Overview of NASA Magnet and Linear Alternator Research Efforts

Steven M. Geng and Gene E. Schwarze
NASA Glenn Research Center
21000 Brookpark Rd.
Cleveland, OH 44135
Steven.M.Geng@nasa.gov
Gene.E.Schwarze@nasa.gov

Janis M. Niedra
QSS Group, Inc.
21000 Brookpark Rd.
Cleveland, OH 44135
Janis.M.Niedra@grc.nasa.gov

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Abstract

The Department of Energy (DOE), Stirling Technology Company (STC), and NASA Glenn Research Center (GRC) are developing a free-piston Stirling power convertor for a high-efficiency Stirling Radioisotope Generator (SRG) for NASA Space Science missions. NASA Glenn is conducting in-house research on permanent magnets and on linear alternators to assist in developing the convertor for space qualification and mission implementation.

The permanent magnet research efforts include magnet characterization, short-term magnet aging tests, and long term magnet aging tests. Magnet characterization was performed on 1-cm cube Neodymium-Iron-Boron (NeFeB) magnet samples obtained from a variety of permanent magnet vendors. The remenance (B_r), intrinsic coercivity (H_{ci}) and the M-H curves were measured for each of the magnet samples over a large temperature range (20°C to 140°C). Based on the results of the magnet characterization effort, several magnet grades were selected for the short-term magnet aging test. The short-term magnet aging test was a 200 hour test where the magnet samples were exposed to a temperature of 150°C and a demagnetization field of -5.0 kOe. Magnet grades that survived the short-term magnet aging test were carried forward to the long-term magnet aging test. The long-term magnet aging test was originally scheduled to be 12,000 hour test where the magnet samples were exposed to a temperature of 120°C and a demagnetization field of -6.0 kOe.

Although the magnet research efforts performed at GRC were conducted on 1-cm cube magnet samples, a special magnet fixture was designed and built by KJS Associates, Inc., for GRC to measure the intrinsic coercivity of the actual magnets used in STC's 55We Stirling power convertor. Due to nature of the magnet geometry, the accuracy of the H_{ci} measurements on the actual Stirling power convertor magnets is less than that for the 1-cm cubes. However, the special magnet fixture may be of use in performing a relative comparison between actual Stirling power convertor magnets to weed-out those with performance issues.

Linear alternator research efforts have just recently begun at GRC with the characterization of a moving iron type linear alternator using GRC's alternator test rig (ATR). The linear alternator performance was mapped over a range of temperatures, mover amplitudes, and alternator loads. The power output, voltage, current, power factor, and alternator efficiency were measured.

This paper reports on the progress and future plans of GRC's magnet and linear alternator research efforts.

Overview of NASA Magnet and Linear Alternator Research Efforts

Steven M. Geng[1a], Janis M. Niedra[2], and Gene E. Schwarze[1b]

[1a]*Thermal Energy Conversion Branch, and* [1b]*Advanced Electrical Systems Branch, NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135, USA*
[2]*QSS Group, Inc., 21000 Brookpark Rd., Cleveland, OH 44135, USA*
[1a]*(216) 433-6145, Steven.M.Geng@nasa.gov*

Abstract. The Department of Energy, Lockheed Martin, Stirling Technology Company, and NASA Glenn Research Center are developing a high-efficiency, 110 watt Stirling Radioisotope Generator (SRG110) for NASA Space Science missions. NASA Glenn is conducting in-house research on rare earth permanent magnets and on linear alternators to assist in developing a free-piston Stirling convertor for the SRG110 and for developing advanced technology. The permanent magnet research efforts include magnet characterization, short-term magnet aging tests, and long-term magnet aging tests. Linear alternator research efforts have begun just recently at GRC with the characterization of a moving iron type linear alternator using GRC's alternator test rig. This paper reports on the progress and future plans of GRC's magnet and linear alternator research efforts.

INTRODUCTION

The Department of Energy (DOE), Lockheed Martin (LM) of Valley Forge, PA, Stirling Technology Company (STC) of Kennewick, WA, and NASA Glenn Research Center (GRC) are developing a high-efficiency, 110 watt Stirling Radioisotope Generator (SRG110) for possible use on future NASA Space Science missions (Cockfield and Chan, 2002) (Schreiber and Thieme, 2004). To assist in the development of a free-piston Stirling convertor for the SRG110, GRC is conducting in-house research on rare earth permanent magnets (REPM) and on linear alternators. The REPM research efforts include magnet characterization, short-term magnet aging tests, and long-term magnet aging tests.

Magnet characterization was performed on 1-cm cube neodymium-iron-boron rare earth permanent magnets obtained from various vendors. The remanence (B_r), intrinsic coercivity (H_{ci}) and the magnetization (M) were measured for each of the magnet samples over the temperature range of 20 °C to 140 °C.

Based on the results of the magnet characterization tests, several magnet grades were selected for the short-term magnet aging test. The short-term magnet aging test was a 200 hour test, with the magnet samples exposed to a temperature of 150 °C and a demagnetizing field of -5.0 kOe. Magnet grades that suffered the least amount of magnetic property loss during the short-term magnet aging test were then subjected to the long-term magnet aging test. The long-term magnet aging test was originally scheduled to be a 12,000 hour test, with the magnet samples exposed to a temperature of 120 °C and a demagnetizing field of -6.0 kOe. The long-term magnet aging test was extended and lasted for 18,000 hours.

Although the magnet research efforts performed at GRC were conducted on 1-cm cubic magnet samples, a special arc-magnet fixture was designed and built to measure the intrinsic coercivity of the actual magnets used in a Stirling convertor application. Due to the nature of the magnet geometry, the accuracy of the H_{ci} measurements on the Stirling power convertor magnets is less than that for the 1-cm cubes. However, the arc-magnet fixture may be of use in performing a relative comparison between Stirling power convertor magnets to exclude those magnets that may lead to performance issues.

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By:

Steven M. Geng and Gene E. Schwarze
NASA Glenn Research Center
and
Janis M. Niedra
QSS Group, Inc.

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Agenda

- Introduction
- Magnet Characterization
- Magnet Aging Tests
  - Short-Term
  - Long-Term
- Present Status
- Characterization of Arc-Shaped Magnets
- Linear Alternator Characterization
- Future Plans
- Concluding Remarks

Introduction

- GRC conducting in-house research on rare earth permanent magnets (REPMs) and on linear alternators (Las) to assist in developing a free-piston Stirling convertor (FPSC) for the 110 We Stirling Radioisotope Generator (SRG110) and for developing advanced technology

- REPM research efforts include magnet characterization, short-term magnet aging tests, and long-term magnet aging tests

- LA research efforts include performance mapping and alternator characterization

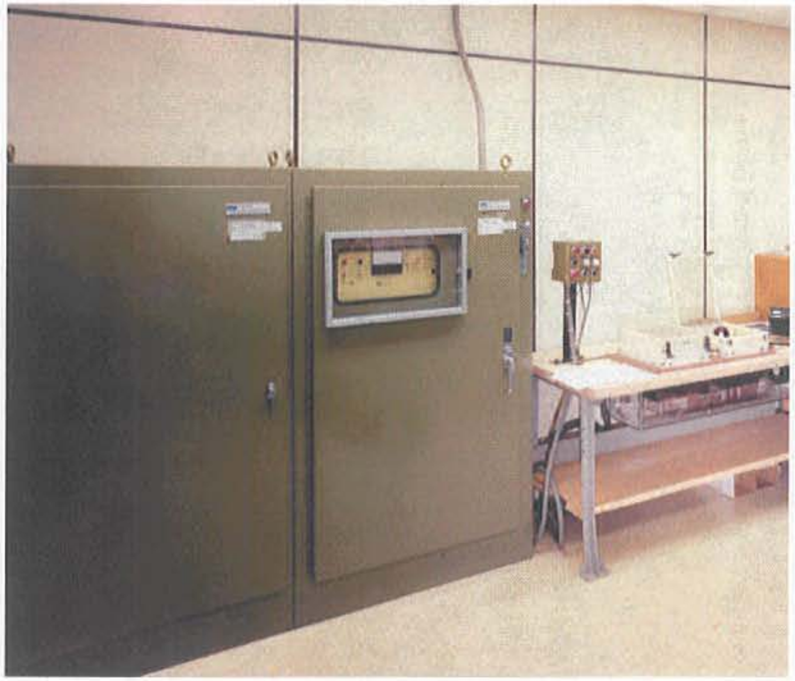
Magnet Characterization

- **NdFeB REPMs Investigated**

•Ugimag	40HC2
	38KC2
	35UC1
•VAC	383HR
	396HR
	400HR
	655HR
	677HR
•Magnequench	MQ3-F36H
	MQ3-F42
	MQ3-G32SH

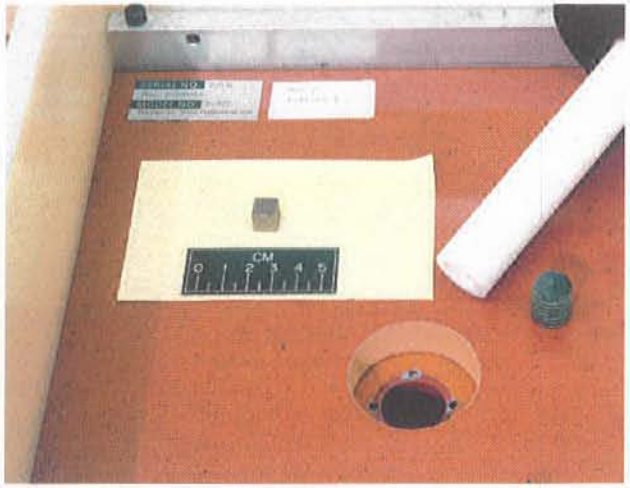
- Selection Criteria
  - Highest B_r, H_c, H_{ci}
  - Multiple Vendors
- Today, availability of magnet types is questionable due to the consolidation of the REPM industry

Magnet Characterization



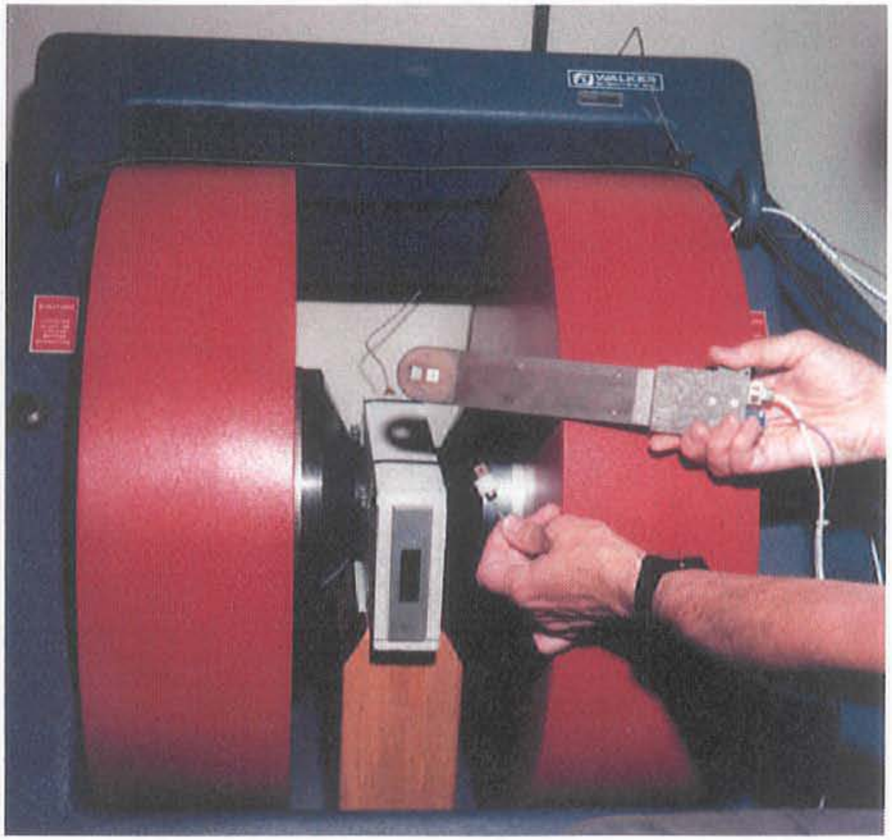
Pulse Magnetizer (Mercury-Ignitron-Switched, Capacitor-Discharge Type)

- Maximum of 24 kJ can be stored at 2000 V on a 0.012 F capacitor bank
- Bank can be connect to either one of two solenoids
  - 2.54 cm bore providing peak fields up to 13 T
  - 4.45 cm bore providing peak fields up to 10 T

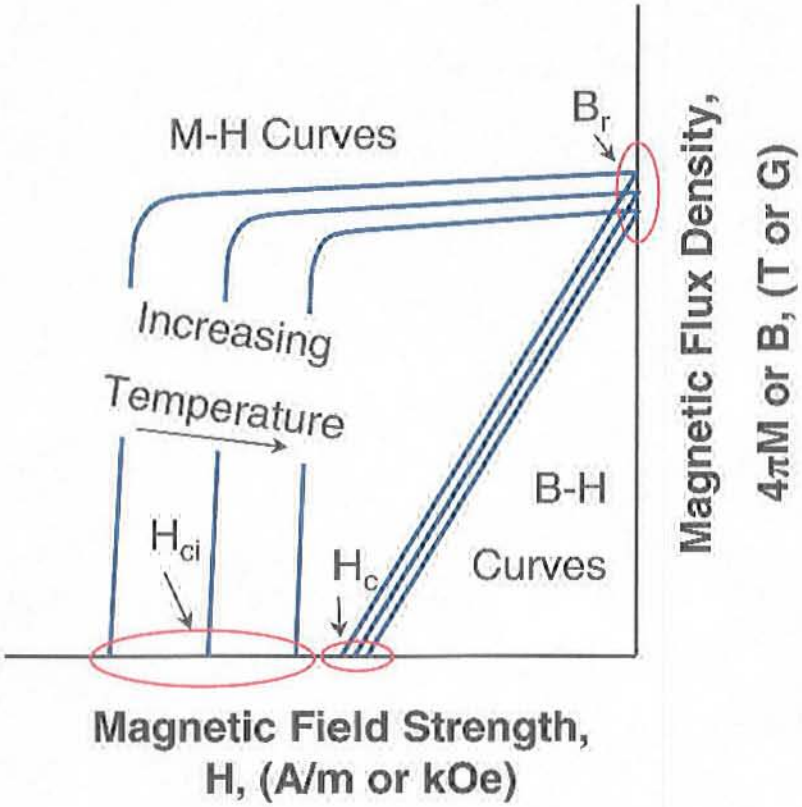


Charge Table

Magnet Characterization

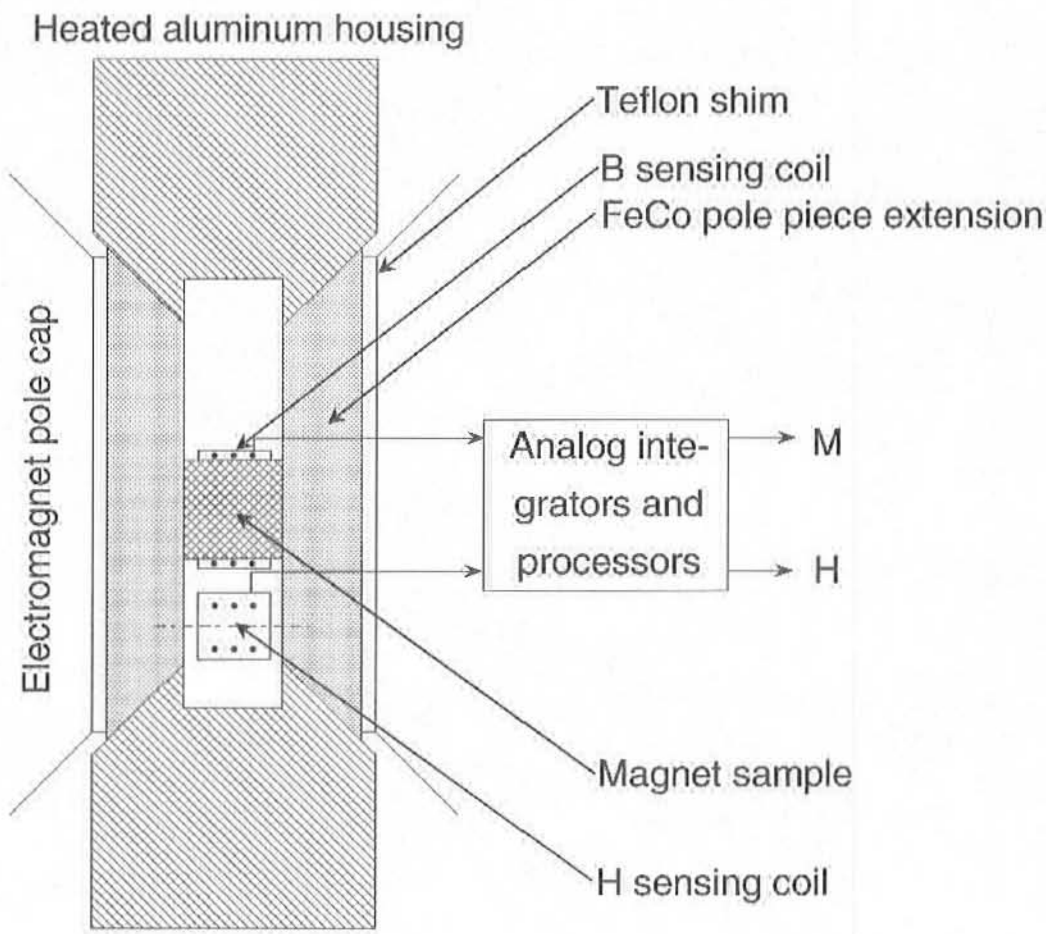


GRCs Magnet Characterization Apparatus



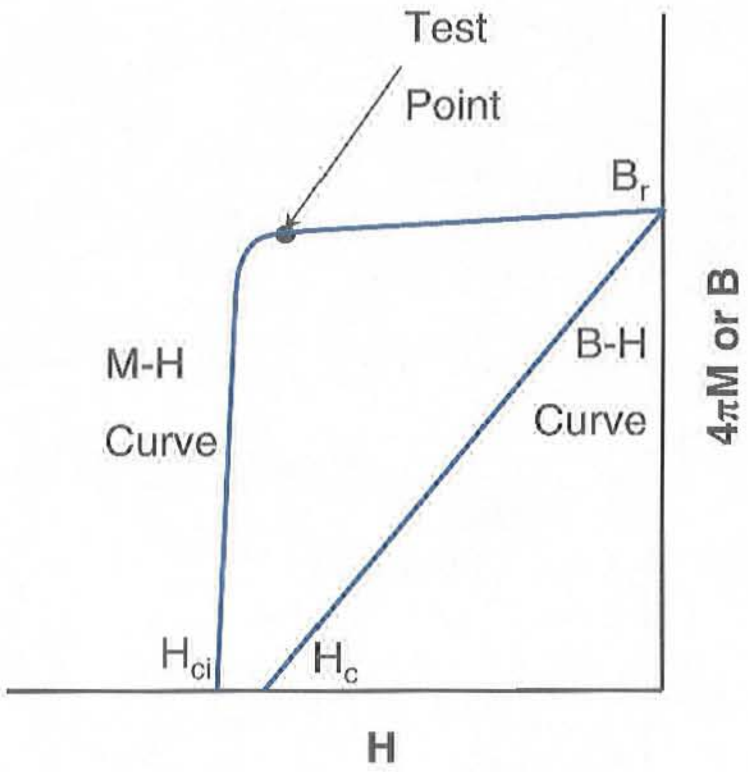
Magnet Characterization

- Magnet samples can be heated to 300 °C
- Fixture located between tapered pole caps of 10-inch electromagnet



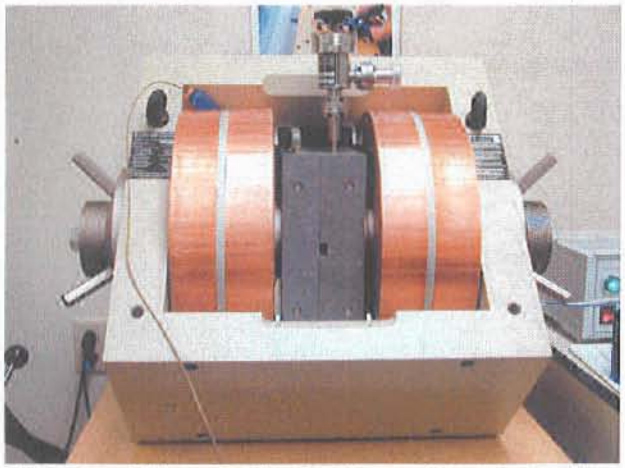
Magnet Aging Tests

- Short-Term Aging Test Conditions
  - 150 °C
  - -5.0 kOe
  - 200 hrs
- Long-Term Aging Test Conditions
  - 120 °C
  - -6.0 kOe
  - 12,000 hrs

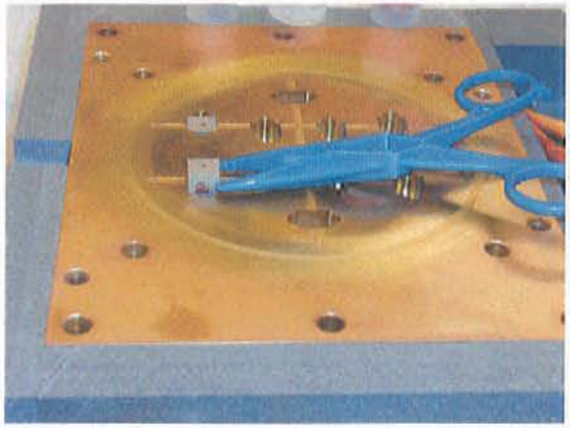


Magnet Aging Tests

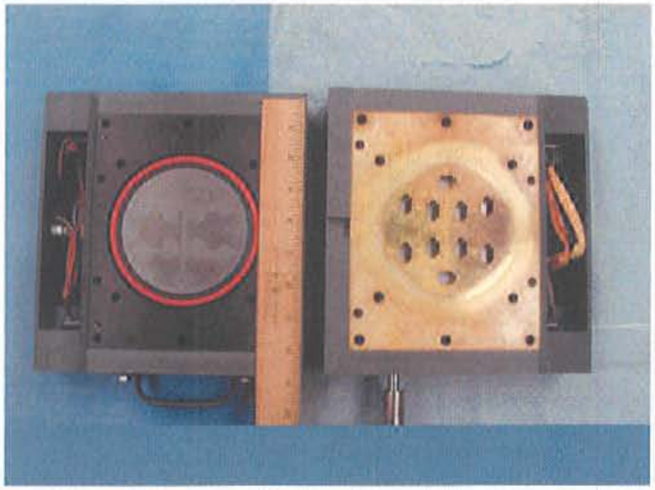
- Accommodates (qty) 10, 1-cm cube magnet samples
- Located between 4-inch diameter Fe-Co alloy poles of electro-magnet (EM)
- Distributes samples over pole face to minimize sample-to-sample interference
- Temperature limit of 200 °C



GRCs Magnet Aging Apparatus



Nd-Fe-B Magnet Sample Being Placed in Fixture



GRCs Magnet Aging Fixture

Magnet Aging Tests

- **Short-Term**

SAMPLE	B_r Initial on Recoil Line (T)	B_r Final on Recoil Line (T)	$\frac{\Delta B_r}{B_r}$ (%)	Intrinsic Coercivity Initial (kOe)	Intrinsic Coercivity Final (kOe)	$\frac{\Delta H_{ci}}{H_{ci}}$ (%)
VAC						
396HR-1	1.06	1. 06	**+0.00**	10.8	10.75	**–0.50**
383HR-2	1.10	1.08	**-1.8**	8.50	8.35	**–1.80**
UGIMAG						
40HC2-3	1.15	1.145	**–0.4**	8.65	8.55	**–1.20**
40HC2-4	1.15	1.15	**+0.00**	8.75	8.52	**–2.60**
38KC2-5	1.15	1.14	**–0.87**	8.75	8.60	**–1.70**
38KC2-6	1.15	1.14	**–0.87**	8.65	8.5	**–1.70**
MAGNEQ						
MQ3-F42-7	1.18	1.125	**-4.6**	8.75	8.45	**-3.40**
MQ3-F42-8	1.16	1.125	**-3.0**	8.90	8.55	**-3.90**
MQ3-F36-9	1.14	1.06	**-7.0**	8.38	8.25	**-1.60**
MQ3-F36-10	1.12	1.04	**-7.1**	8.4	8.25	**-1.80**

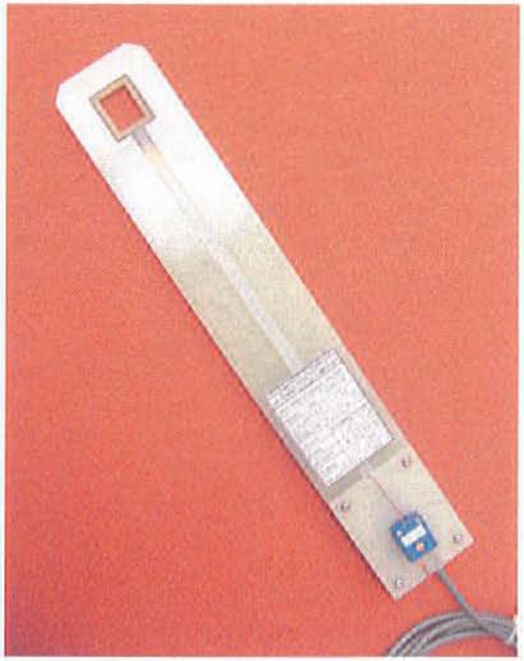
$\frac{\Delta B_r}{B_r}$ = Percentage change in remanence at 120°C on the recoil line, which was originally established at 150°C, -6.0 kOe.

$\frac{\Delta H_{ci}}{H_{ci}}$ = Percentage change in "aged" curve intrinsic coercivity compared to the initial one, at 120°C.

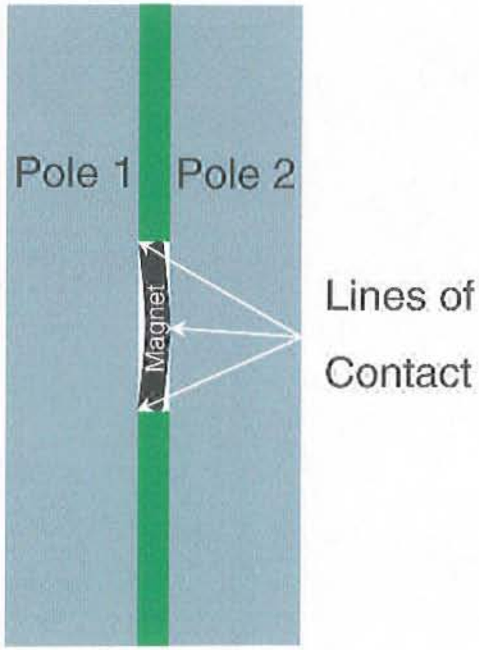
Present Status

- Four new Nd-Fe-B magnet types were identified and characterized to verify performance advertised by the vendor
- No short-term degradation was observed at elevated temperature (150 °C) under external demagnetization field (-5 kOe)
- Analysis performed to determine the temperature capability of all four of the new magnet types
- With the final selection, an additional 35 °C capability has been realized in the alternator (101 °C to 136 °C)
- Preparations are currently underway for long-term aging test (120 °C and -6kOe) of two of these Nd-Fe-B magnet types

Characterization of Arc-Shaped Magnets



Arc-Magnet Characterization Paddle



Arc-Magnet in Contact with Pole Faces

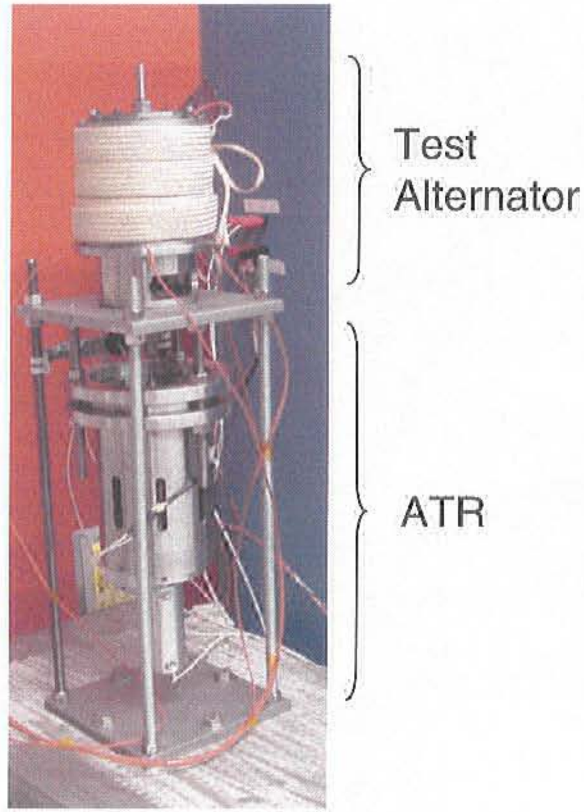
- Fundamentally the same as 1-cm cube paddle
- H-coil geometry is different

Characterization of Arc-Shaped Magnets

- Useful for H_{ci} measurement of actual LA magnets
- Characterization paddle accurate to within -9% of actual H_{ci}
- Arc-shaped EM pole extensions to be fabricated facilitating surface-to-surface contact between magnet sample and EM pole faces

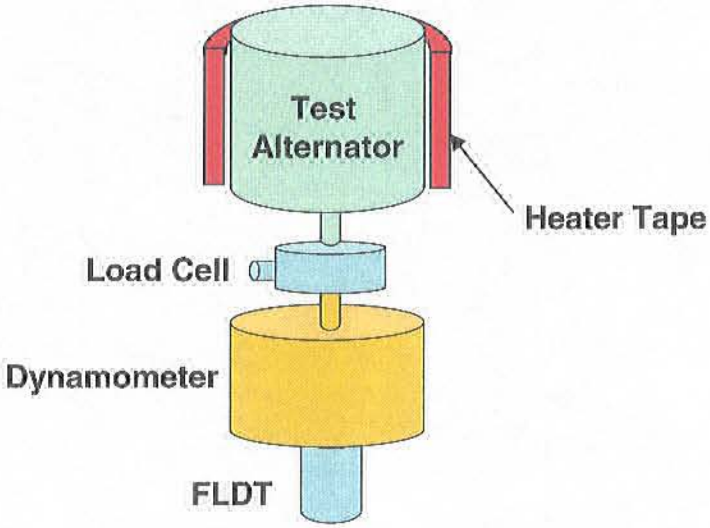
Linear Alternator Characterization

- Linear alternators can be tested to characterize performance over a range of operating conditions
  - Frequency up to 120 Hz
  - Amplitude up to 6.5 mm
  - Nominal 150 W, 122 N force capability
  - LA Test Temperature up to 150°C
  - Resistive Load from short-circuit to 10 kΩ
- Tests were conducted on STC 55 We linear alternator over a range of mover amplitudes (4 to 6 mm), temperatures (23 to 60°C), and loads (80 to 160 Ω)
- Efficiency measured ~ 80 to 85%, primarily a function of load
  - LA current decreases as load resistance increases
  - I^2R loss decreases as LA current decreases
  - LA η increases as load resistance increases
- Data validates STC efficiency projections and GRC LA analysis

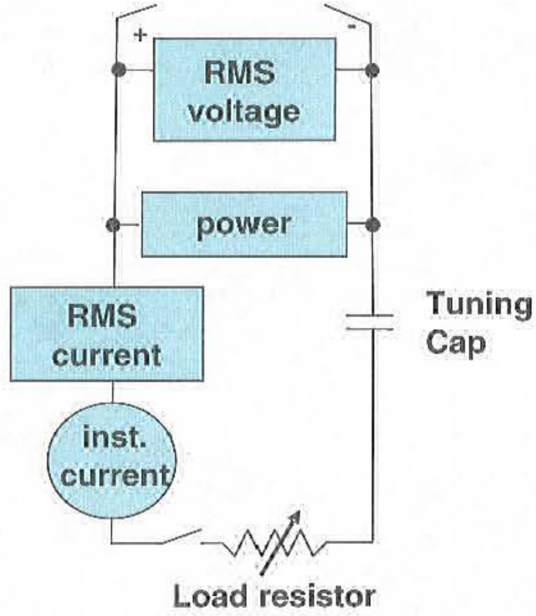


Alternator Test Rig (ATR)

Linear Alternator Characterization

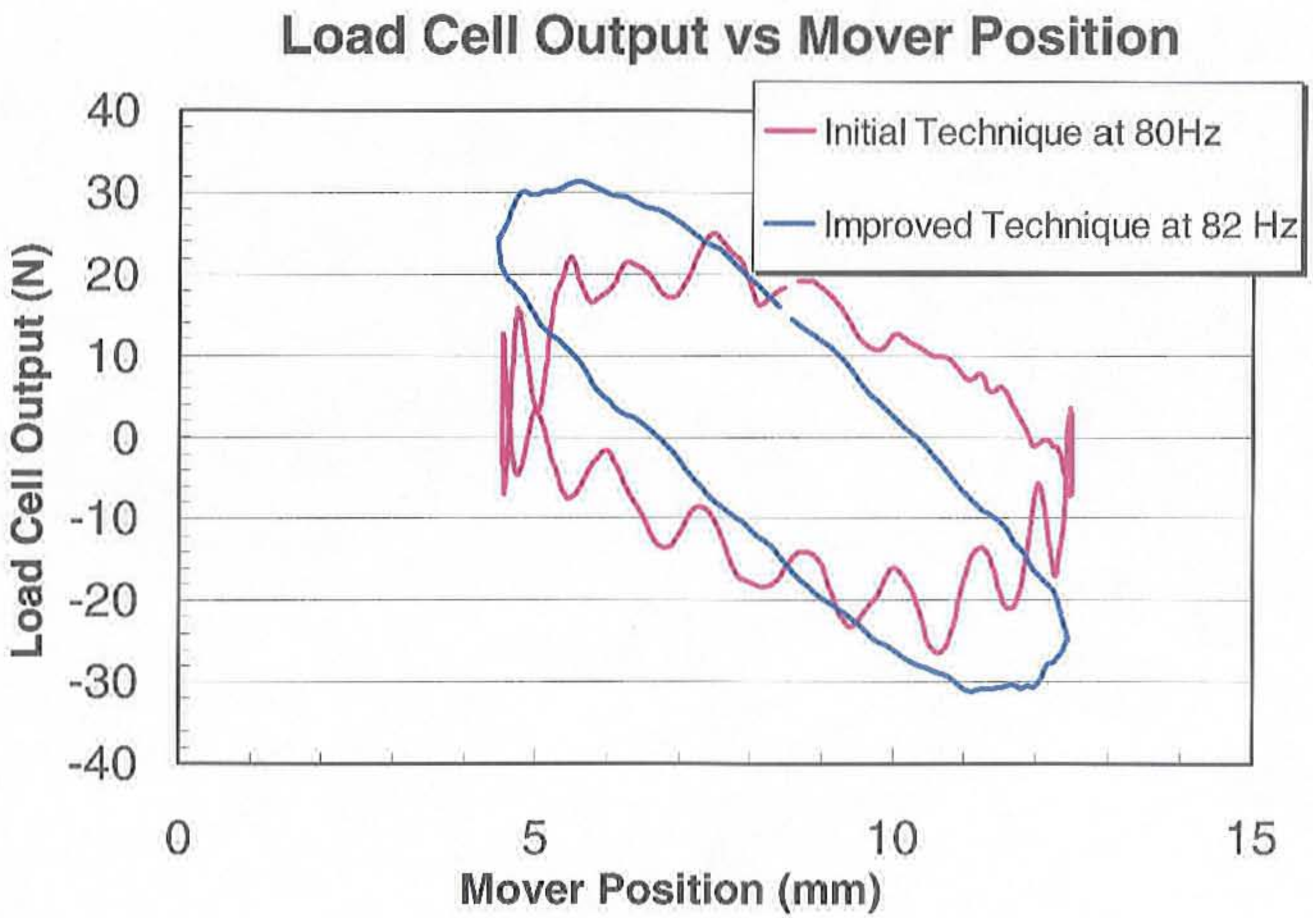


ATR Set-up



Wiring of Instrumentation and Test Alternator Load

Linear Alternator Characterization



Future Plans

- Continue aging tests on other types of Nd-Fe-B magnets of interest to the Stirling convertor application
- Assemble a 2nd magnet aging apparatus to allow concurrent testing of Sm-Co magnets
- Use ATR to evaluate thermal and load effects on LA performance
- Use ATR to map performance of various competing LA designs to better understand their differences

Concluding Remarks

- GRC is conducting in-house research on permanent magnets and on linear alternators to assist in the development of Stirling convertors
- Magnet characterization and aging tests have recently been completed on various types of Nd-Fe-B magnets
- ATR assembled to performance map linear alternators over a range of temperatures, mover amplitudes, and alternator loads.