Final Results for the GRC Supporting Technology Development Project for the 110-Watt Stirling Radioisotope Generator (SRG110)

Jeffrey G. Schreiber and Lanny G. Thieme

Abstract. From 1999-2006, the NASA Glenn Research Center (GRC) supported the development of a high-efficiency, nominal 110-We Stirling Radioisotope Generator (SRG110) for potential use on NASA missions, including deep space missions, Mars rovers, and lunar applications. Lockheed Martin (LM) was the system integrator for the SRG110, under contract to the Department of Energy (DOE). Infinia Corporation (formerly Stirling Technology Company) developed the Stirling convertor, first as a contractor to DOE and then under subcontract to LM. The SRG110 development has been redirected, and recent program changes have been made to significantly increase the specific power of the generator. System development of an Advanced Stirling Radioisotope Generator (ASRG) has now begun, using a lightweight, advanced convertor from Sunpower, Inc. This paper summarizes the results of the supporting technology effort that GRC completed for the SRG110. GRC tasks included convertor extended-duration testing in air and thermal vacuum environments, heater head life assessment, materials studies, permanent magnet aging characterization, linear alternator evaluations, structural dynamics testing, electromagnetic interference (EMI) and electromagnetic compatibility (EMC) characterization, organic materials evaluations, reliability studies, and development of an end-to-end system dynamic model. Related efforts are now continuing in many of these areas to support ASRG development.

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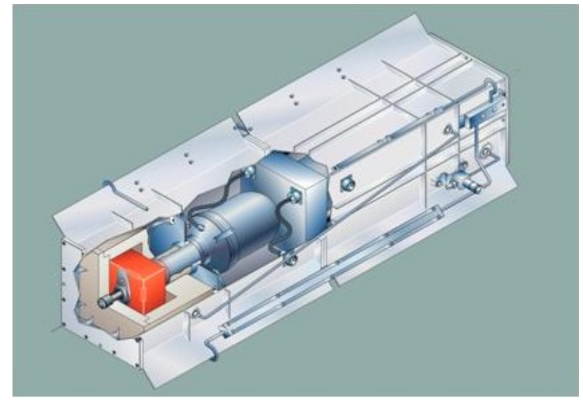
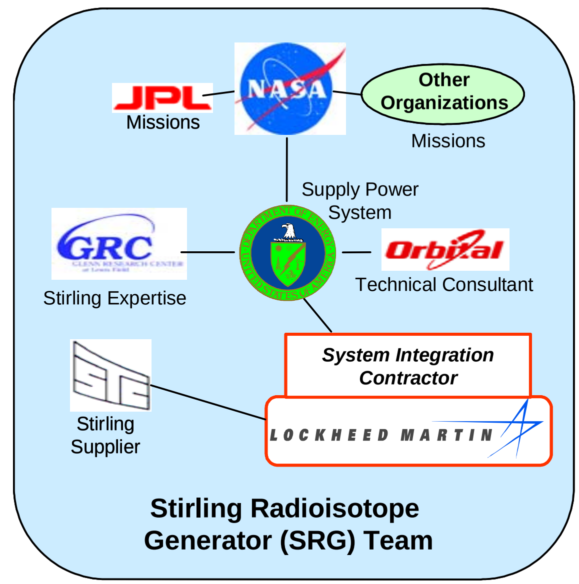
Development of the SRG110

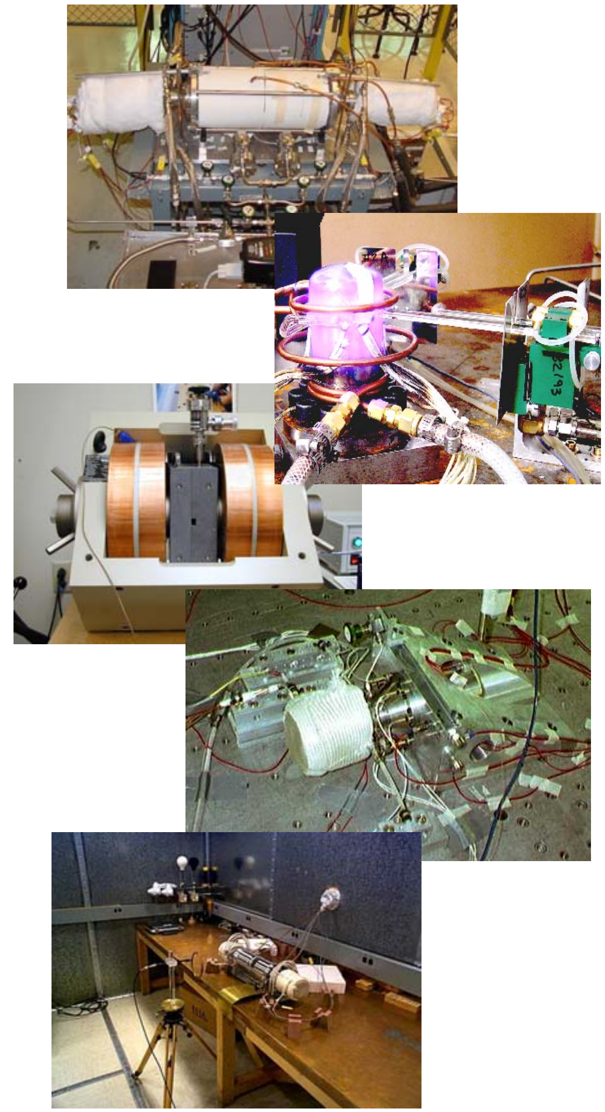
- 100-W class, high-efficiency power source for NASA Space Science missions
  - Unmanned Mars rovers for long-duration missions
  - Spacecraft electric power for deep space missions
  - Potential for lunar distributed power
- Infinia developed the Technology Demonstration Convertor under contract to DOE starting in 1998
- Technology Readiness Assessment in 1999
- LM was selected as the System Integration Contractor for the SRG110 in May 2002
- Flight development continued at LM, Infinia, and GRC working in partnership through 2005
- NASA GRC provided:
  - Technical consulting for DOE/LM
  - In-house supporting technology development project





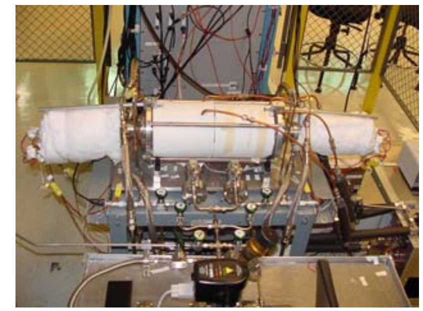
GRC Supporting Technology for the SRG110

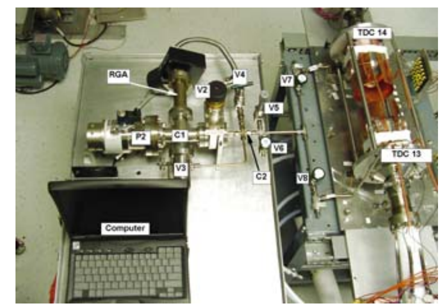
- Convertor performance verification
  - Extended operation
  - Controller tests
  - Thermal vacuum test
- Heater head life assessment and materials studies
- Magnet aging characterization and linear alternator analysis and testing
- Convertor structural dynamics
- EMI/EMC reduction and characterization
- Evaluation of convertor organics
- Reliability evaluation
- Electrical interface
- Thermodynamic and system dynamic analyses

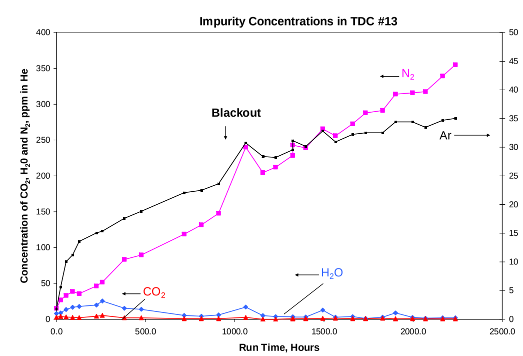


Stirling Convertor Testing at GRC

- Extended Operation of TDC's #13 and #14
  - Built under QA system, but not hermetically sealed
  - 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
  - Extended operation began in June 03 following 40 hours of check out
  - By October 03, after 2,300 hours of operation, performance was decreasing very slowly
    - Loss of ~0.5 W per 1,000 hours
    - 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

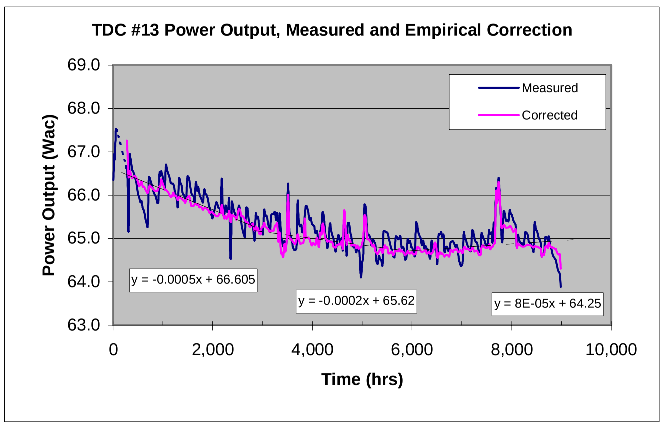


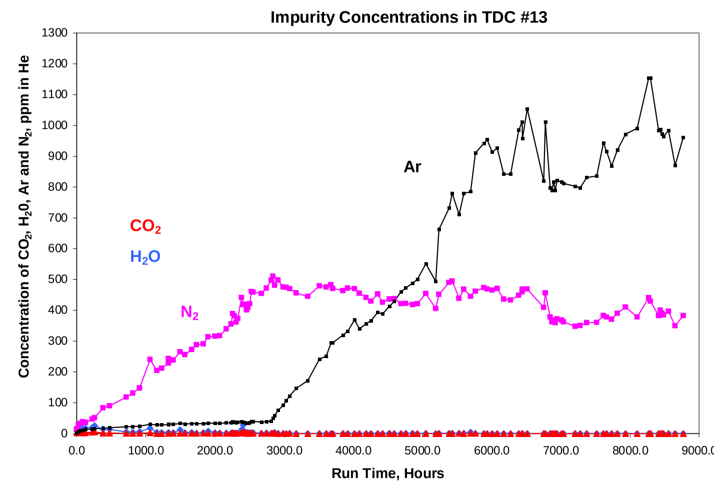




Stirling Convertor Testing at GRC

- Argon purge rings were added over the bolted flanges
- Nitrogen concentration and performance leveled off, argon rose more quickly
- Purge gas was changed to helium in after 5,873 hours
- Operation continued thought August 04, at 9,045 hours move to new facility

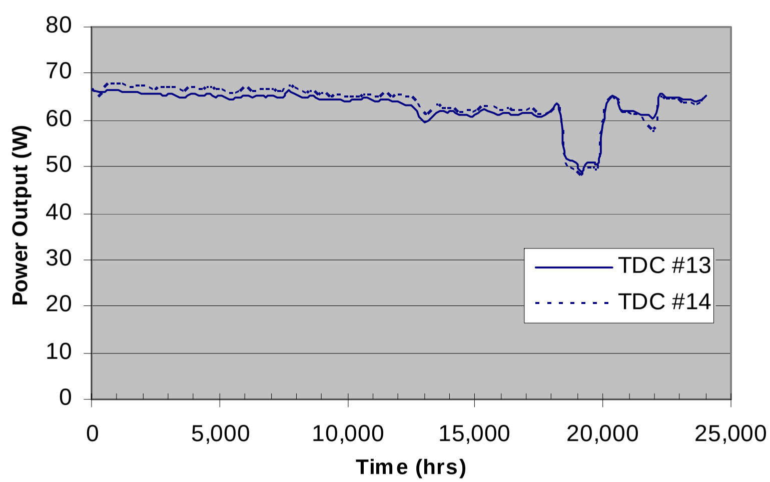


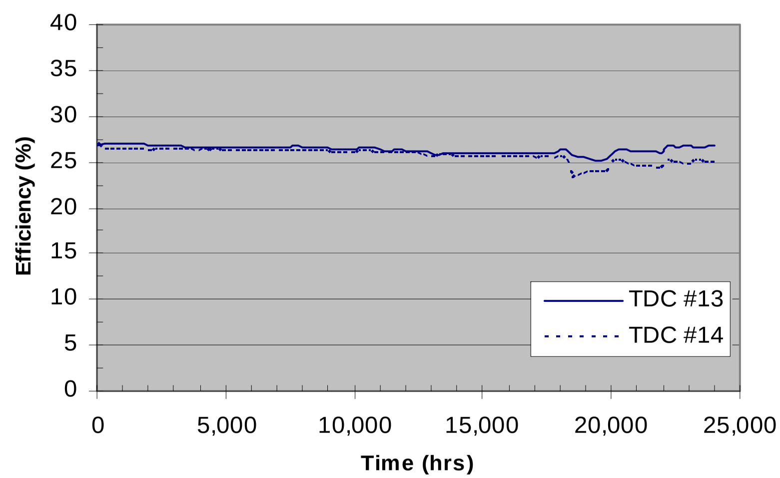


- Operation continued until shutdown for hermetic seal welding in January 06 after 19,108 hours
  - Fill tube was not sealed to allow analysis of working fluid composition
- Visual inspection of internal components showed no signs of wear or degradation

Stirling Convertor Testing at GRC

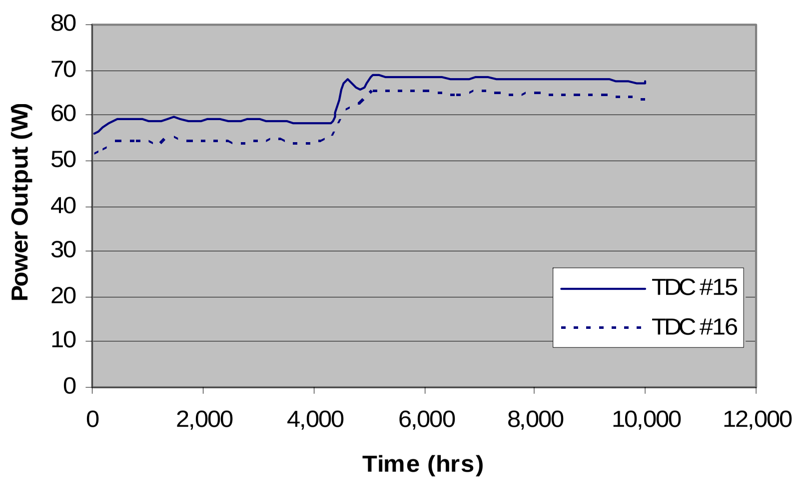
- TDC's #13 and #14 are currently at 27,044 hours
- Appears to be no degradation other than due to initial operation with oxygen permeation
- Variations in performance are mostly the result of the operating point
- No sign of working fluid changing due to outgassing or decomposition of the organics

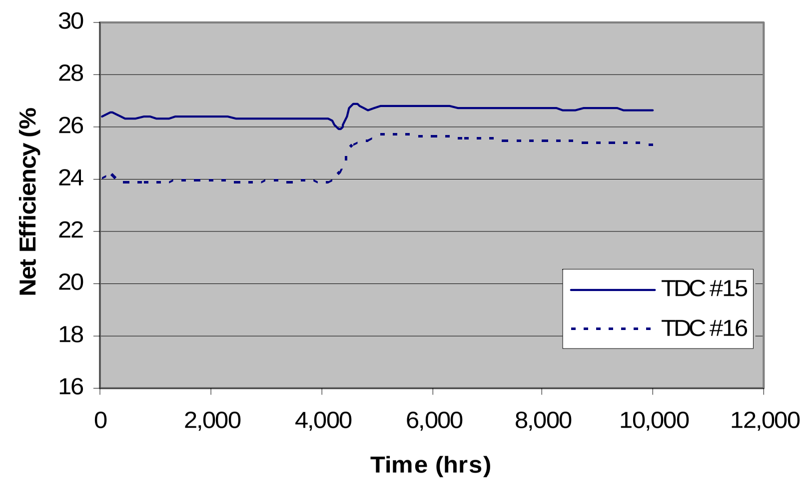




Stirling Convertor Testing at GRC

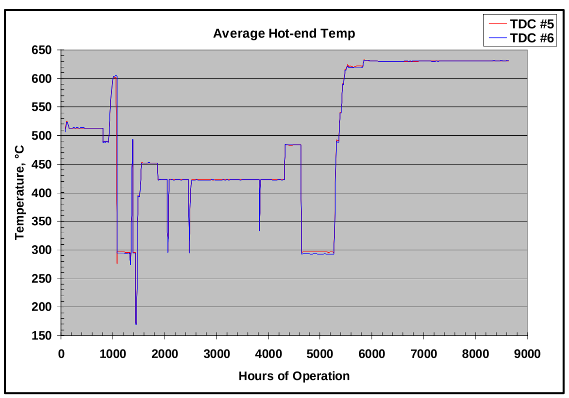
- TDC's #15 and #16 started extended operation in March 2005
- Operation before hermetic seal welding was at reduced temperatures
- Hermetic welded October 2005 at 4,413 hours
- No sign of working fluid changing due to outgassing or decomposition of the organics
- Currently at 13,009 hours

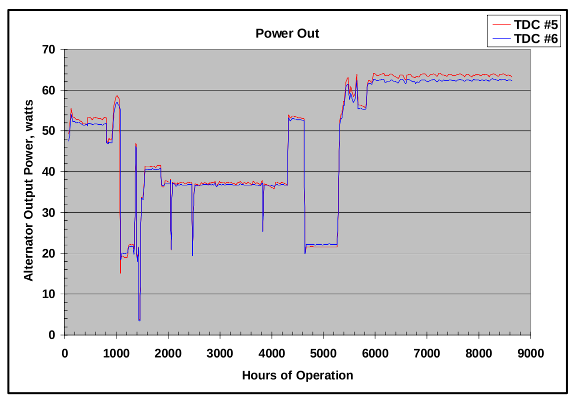


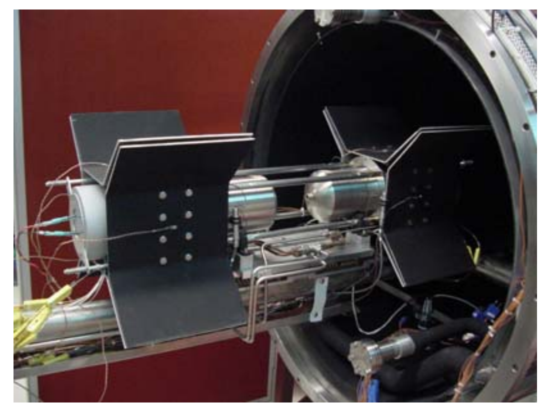


Stirling Convertor Testing at GRC

- TDC’s #5 and #6 were operated in focused tests before extended operation in 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
- Operation in thermal vacuum began in November 04, 24/7 in December 04
- Some hardware modifications were required,
  - Heater electric leads, size of radiator panels, emissivity of the pressure vessel
- Completed at 10,015 hours with no change in Stirling performance







Over 104,000 hours of operation on TDC’s at GRC

Controller Development

- Controller development was being led by Lockheed Martin
  - Architecture was based on zener diode circuit to clamp voltage with series/parallel tuning capacitors
  - Features to accommodate:
    - End user short circuit (over-current, too much load on Stirling)
    - End user open circuit (no power draw, power dissipated by shunt resistors)
- GRC supported LM effort through a series of tests and analyses
  - Start-up tests
  - Transient response tests
  - Frequency response tests
  - Performance mapping over anticipated operating conditions
  - Testing with various limiting scenarios to investigate system stability
  - System Dynamic Modeling of convertors with key features of the controller

Metallic Materials

- Characterized IN718 heater head material and optimized the processing for long life
- Developed data to represent the material on a probabilistic basis, conduct life analysis in probabilistic terms
- Based on GRC thin-specimen (0.5 and 1.0 mm) creep testing and extensive ORNL database (up to 87,000 hours)
  - 3 samples still under test from 1st heat – longest test to date is 47,430 hours
- 2nd heat of IN718 was purchased and samples were tested at GRC
  - 1 sample still under test from 2nd heat – longest test at 20,208 hours
  - Show properties to be equivalent to the original heat
- 255,411 total hours of creep tests

- Regenerator sintering optimization to enhance bond strength and eliminate shedding
- Braze process verification

Heater Head Structural Benchmark Testing

- 1, 3, and 12-month heater head structural benchmark tests were performed to factor in biaxial stress state and validate analysis
  - Tests were performed at design temperature with increased pressure
  - Extremely small creep strains were measured optically and with extensometers
  - One test included heat collector and axial preload

Benchmark Test Type		Accelerated				Non-Accelerated	
Test Article		Bitec1	Bitec2	Bitec3	STC209	STC206	STC212
Predicted	creep rate	high	mod. high	mod. high	moderate	very low	very low
	time to tertiary (days)	22	67	67	moderate	high	high
Observed	creep rate	very high	high	v. v. high	low	very low	low
	test duration (days)	30	59	25 (rupture)	131	235 (ongoing)	330 (ongoing)
	creep rate anisotropy	1.2:1	3:1	2:1	1:1	5.5:1	20:1

Heater head structural benchmark test

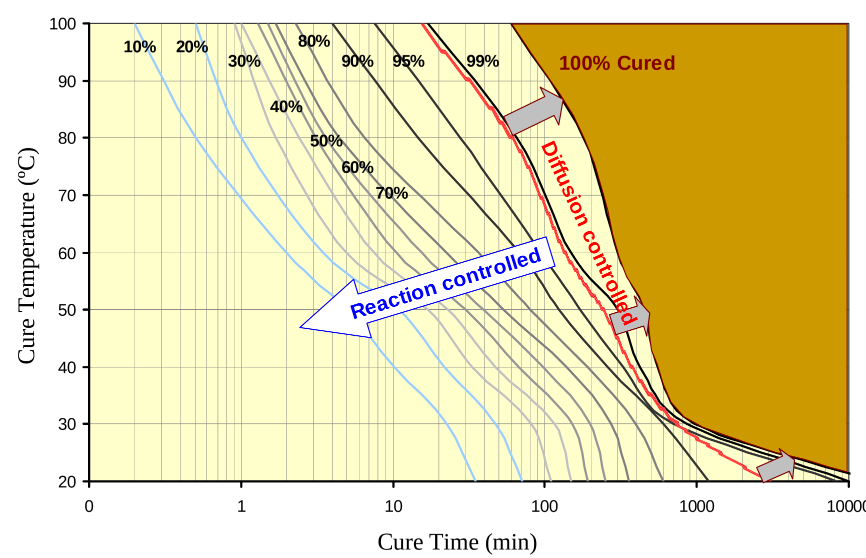
- Heater head probabilistic life prediction completed
  - 140,000 hours (16.0 years) at 650 °C and 99.99% probability of survival (PoS)
  - 218,000 hours (24.9 years) for PoS of 99.9%

Organics

- Organics are used as surface coatings, insulation, and adhesives
- Cure kinetics of critical adhesives were characterized and optimized
- Aging tests of the organics were conducted
- Initial assessment of radiation tolerance

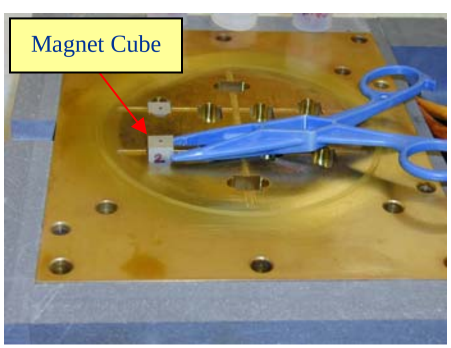
Results

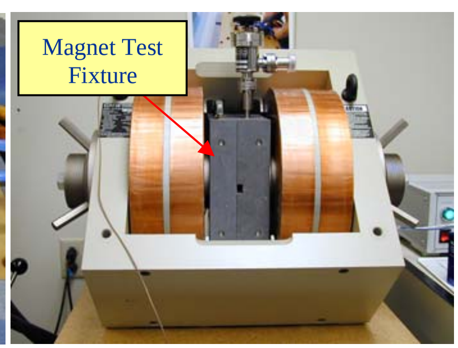
- Optimized cure process resulted in 40% increase in adhesive strength
- Performed assessment of radiation tolerance by working with vendors, literature, and JPL data
- Evaluation of outgassing through accelerated aging tests and convertor operation
  - No signs of outgassing after 27,000 hours

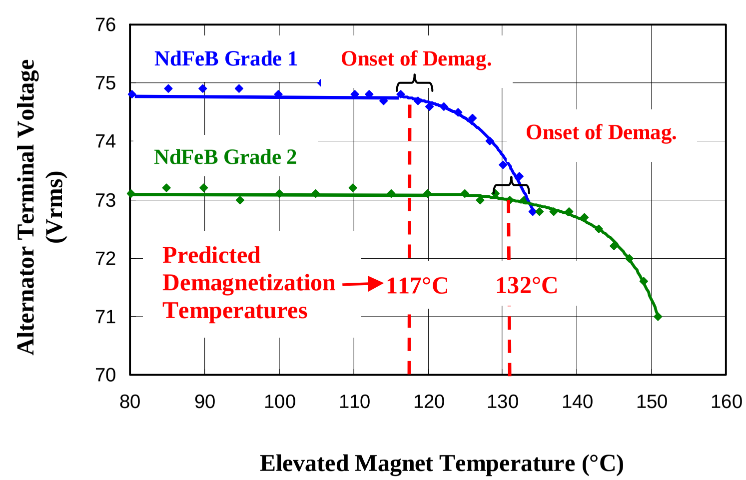


Magnets

- Characterize magnet types that were being considered
- Create technique for 3-D magnetostatic linear alternator analysis
- Able to predict conditions for demagnetization in a linear alternator and validate through tests
- Develop short-term and long-term magnet aging tests
  - No degradation was found following 18,000 hours at elevated temperature in demagnetization field
- Develop technique to characterize performance of curved magnets

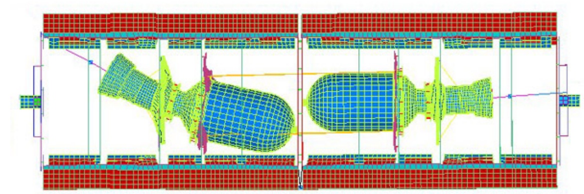




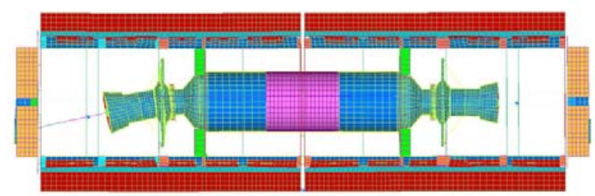


Structural Dynamics

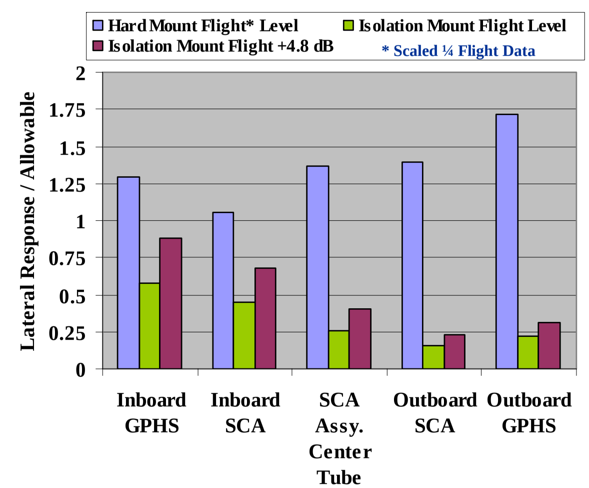
- Demonstrate full power operation of convertor up to 12.3 grms, 0.2 g^2/Hz
- 7 tests were used to fully characterize modal response of the Stirling convertor and the generator
- Developed the concept for structural integration of Stirling convertors into the generator to reduce launch loads
- Develop spacecraft adapter that could be used to reduce launch loads if needed
- Validate structural model through generator simulator test up to 15.1 grms
  - Showed that SRG-like generator could survive up to 15.1 grms, 0.3g^2/Hz



Original Configuration of Generator



Configuration with Connecting Tube



EMI/EMC

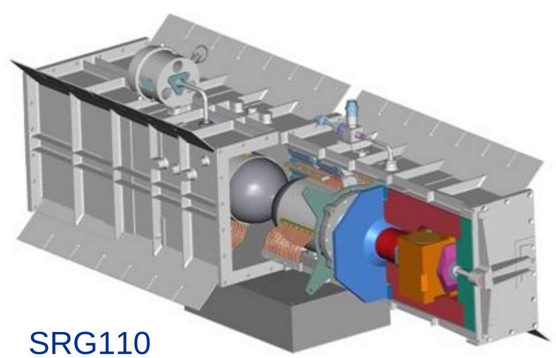
- Three tests were conducted at GRC and JPL
- It remains the finding that the SRG110 could meet general requirements of the science community, but may need a mission kit for the more demanding missions
  - Standard suppression techniques were demonstrated to be effective
- EMI remains a system level issue, requiring characterization of a complete generator

Reliability

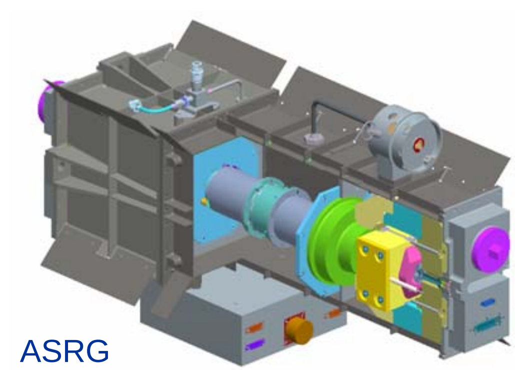
- Due to the nature of systems with no wear-out mechanisms, the reliability effort was multi-faceted
  - Classic techniques such as FMECA & FTA
  - Physics based probabilistic analyses
  - Extended operation of convertors
  - Wide range of component tests
  - Investigate relevant databases such as flight cyrocoolers
- Techniques for probabilistic analysis have been applied to all critical components
- Need to combine individual analyses into a single Stirling convertor analysis
- There is an inherent difficulty in verifying life and reliability of a device with no wear mechanism
  - Same challenge was faced as Stirling coolers transitioned to flight
  - Experience from long life Stirling cryocoolers is directly applicable
- Over 104,000 hours of operation at GRC, over 10,000 in thermal vacuum

Summary

- GRC supporting technology effort for the SRG110 was designed to mitigate risk
- There were no fundamental barriers found to achieving a level of reliability necessary for transition to flight
- Similar efforts are now underway at GRC to support development of the ASRG



SRG110



ASRG

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