Abstract for Presentation
for paper entitled
Overview of NASA GRC Stirling Technology Development
presented at the
2003 International Energy Conversion Engineering Conference
Portsmouth, VA
August 18-21, 2003

The Stirling Radioisotope Generator (SRG) is currently being developed by Lockheed Martin Astronautics (LMA) under contract to the Department of Energy (DOE). The generator will be a high efficiency electric power source for NASA Space Science missions with the capability to operate in the vacuum of deep space or in an atmosphere such as on the surface of Mars. High system efficiency is obtained through the use of free-piston Stirling power conversion technology. Power output of the generator will be greater than 100 watts at the beginning of life with the decline in power being largely due to the decay of the plutonium heat source. In support of the DOE SRG project, the NASA Glenn Research Center (GRC) has established a near-term technology effort to provide some of the critical data to ensure a successful transition to flight for what will be the first dynamic power system used in space. Initially, a limited number of technical areas were selected for the GRC effort, however this is now being expanded to more thoroughly cover a range of technical issues. The tasks include in-house testing of Stirling convertors and controllers, materials evaluation and heater head life assessment, structural dynamics, electromagnetic interference, organics evaluation, and reliability analysis. Most of these high-level tasks have several subtasks within. There is also an advanced technology effort that is complementary near-term technology effort.

Many of the tests make use of the 55-We Technology Demonstration Convertor (TDC). There have been multiple controller tests to support the LMA flight controller design effort. Preparation is continuing for a thermal/vacuum system demonstration. A pair of flight prototype TDC's have recently been placed on an extended test with unattended, continuous operation. Heater head life assessment efforts continue, with the material data being refined and the analysis moving toward the system perspective. Long-term magnet aging tests are continuing to characterize any possible aging in the strength or demagnetization resistance of the permanent magnets used in the linear alternator. In a parallel effort, higher performance magnets are also being evaluated. A reliability effort is being initiated that will help to guide the development activities with an increased focus on the necessary components and subsystems. Some other disciplines that are active in the GRC technology effort include structural dynamics, linear alternator analysis, EMI/EMC, controls, and mechanical design evaluation. This paper will provide an overview of some of the GRC technical efforts, including the current status, and a description of future efforts.

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Portsmouth, VA

by

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August 21, 2003

Stirling Radioisotope Power Stirling Technology Tasks at GRC

Objective: Support development of Stirling convertor for qualification and mission implementation

4.1 Independent Validation and Verification (IV&V) for the TDC's

- *TDC #5 - #8 performance mapping*
- *Thermal vacuum test*
- *Controller tests*
- *TDC #13 & #14 extended operation*

4.2 Heater Head Life Assessment and Materials Studies

- *Heater head life assessment*
- *Regenerator material*
- *Braze verification*
- *FWPF/CO_2 testing*

4.3 Magnet Aging Characterization and Linear Alternator Evaluation

- *Magnet aging characterization*
- *Linear alternator analysis*

4.4 Launch Environment Testing

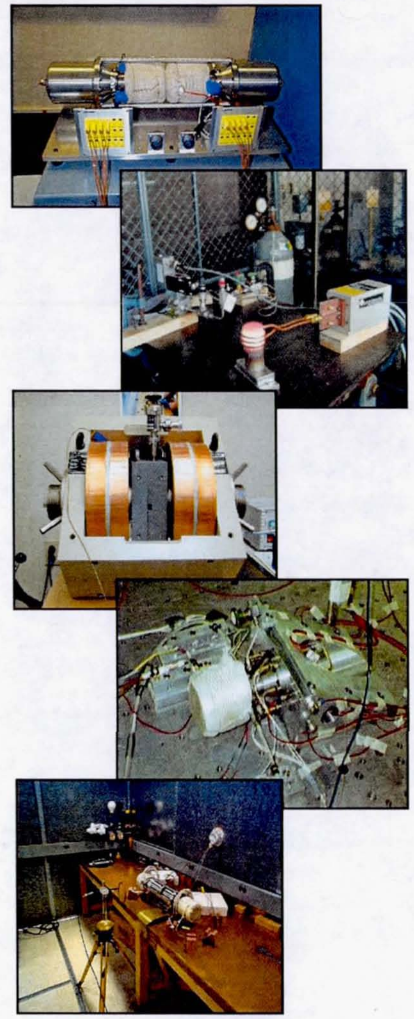
4.6 Electromagnetic Interference / Electromagnetic Compatibility

4.7 Organics

- *Magnet/lamination bond*
- *Helium charging cart*
- *Alternate lamination stacks*

4.8 Reliability

- *Probabilistic Analysis*
- *Fastener Audit*



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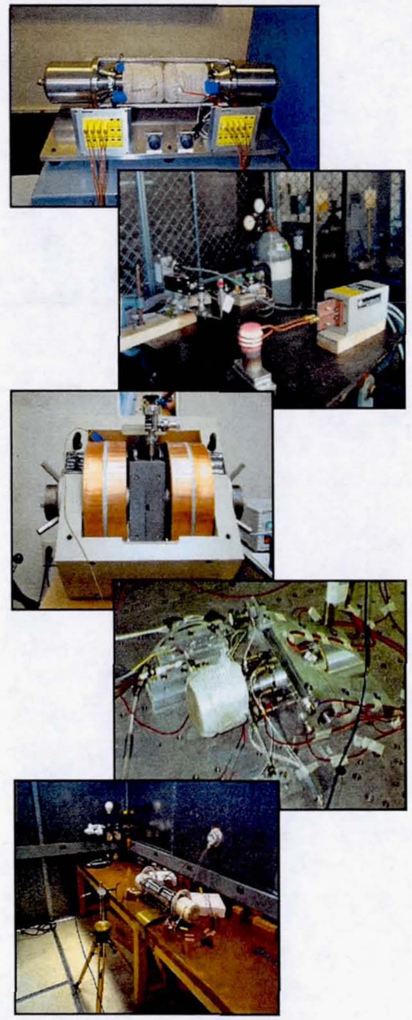
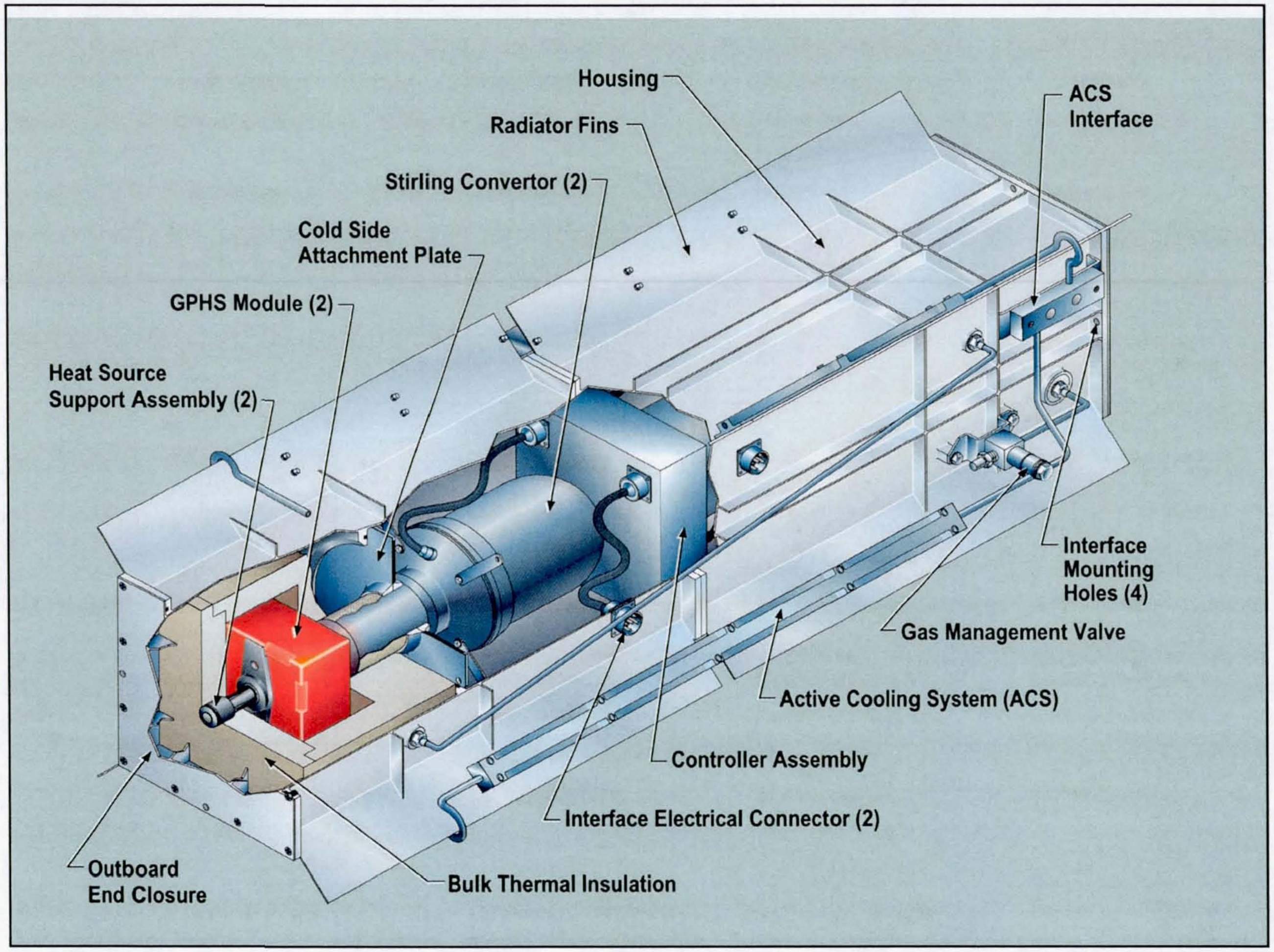


Advanced Stirling Radioisotope Generator

The First Generation SRG

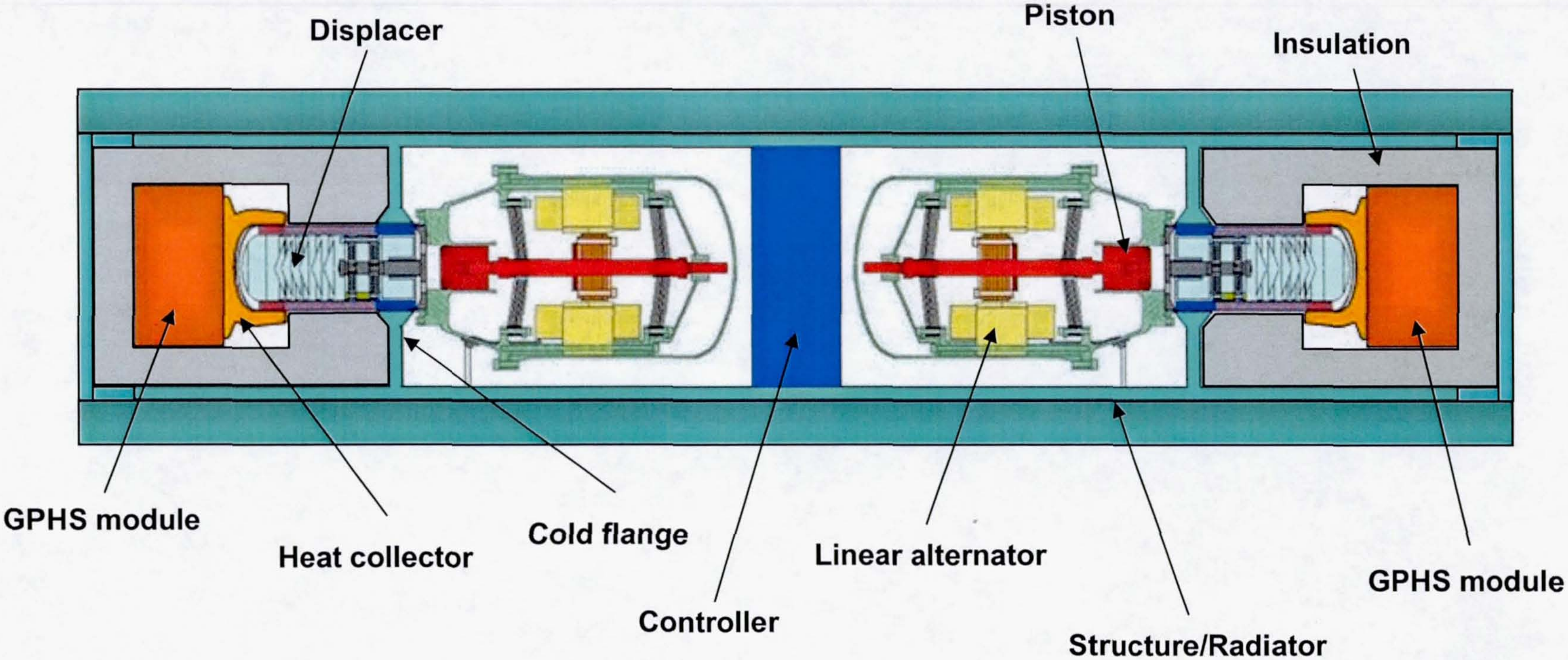


- **DOE development effort**
- **Lockheed Martin & Stirling Technology Company**
- **Heated by 2 GPHS modules**
- **114 Wdc at BOM**
- **27 kg projected mass (includes margin)**
- **4.2 W/kg specific power**
- **100,000 hour design life**
- **Operates in atmosphere or vacuum**
- **Uses the Stirling Technology Demonstration Convertor (TDC)**
- **Based on common aerospace industry materials**
- **Uses common aerospace industry fabrication & inspection techniques**

Advanced Stirling Radioisotope Generator

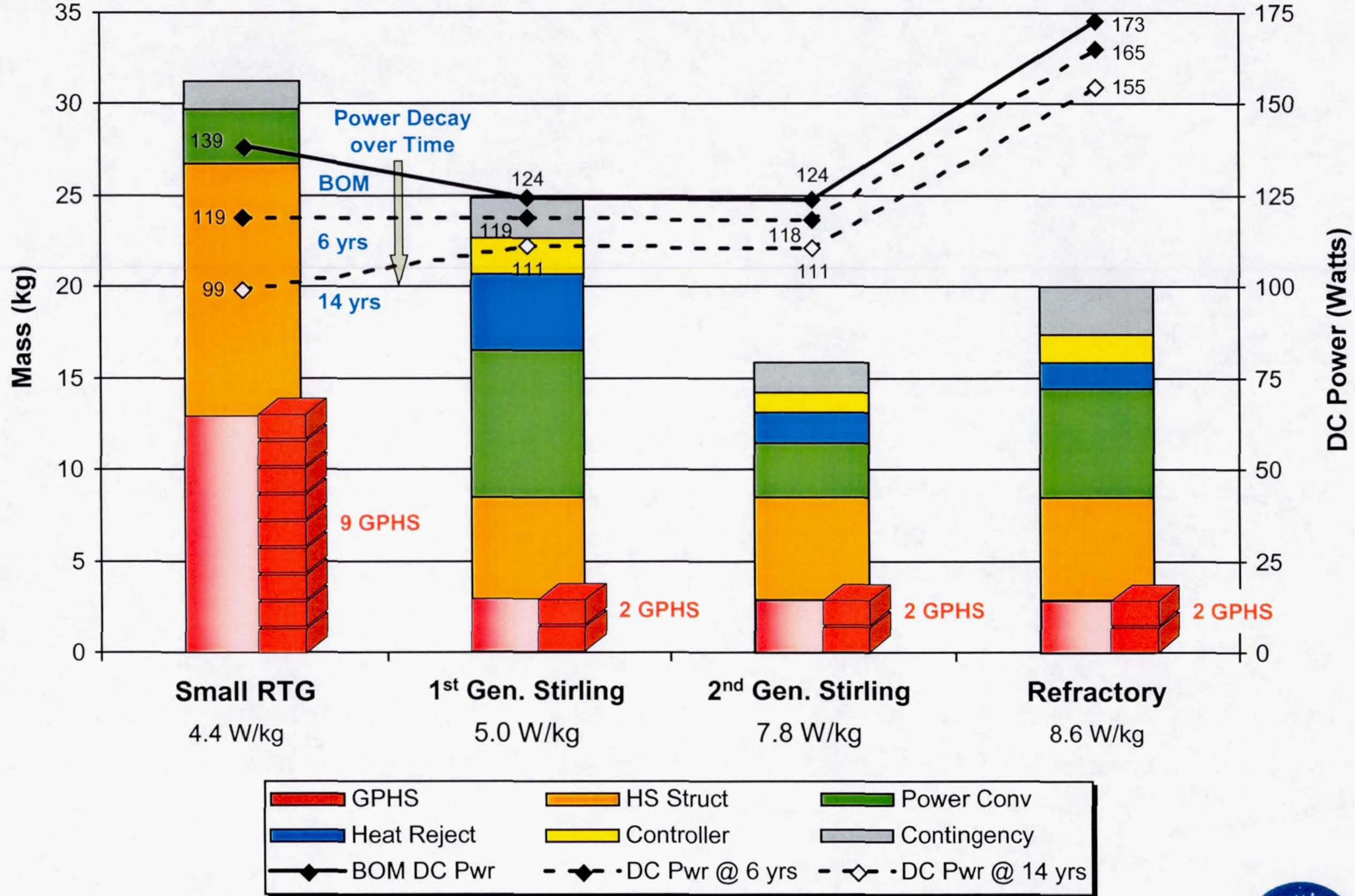
The First Generation SRG

Dual opposed configuration
- Synchronized operation
- Cancellation of Dynamic Forces



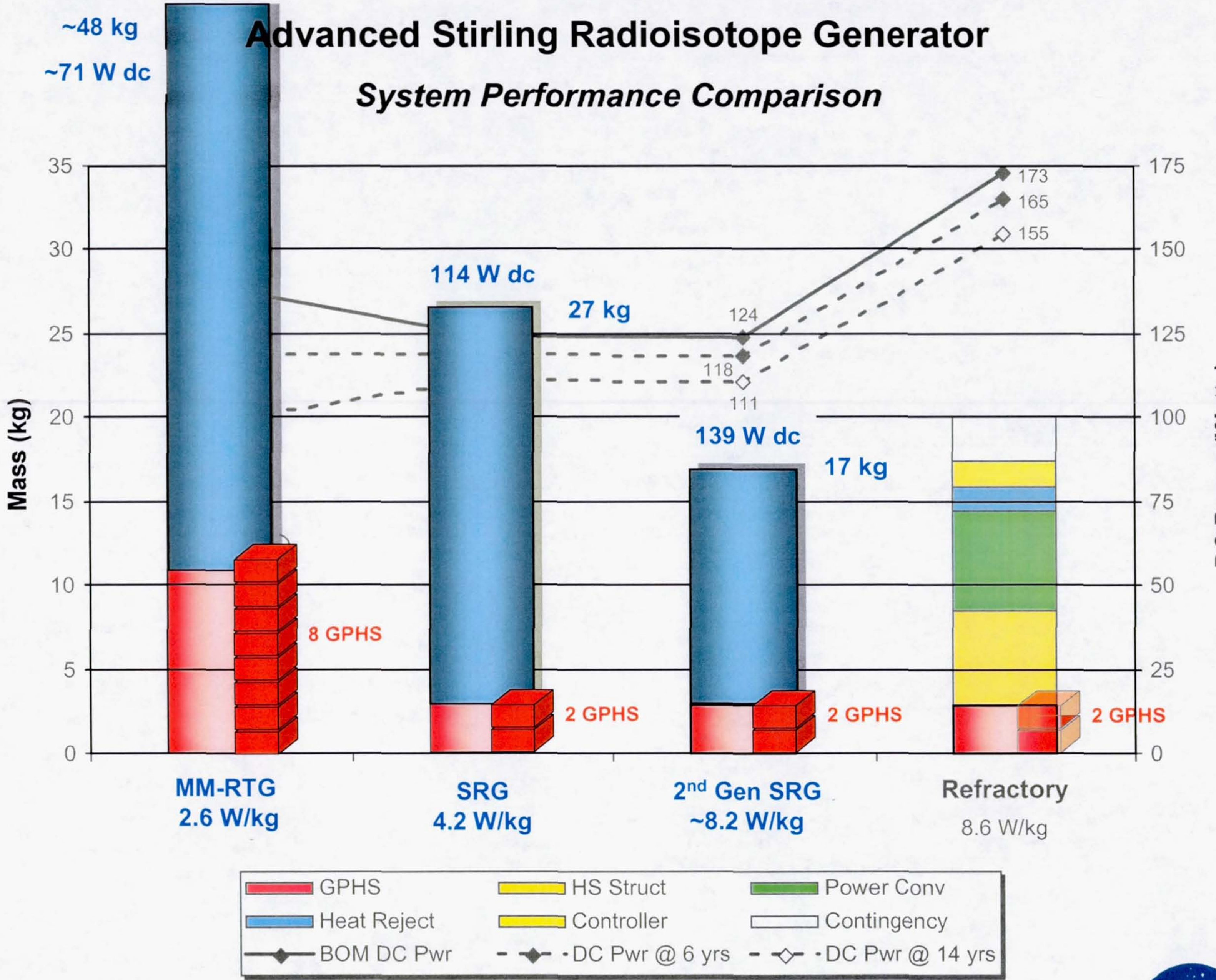
Advanced Stirling Radioisotope Generator

Projected System Performance Comparison - 2002



Advanced Stirling Radioisotope Generator

System Performance Comparison



GRC Stirling Test Facilities

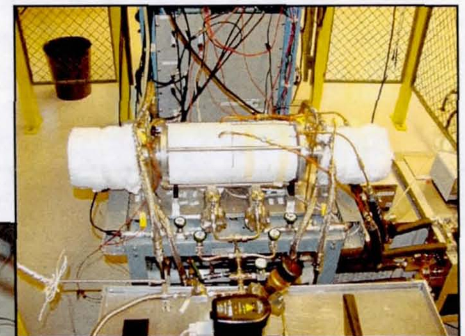
TDC #13 & #14 Independent Validation & Verification Testing

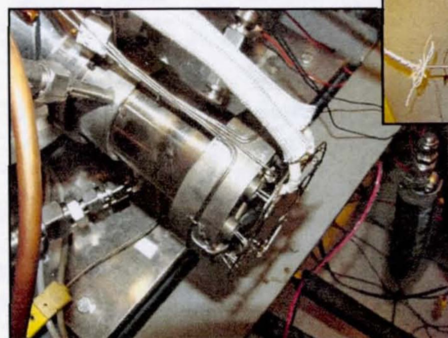
Objective: Characterize TDC #13 & #14 performance

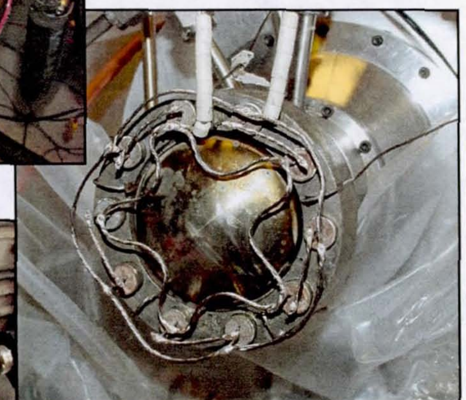
- *Vacuum Bake Out*
- *Thermal insulation Loss*
- *Acceptance Testing*
- *Performance Mapping*
- *Extended Operation*

Status

- Flight Prototype TDCs delivered to GRC February 14, 2003
- Charging Cart (with Gas Analysis) operational, March 2003
- 500 hour bake out completed, April 9
- TDC #14 Proof Pressure Test completed, April 22
- Thermal Insulation Loss Test completed, May 15
- Full Power Test Completed, May 22
- Single-Shift Extended Operation initiated on June 3
- Heater connections rewired, July 12
- Continuous Unattended Operation started, July 18, 2003
- First top-off with TDCs operational, July 18, 2003
- TDCs accumulated 1061 hours, as of 8:00 am, August 21, 2003
- Over 4,700 hours total on all TDC's at GRC







Planned Activities

- Complete TDC 1000 hour Gas Analysis
- Document gas sample analysis
- Conduct Performance Mapping Tests
- Revise operating point for Extended Operation

GRC Stirling Test Facilities

In-house Test Activities

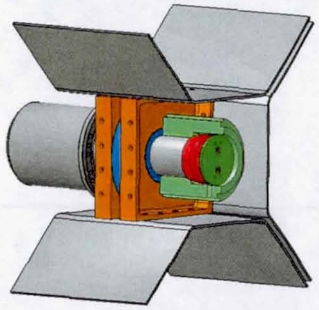
Requirements	No.	NASA No.	Test	Procedure	Status	Notes
Determine the convertors DC output impedance over multiple operating points (VI curves) to define controller stability requirements.	1	TR55-020	Load Convertor with a controller and apply a constant Net heat.	Maintain constant Net heat, vary DC node voltage, let stabilize and measure VI characteristics. Repeat at various heat inputs.	Test Report Complete	
	2	TR55-021	Load convertor with a resistive load and apply a constant Net heat.	Maintain constant Net heat, vary DC node voltage, let stabilize and measure VI characteristics. Repeat at various heat inputs.	Test Report Complete	
	3	TR55-023	Repeat Tests 1 & 2 and apply a constant Gross heat.	Repeat Tests 1 & 2 with a Gross heat allowing the Net heat to vary.	Test Report Complete	
	3a		Repeat Test 3, with improved insulation	see 1,2,3 above	start: TBD	Cancel
Determine the convertor's response to varying loads to define the Controller's bandwidth requirements.	4		Determine the convertor's frequency response (small signal).	Inject an ac signal at various frequencies on the DC node voltage and measure the convertor's current.	start: TBD	Keep, test procedure being developed
	5	TR55-026	Determine the convertor's transient response.	Using resistive load, measure transient reqponse to step load changes -- ac-side only	prelim. Test report received	Need to send final report
	5a		Determine convertor's response to gross transients	Overload increased to short.	start: TBD	Document
Measure the convertor's start-up characteristics with respect to input temperature to define the controller start-up load requirements.	6	TR55-022	Characterize the convertor as heat increases.	Measure convertor output to determine the temperatures that the engine starts at various loads.	Test Report Complete	
Test 2 convertors together to define the controllers synchronization requirements.	7		Characterize the convertor with respect to different controller nodes.	Connect 2 convertors to various electrical nodes with-in the Controller to determine the optimal point to force in-phase electrical operation.	start: TBD	Modify to sensitivity test (tuning cap)
Determine the sensitivity of the operating point and dc output impedance vs. alternator temperature.	8		Characterize the convertor with varying alternator housing temperatures.	Repeat test number 2, taking data at various alternator temperatures.	raw data received	Need to send test report
Determine the sensitivity of the operating point and dc output impedance vs. tuning capacitor value.	9		Expand on previous NASA Test 9/01 TR55-014.	Increase capacitor up to 30uF at 601C and higher.	start: TBD	On hold

GRC Stirling Test Facilities

Thermal Vacuum Testing

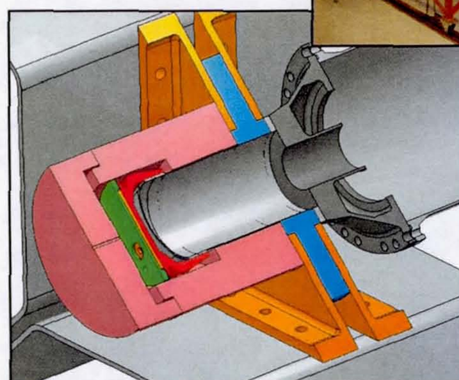
Objective: Characterize TDC performance under thermal vacuum conditions

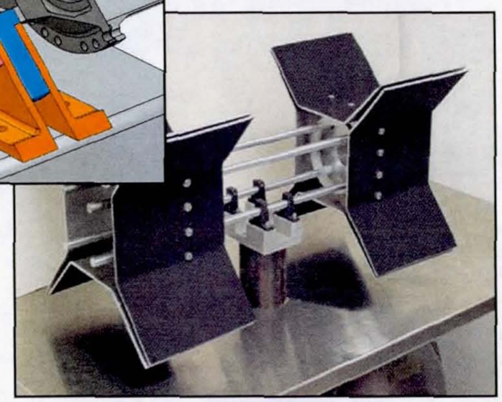
- *Demonstrate operation in a thermal/vacuum environment*
- *Provide data to validate thermal modeling*



Status

- VF 67 has been moved to the SRL
  - 2-stage roughing pump
  - Cryogenic pump
  - LN2 cold wall instrumented and installed
- Boralectric heat source designed and procured
- GRC heat collector design has been reviewed by STC, being fabricated
- Radiators designed and fabricated
- Radiator panel cold flange design nearing completion
  - Nickel flange braze to heater head
  - Copper flanges mate to radiators
  - Thermagon used at clamped interfaces



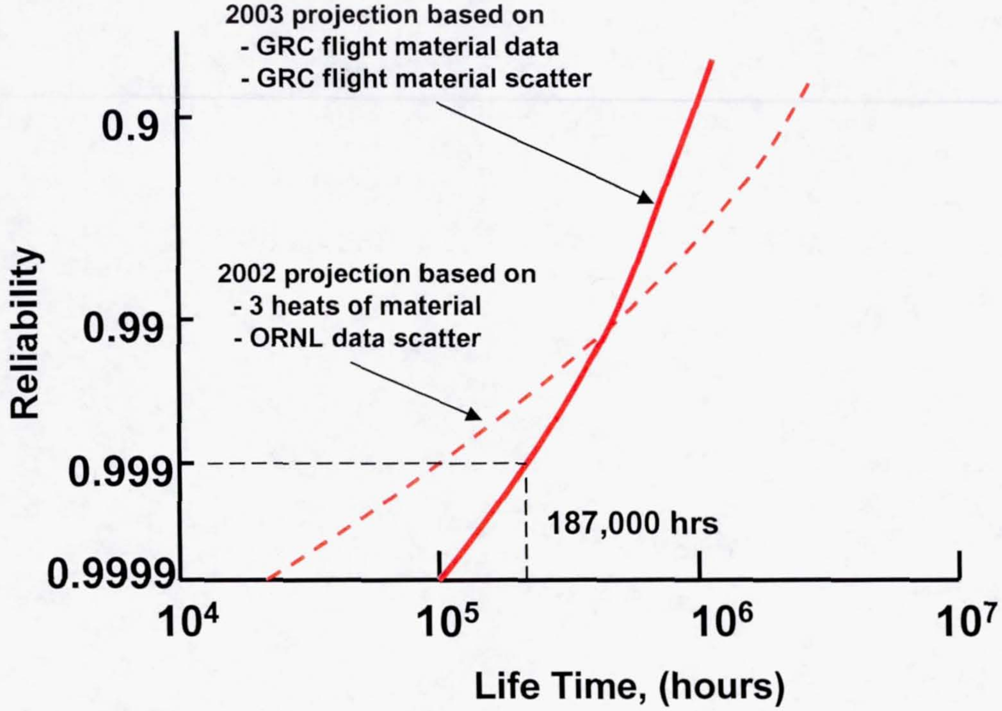


Planned Activities

- Fabricate and install new heater heads with brazed-on components onto TDC #5 & #6
- VF67 operational in September '03
- Test article installation planned for Q1 FY '04

Heater Head Life Assessment

New Data/Analysis Predicts Increased Creep Life



Probabilistic Analysis

- Combined GRC creep data for flight material and samples from 3 heats of non-optimized material to establish scatter
  - much lower than ORNL scatter
- Latest creep analysis with GRC flight material data shows:
  - lower mean creep life than GRC data for initial 3 heats, but with
  - much lower scatter than assumed from ORNL data
- Heater head life greater than Feb. 2002 calculations by:
  - 2X for 99.90% Reliability
  - 5X for 99.99% Reliability

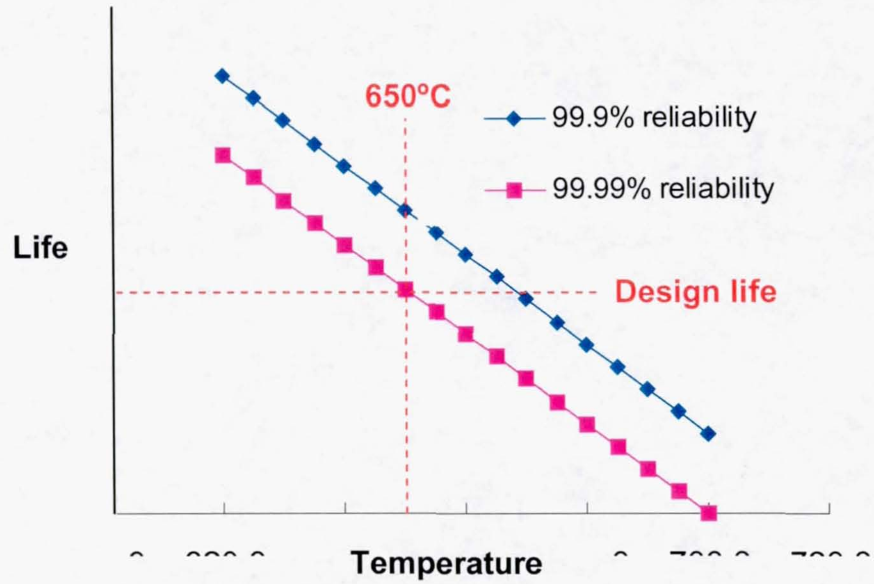
Heater Head Life Assessment

Probabilistic Creep-Lifing Analysis for Off-Design Temperatures

Operation above or below the 650°C design point alters the Life & Probability of Survival

Assumptions

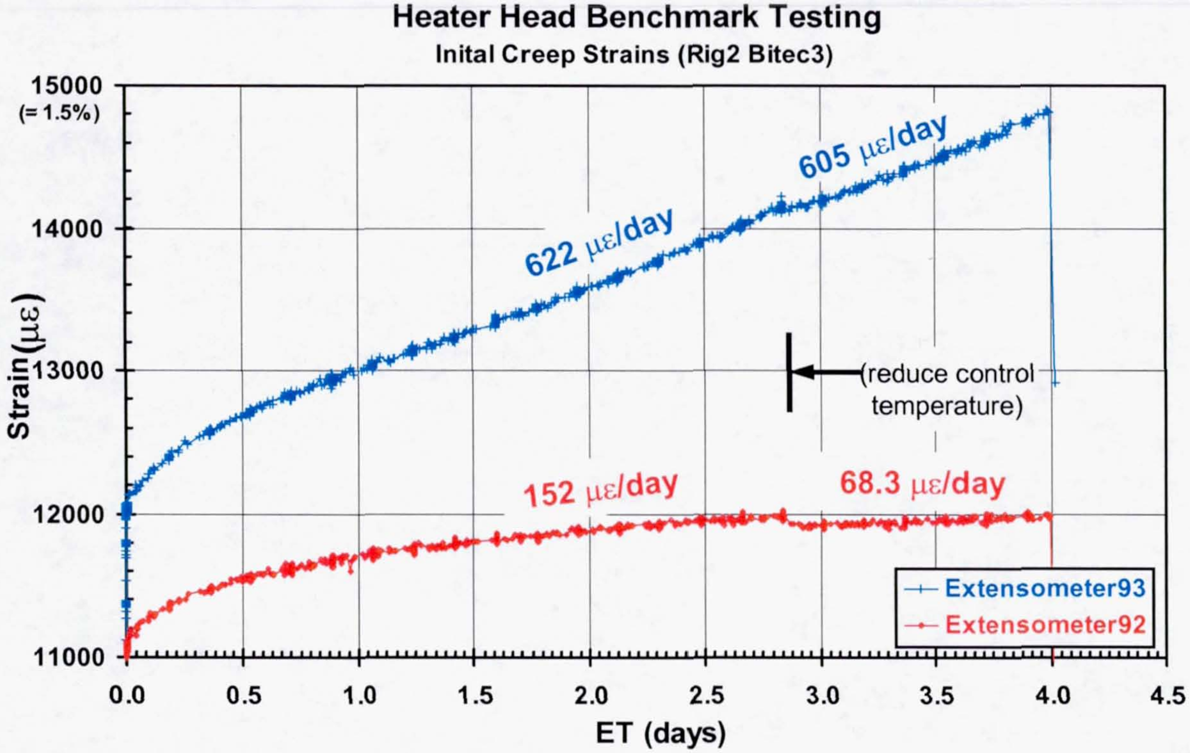
- **Creep is based on a shift in mean value from ORNL data**
- **Scatter and probability distribution at all temperature levels remain the same as at 650°C**
- **Analysis neglects scatter in wall thickness, axial preload, internal pressure**
- **Additional parameters will be included in analysis in August '03**

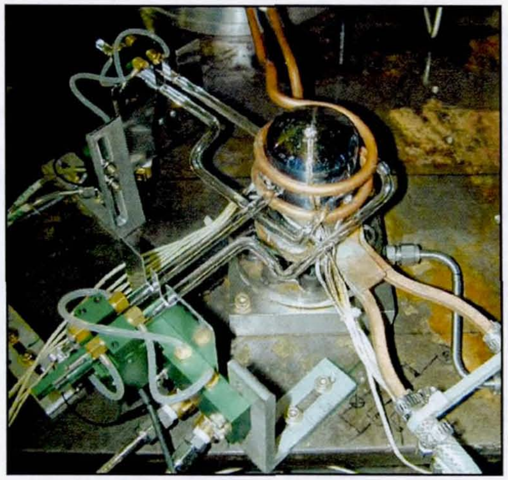


Heater Head Life Assessment

Structural Benchmark Test

- 3-month benchmark test initiated on July 21, 2003
- Accelerated-life (thin wall) specimen
- 890 psig (54 ksi), 650°C
- Now analyzing creep rate disparity for two perpendicular measurements



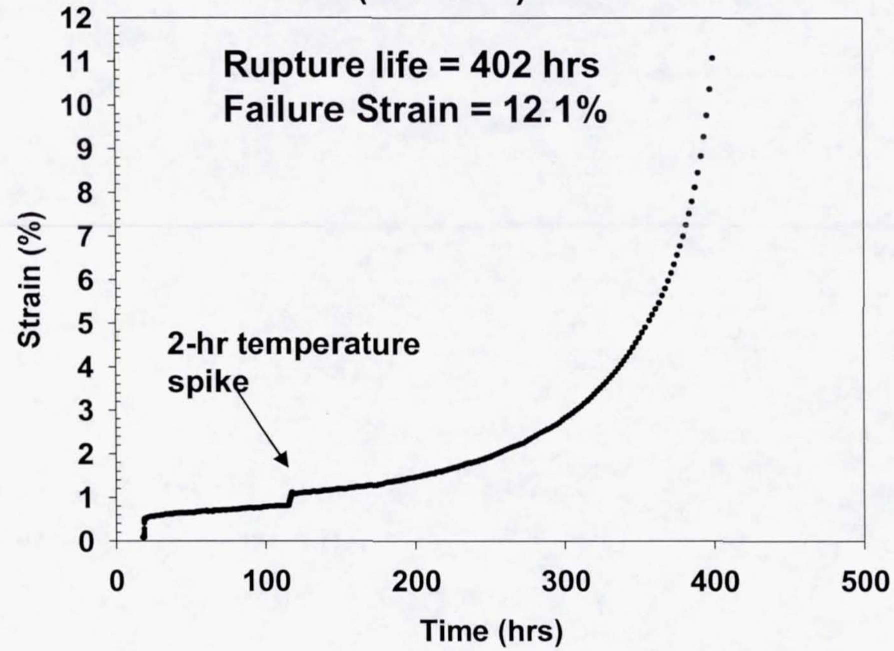


Bitec 3 on benchmark test rig

Heater Head Materials Evaluation

Evaluating the Effect of Temperature Excursions on the Creep Rate of IN718

Creep tests being performed at 650°C and 70 ksi (480 MPa) stress



Status

- A test was conducted with the temperature excursion to <u>700°C</u> for two hours and then returned to 650°C

At 650°C, before temp. excursion:

Strain = 0.82%

Strain Rate = 7.3×10^{-9} /sec

At 650°C, after temp. excursion:

Strain = 1.08%

Strain Rate = 9.4×10^{-9} /sec

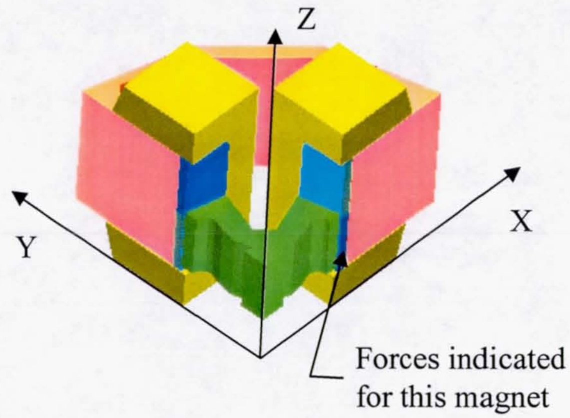
- Creep Rate did not return to the original value for these conditions

- Additional tests were performed for other temperature spikes and times
- In all cases examined, a spike in temperature resulted in a reduction in rupture life compared to the isothermal tests

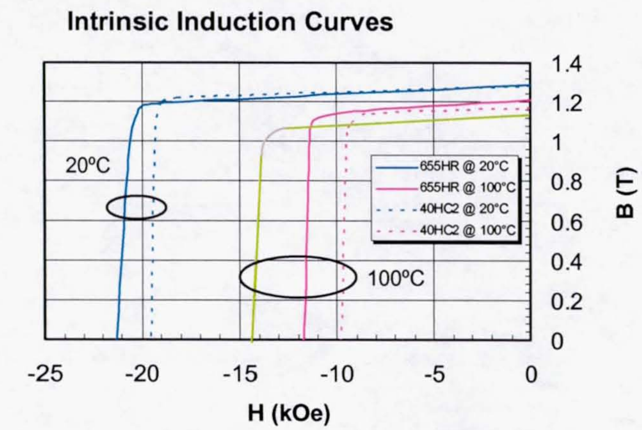
Linear Alternator Evaluation

Objective: To evaluate linear alternator designs that support the development of the Stirling Radioisotope Generator

- **3-D finite element magnetostatic modeling**
  - **Used to predict conditions which may result in damage to the magnets**
  - **Used to evaluate magnet forces in support of the magnet/lamination bond testing to be conducted by GRC**
    - **Under normal alternator loading with 80°C magnets for mover/magnet clearance between $^{1}/_{3}$ design gap and $1^{2}/_{3\text{design}}$ gap**
      - Forces in direction that holds magnets to stator lams (x-direction)
      - Forces in direction that pushes magnet off stator lams (z-direction)
      - Peak forces may increase by 30% in the x-direction and 46% in the z-direction for a 2.7A current spike.



  - **Currently being used to evaluate several design options which can potentially provide additional margin**
    - **Replace baseline magnets with new magnet type without changing magnet or alternator dimensions**
    - **1 or 2 new magnets may be selected pending results of preliminary characterization for thorough evaluation**



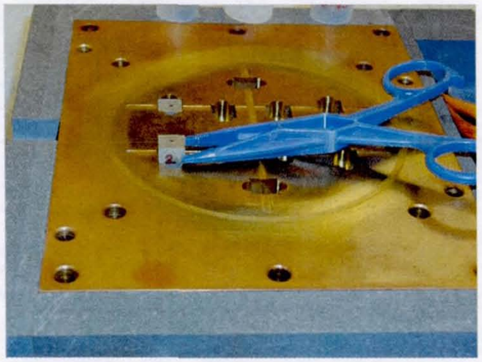
Permanent Magnet Aging Tests

Objective: Experimentally determine long-term aging of candidate linear alternator permanent magnets

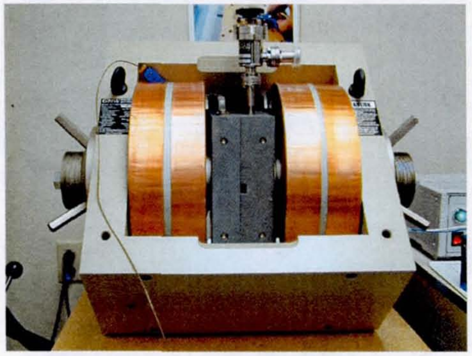
- ***Combined effects of temperature and DC demagnetizing field on strength and demagnetization resistance***

Status

- **Baseline Ugimag magnets have completed over 15,000 hours in long-term aging test**
  - 120°C, 6kOe demagnetization field
- **Completed preliminary characterization of VACODYM 655HR magnets**
  - Received magnets made to spec on May 1, 2003.
  - Measured average reminance (Br) at 20°C, was marginally higher than the vendor nominal Br *(+ better than vendor data)*
  - Measured average intrinsic coercivity (Hci) at 20°C was slightly less than the vendor nominal value *(x less than vendor nominal data)*
  - Measured Hci over the range of 20°C to 150°C, was between 5% and 8% lower than the vendor nominal values
  - This is 6% to 14% higher than the baseline magnet vendor nominal values
- **Preliminary characterization of new magnet types is currently underway**



Magnet samples in aging test fixture



Aging test fixture in electromagnet

Future Plans

- **1 or 2 new magnet types may be selected for 200 hour aging tests**

Reliability
Stirling Convertor and System Analysis

3 parallel efforts to assess and enhance reliability

Reliability Analysis
- Similar to Heater Head Durability Analysis
- Expand to include the entire of the Stirling convertor

Fastener Assessment
- Evaluate margins of the fasteners
- Focus on the most critical fasteners
- Scheduled to provide input in support of the PDR

Supplementary Reliability Effort
- Sest, Inc. and Swales
- Tap into cryocooler experience in flight acceptance
- Study previous reliability analysis
- Task placed with Sest, Inc. on August 19, 2003

Reliability

Stirling Convertor and System Reliability Analysis

Objective

- Perform a reliability analysis of the TDC and then the SRG to quantify the mission reliability
- Identify the uncertainty in the estimated mission reliability
- Perform a reliability sensitivity study for the convertor and other system components
- Develop draft plan for future analyses and testing to support development
- Develop guidelines to minimize the number of experiments to demonstrate reliability

Status

- Detailed analysis approach for Stirling convertor has been developed and documented
- Effort will be NASA led with contractor support (SAIC and Sest, Inc.) that will:
  - Identify analysis disciplines for convertor components and design variables
  - Determine interaction between components and uncertainties in response variables
  - Allow flexibility for math models other than classic reliability block diagrams
  - Fall back on inference to similar equipment or expert elicitation if necessary for component failure probabilities when necessary
- SAIC and Sest contracts have been finalized

Planned Activities

- Coordinate start of analysis between contractors in Q4 FY'03
- Perform analysis looking specifically at the fasteners, starting in Q4 FY'03

Advanced Technology

- Multi-dimensional thermodynamic analysis
- Linear alternator test rig
- Low vibration technology
- Controller research
- 2^{nd} generation power conversion
- High temperature heater head development

Conclusions

- Efforts are progressing to ensure a successful transition to flight
  - TDC's #13 & #14 are on Extended Operation Test
  - TDC's #5 & #6 will be tested in thermal vacuum facility
- GRC activities are in areas where there is strength to complement industry
- Many tests and technologies are addressing system level issues
- Results are being used by LMA & STC