioisotope initiative since 1999
  - All about free-piston Stirling power convertors
  - Came from a general collaboration with DOE through the 1990's
  - Power level was ~100 We, lower than previous research
    - Transition to flight
      - High TRL
      - Manufacturability
      - System integration
      - Rise reduction and enhancing reliability
    - Advanced technology
      - Reduced mass
      - Reduced physical size
      - Increased efficiency
      - More robust design
- Extended operation testing was initiated as a means to establish life and reliability
- Few data points of long life Stirling power conversion
  - Harwell TMG, NIH heart engine, Infinia RG-10, CTPC and EM



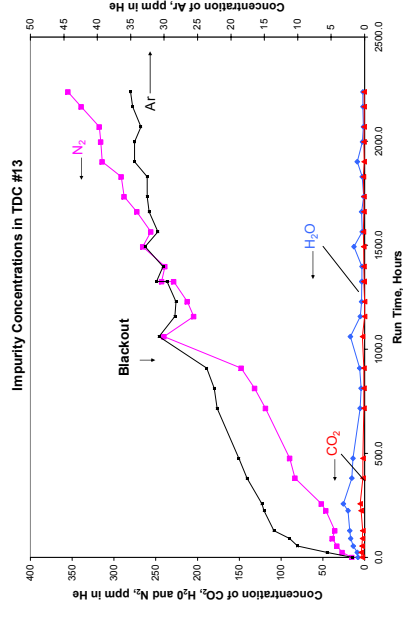
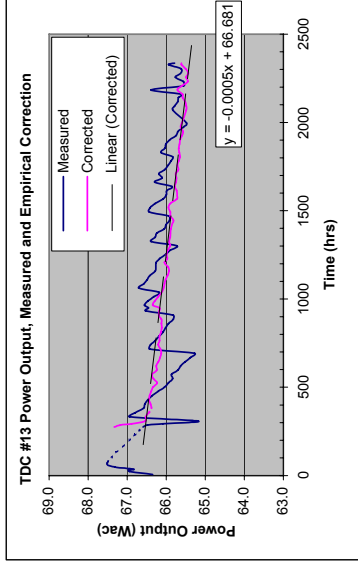
## Stirling Converter Testing at GRC

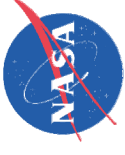
- Purchase TDC #5 and #6 from Infinia (formerly STC)
  - Operation started in October 00
  - Focused tests for performance characterization, controllers, transient response, vibration tests
- Purchase TDC's #7 and #8
  - Operation started in March 01
  - Focused tests for performance characterization, Active Power Factor Correction controller tests, transient response, vibration tests
  - Had plans for operation, vibe test, followed by operation



# Stirling Converter Testing at GRC

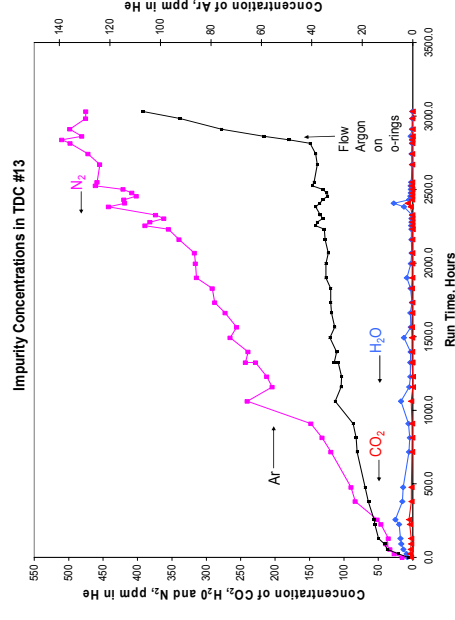
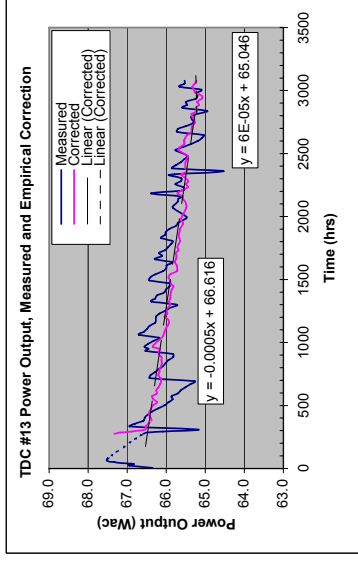
- Extended Operation of TDC's #13 and #14
  - TDC's #13 and #14 were sent to GRC for Extended Operation Test
    - Develop data base of operating hours
    - Look for indications of change in operation
    - Test capability was developed for
      - 24/7 operation, with control of Thot, Tcold, and Tpv
      - Measurements of temperatures, power, vibration, etc
      - Analysis of working fluid composition
  - First operated in April 03
  - Following 40 hours of check out, extended operation began in June 03
  - By October 03, after 2,300 hours of operation, performance was decreasing very slowly
    - At a rate of ~0.5 W per 1000 hours
    - It was also noticed that the working fluid had increasing levels of argon and nitrogen
    - Argon came from an insulation loss test
    - Speculated that increasing level of nitrogen and performance change were linked



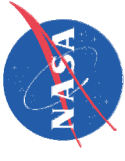


# Stirling Converter Testing at GRC

- Permeation tests with converters evacuated were inconclusive
  - With the converter still or being motored
  - Up to full operating temperatures at the o-rings
    - Noted that argon and nitrogen levels remained constant during permeation tests
  - Returned to operation in November 03, argon appeared to level off, but nitrogen level continued to rise
  - Installed purge rings in November at 2,800 hours
  - Initiated purge with argon because:
    - The test was originally intended to last 5,000 hours
    - Leakage of purge rings was unknown for vacuum or other gasses
  - Results of argon cover gas on o-rings was immediate
    - Nitrogen concentration remained constant
    - Argon concentration began to rise at a greatly increased rate
    - Performance appeared to be degrading more slowly

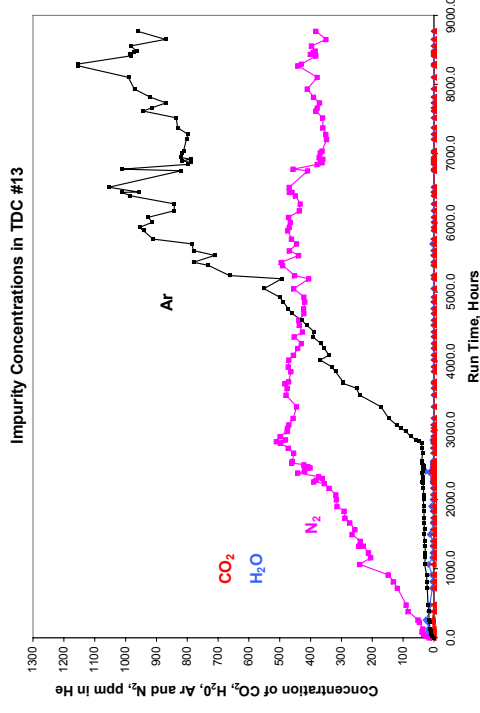
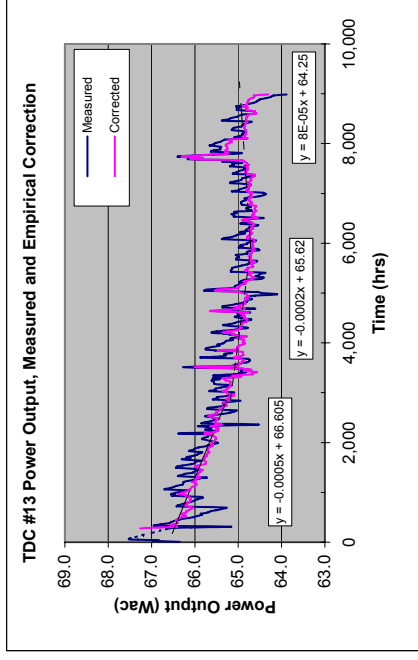




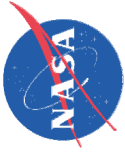


# Stirling Converter Testing at GRC

- As the test was extended, the purge gas was changed to helium in March 04 after 5,873 hours
- Nitrogen concentration and performance leveled off, argon once again rose very slowly
- Operated in this condition thought August 04, at 9,045 hours move to new facility

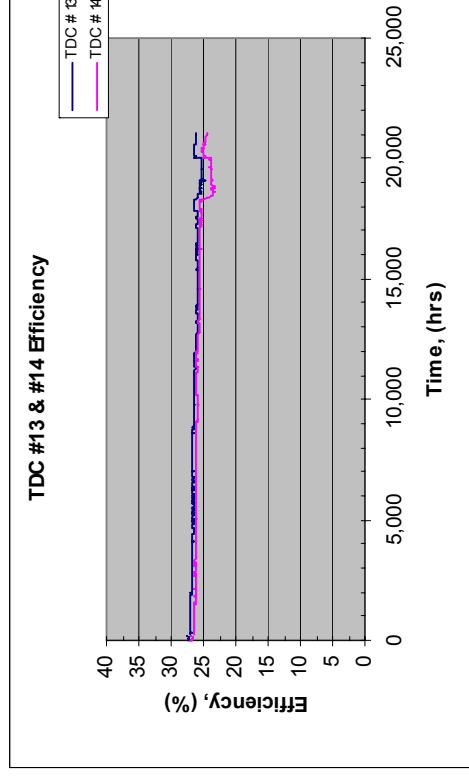
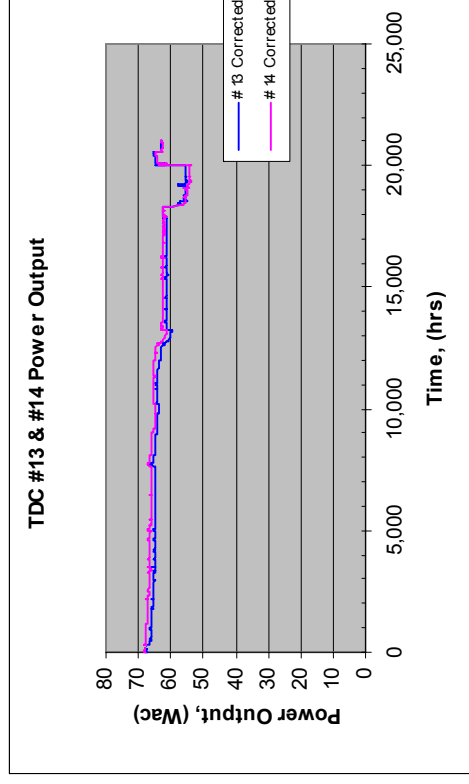


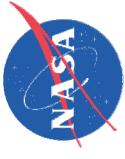
- Operation continued until shutdown for hermetic seal welding in January 06 after 19,108 hours
  - Fill tube was not welded to allow working fluid composition to be analyzed
- Visual inspection of internal components showed no signs of wear or degradation



# Stirling Converter Testing at GRC

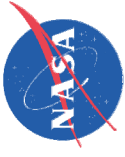
- TDC's #13 and #14 are currently at 22,040 hours
- Presently shut down to replace cartridge heaters, one failed on each TDC
- Appears to be no degradation other than due to initial operation with oxygen permeation
- No sign of working fluid changing due to outgassing or decomposition of the organics





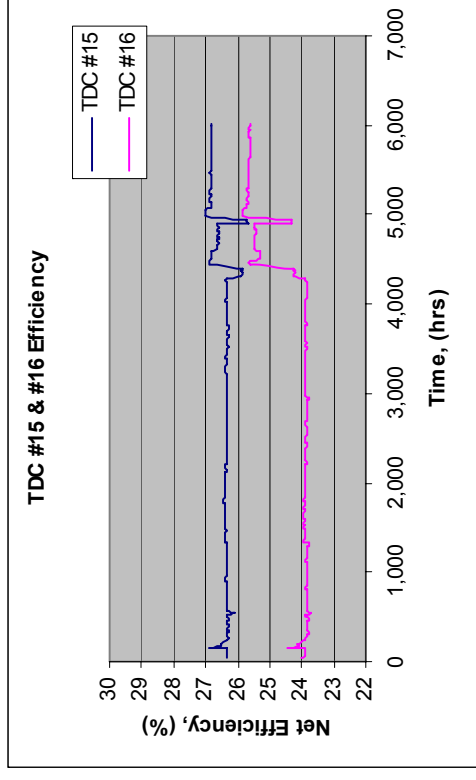
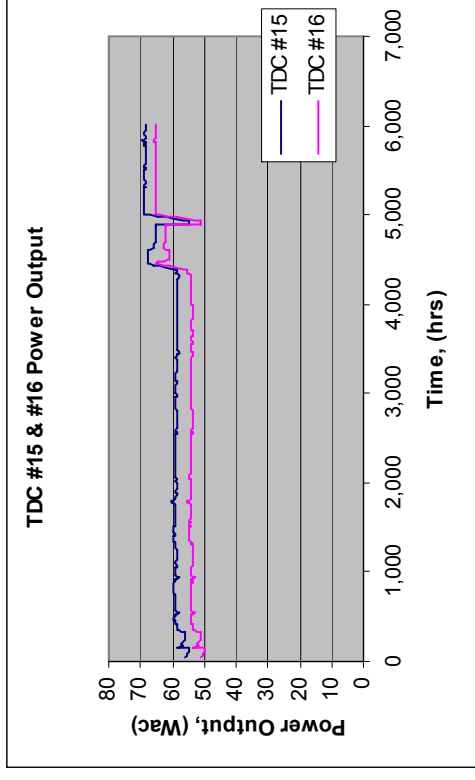
## Stirling Converter Testing at GRC

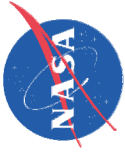
- Extended Operation of TDC's #15 and #16
  - TDC's #15 and #16 were sent to GRC for Extended Operation Test
  - First operated in March 03
  - Operated at reduced temperature because of not being baked out
  - Shut down in October 05, after 4,413 hours for hermetic seal weld
  - Returned to operation in December 05 for check out
  - Bake out in January 06, operated at full design temperature
  - Following heater failure, shut down in February after 4,998 hours to replace all heaters
  - Operation continues, currently at 7,446 hours with no change in performance, no indication of outgassing or decomposition of organics



# Stirling Converter Testing at GRC

- TDC's #15 and #16 are not as well matched as other pairs
- Operation has shown no changes over time in
  - Performance
  - Working fluid composition
  - Vibration signature
- Additional test will be added to characterize operation over time
  - Frequency response test

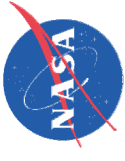




## Stirling Converter Testing at GRC

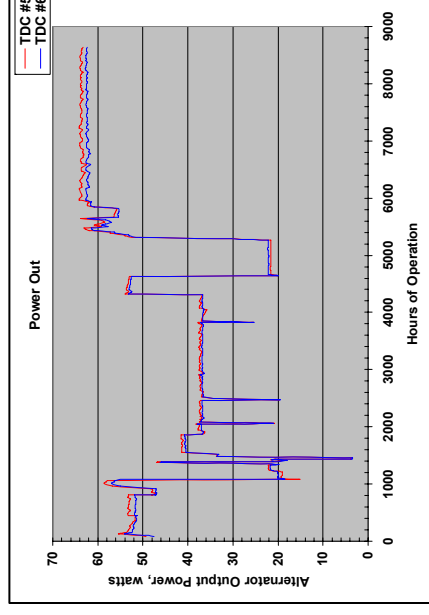
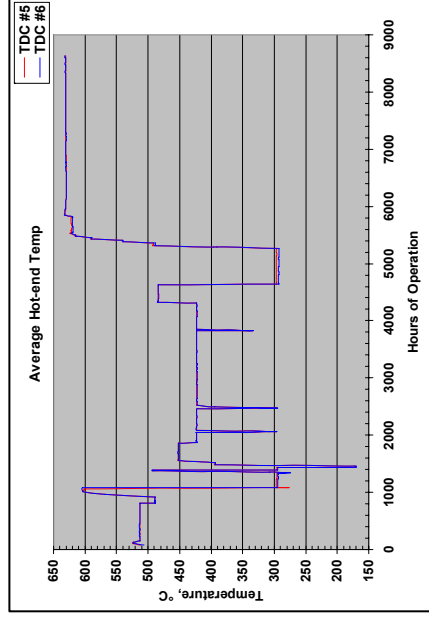
- TDC's #5 and #6 were operated in focused tests for 527 and 366 hours respectively before extended operation
- Extended operation test was planned for thermal vacuum environment
  - Investigate performance in thermal vacuum environment
  - Measure thermal profiles to validate analytical models
  - Hardware similar in configuration to SRG110 but not low mass
  - Nickel heat collector, nickel/copper cold flanges, aluminum radiator panels

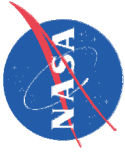




# Stirling Converter Testing at GRC

- Operation in thermal vacuum began in November 04
- 24/7 operation began in December 04
- Some hardware modifications were required,
  - Heater electric leads
  - Radiator panel size
  - Emissivity of the pressure vessel
  - none had to do with the Stirling converters
- Currently at 8,906 hours with no change in Stirling performance





## Conclusion

- Operation at GRC has added to the database of long life Stirling
- Over 80,000 hours of operation, a total of 2.4 billion cycles on TDC designs with no mechanical failures
- Preparations are underway for extended operation testing of Advanced Stirling Convertors in air and in thermal vacuum
- The gas analysis has shown no indication of contaminants generated by the organics
- Performance has remained as expected when operated properly (no permeation, thorough bake out)