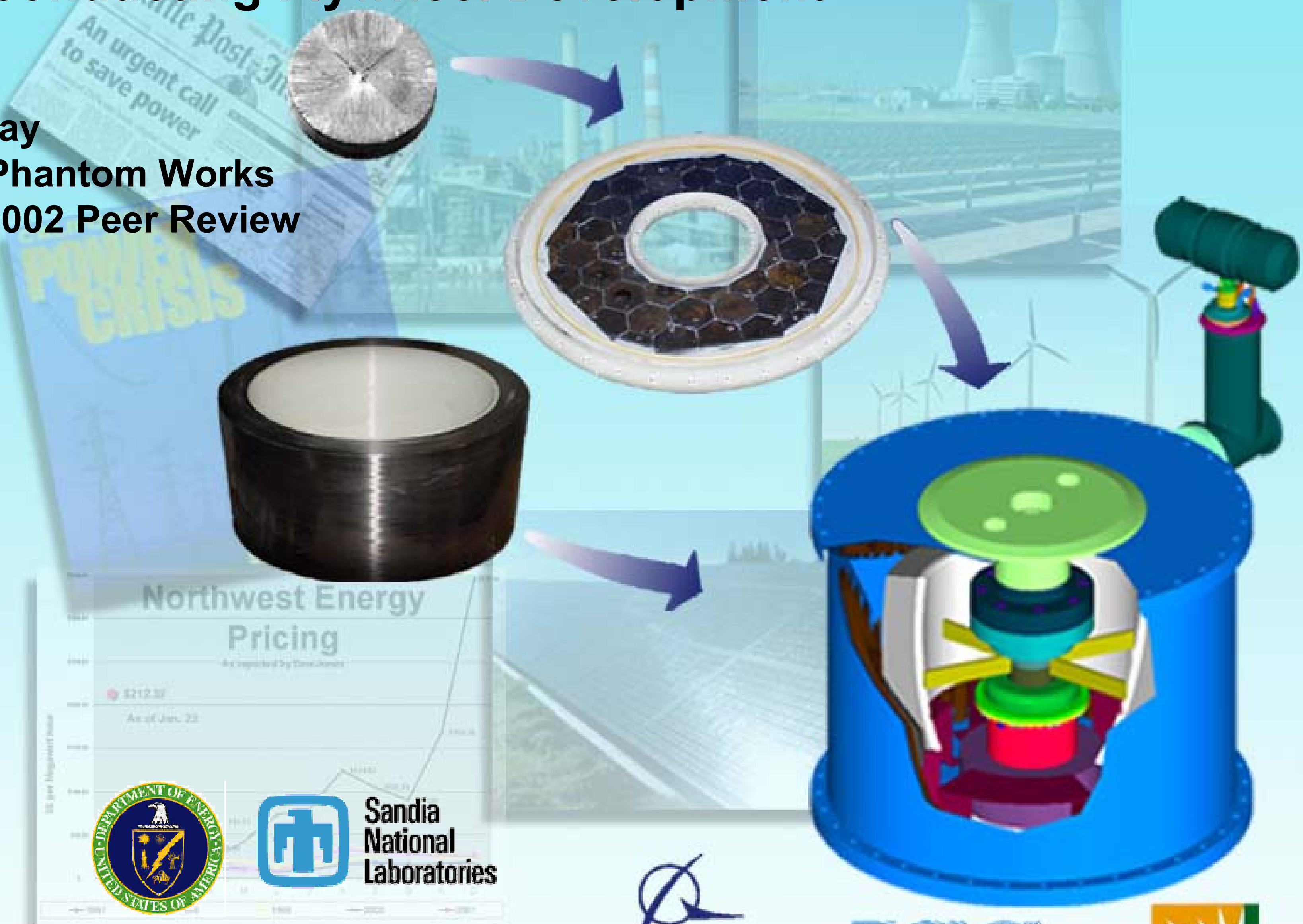
Superconducting Flywheel Development

Arthur Day
Boeing Phantom Works

ESS FY2002 Peer Review



Sandia National Laboratories

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Mesoscopic Devices

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Roles for Flywheels in Energy Storage

- **Remote sites**
  - Wind support
  - PV support
  - Diesel offset
- **Data center security**
  - Quick start
  - 15-minute hold
- **Distributed energy**
  - Peak shaving
  - Secure local supply

Project Roadmap

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6/99 – 9/99

Phase I: Application ID and Initial System Specification

- Applications
- Characteristics
- Planning

5/00 – 3/01
11/01 – 9/02

Phase II: Component Development and Testing

- Rotor/bearing
- Materials
- Reliability

1/02 - 9/03

Phase III: System Integration and Laboratory Testing

- Site selection
- Detail design
- Build/buy
- System test

10/03 - 9/04

Phase IV: Field Test

- Install
- Conduct field testing
- Post-test evaluation

Objectives for FY2002 Work

1) Extend low-cost rotor/bearing work

2) Downselect application

3) Develop preliminary design

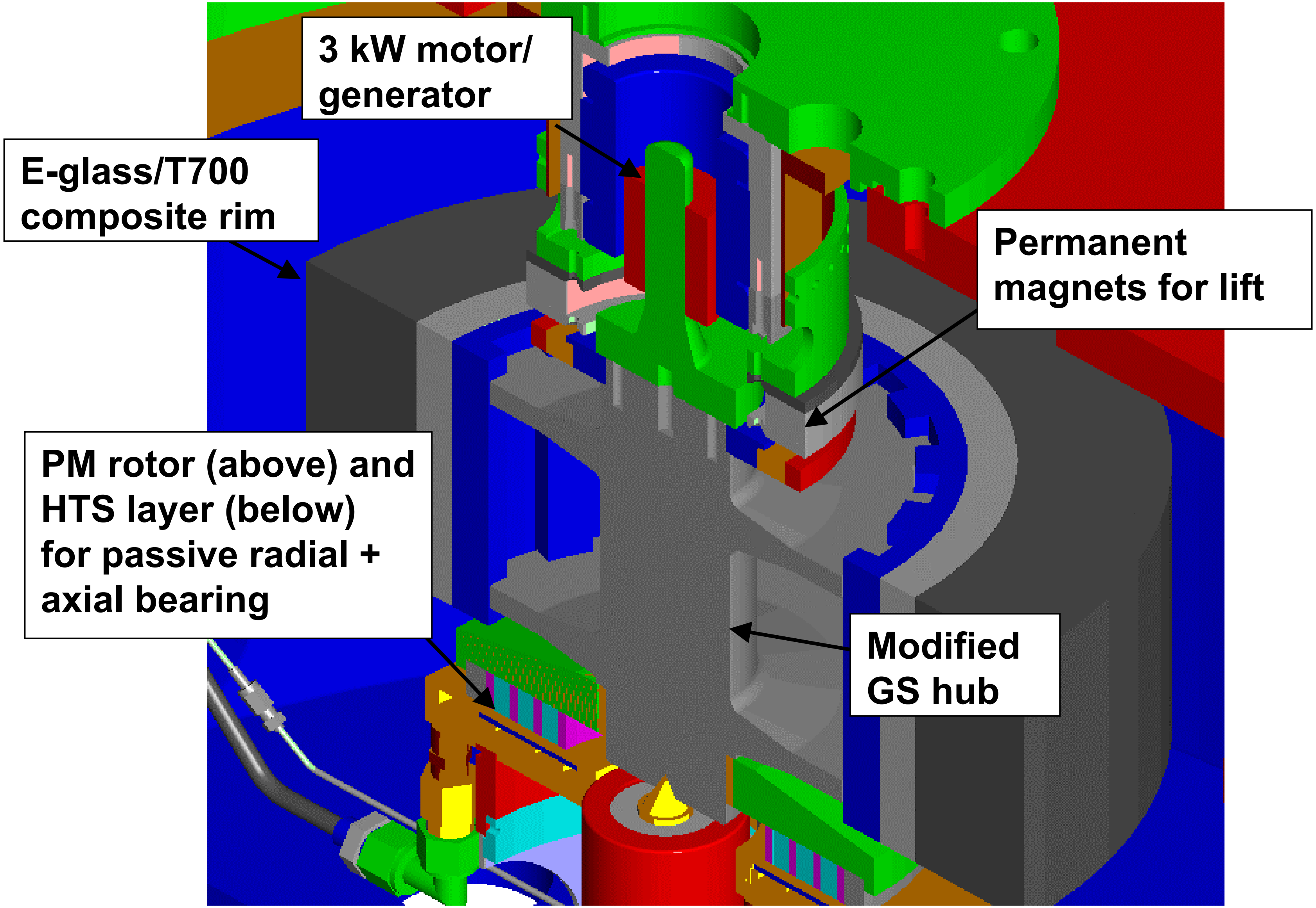
4) Qualification planning / safety and reliability

5) Fabricate superconductors for demo unit

6) Initiate build of flywheel rotor

7) Communicate results

Features of 1 kWh Low-cost Rotor Design

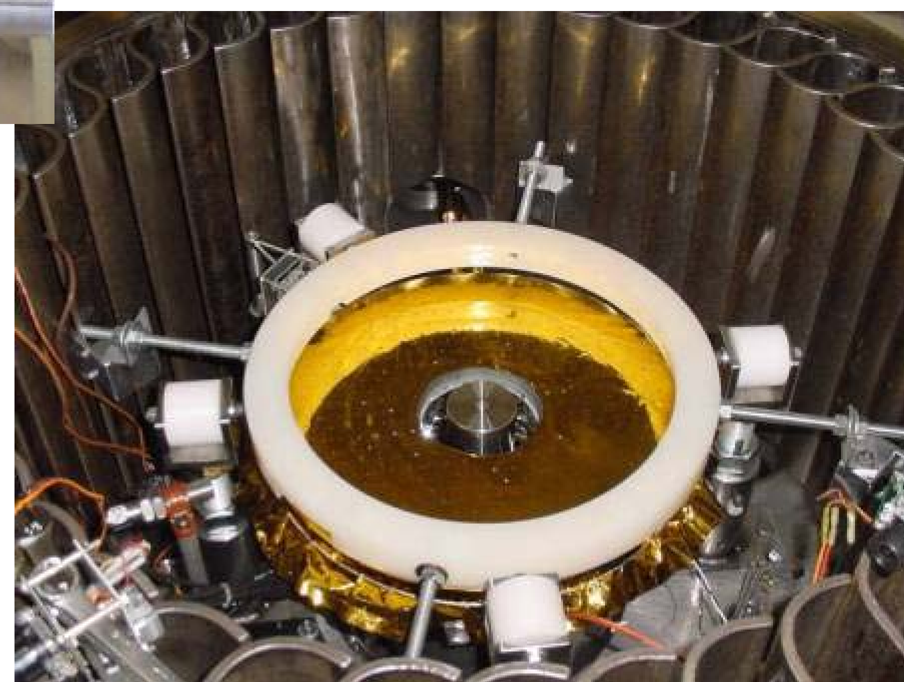


1 kWh Flywheel Rotor and Bearing

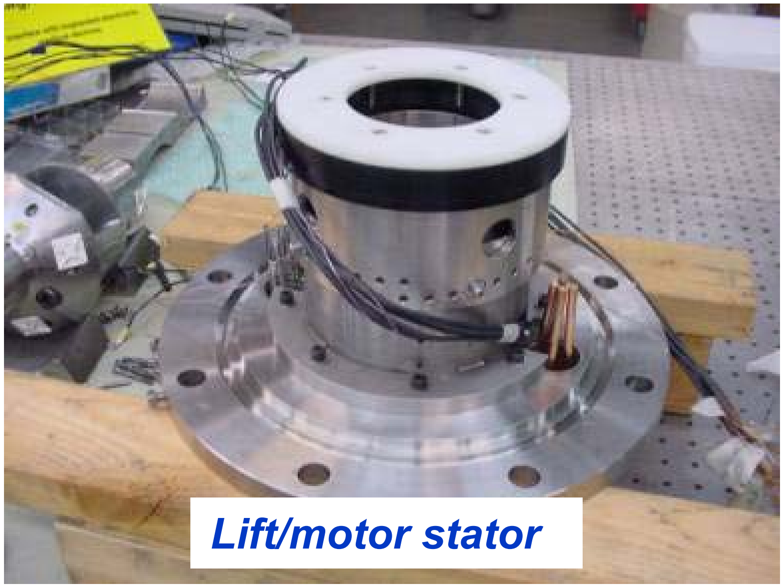
Underside of rotor with magnet array

YBaCuO wafers

Cryostat in test chamber

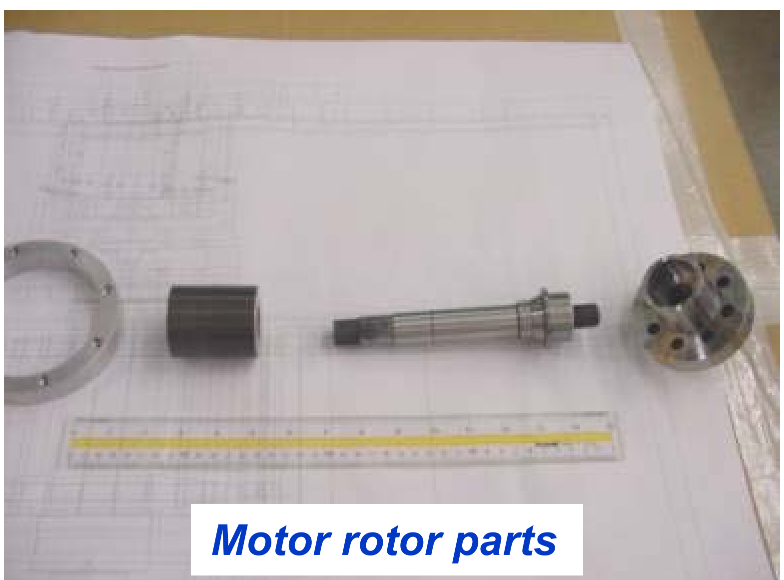


Final Stages in Construction of 1 kWh Test Unit



Lift/motor stator

Complete flywheel



Motor rotor parts

Final test preparation

1 kWh Flywheel in Position for Testing

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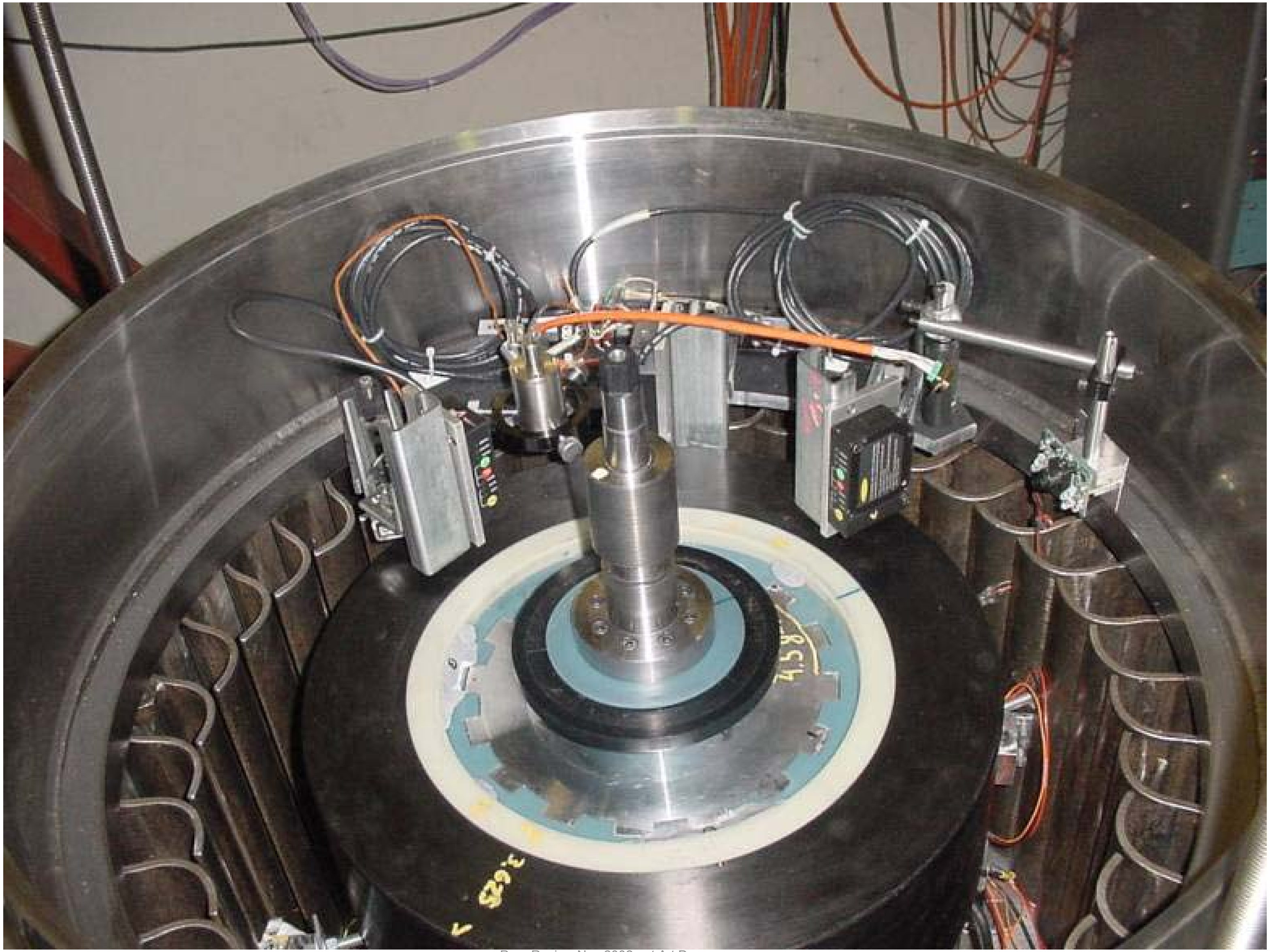

Boeing Spin Test Laboratory

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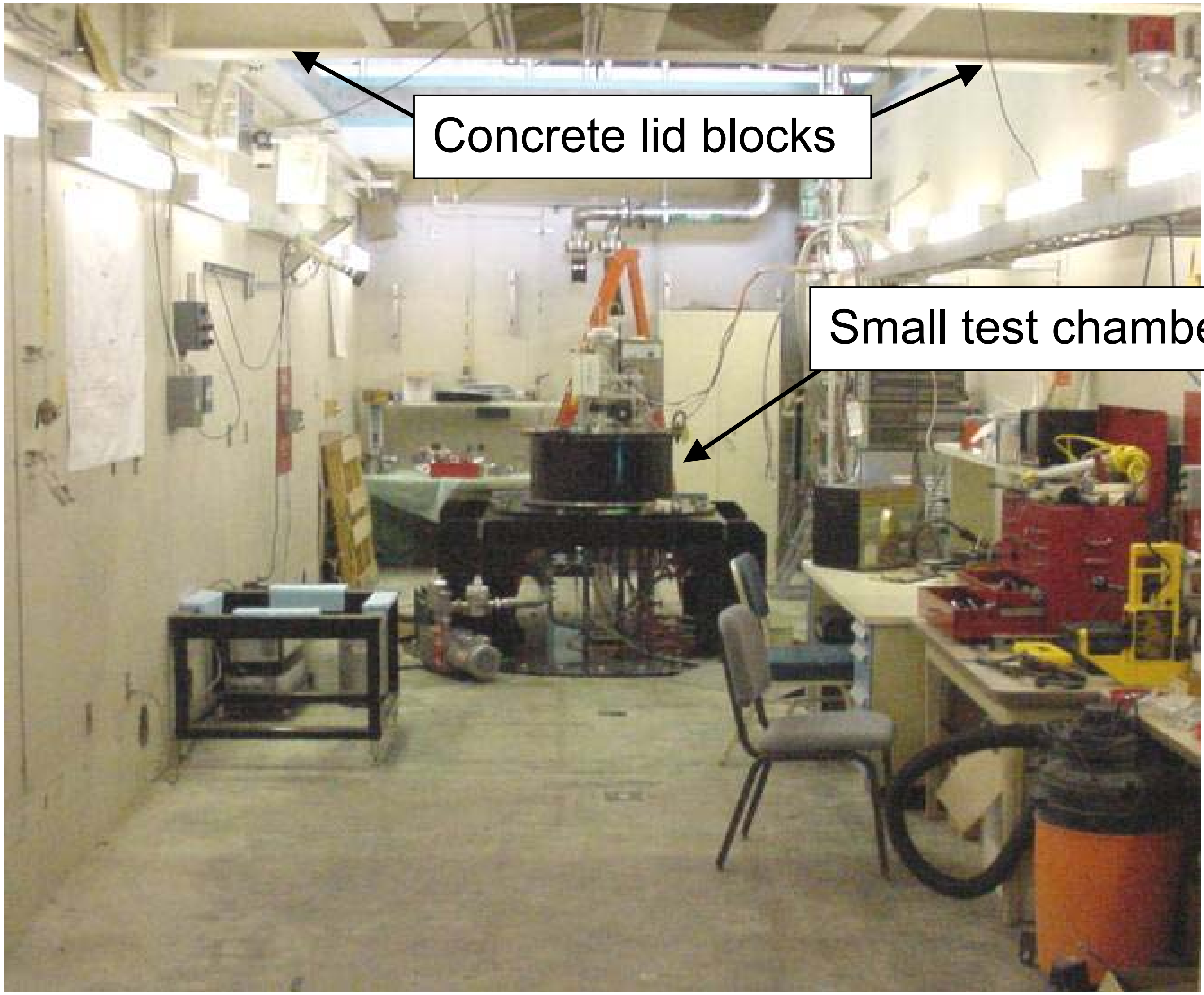

Laboratory in Seattle, Washington

1 kWh Test Plan Brief

3.1 Final setup/pre-test checklist

3.2 Static chill and release test
Purpose: Establish levitation of the rotor.

3.3 Subcritical spinup and spindown test (approx. 300 rpm)
Purpose: Establish M/G and controller operation and start-up stability.

3.4 Critical speed spin test (approx. 350 - 1000 rpm)
Purpose: Pass through critical speed. May require rebalancing or changing clearances to prevent large amplitude vibrations at critical speed.

3.5 Supercritical Spin Torque Test (up to 12,000 rpm operation)
Purposes: Establish M/G and controller stability over broad speed range; charge wheel at up to 3 kW and discharge at 3 kW while measuring efficiencies and temperatures; measure torque ripple; measure vibration to establish dynamic stability at various motor power levels; measure system losses in free spin-down.

3.6 Supercritical Spin Loss Test (up to 12,000 rpm operation)
Purpose: Measure system losses in free spin-down.

3.7 Supercritical Spin Drag Test (up to 12,000 rpm operation)
Purpose: determine air drag contribution.

Speed and Vibration during Typical Run

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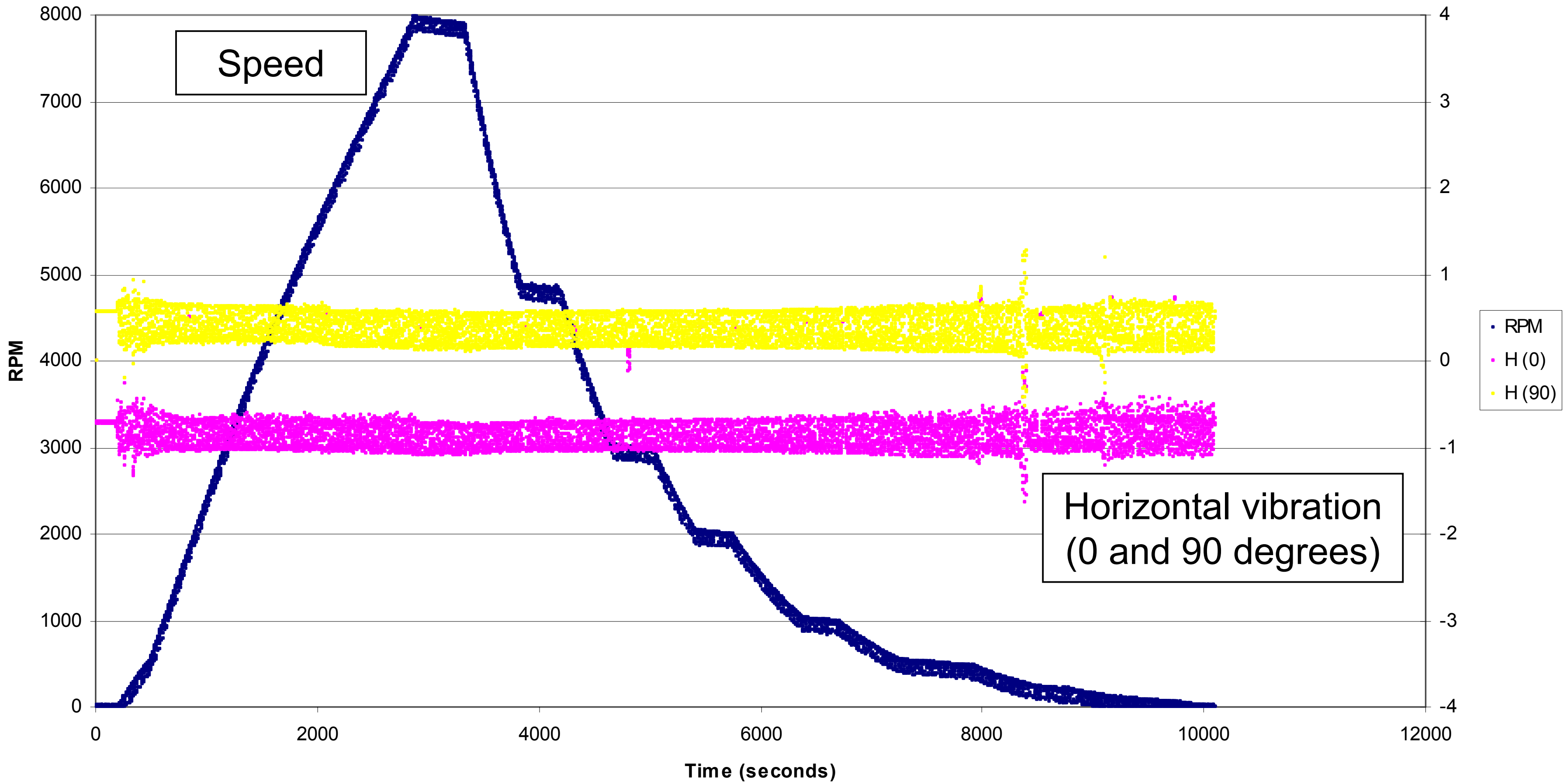

Run of May 30, 2002 with M/G on 1-kWh Flywheel: Establishing M/G operability and rotor stability

Motor Stator Temperatures During Run

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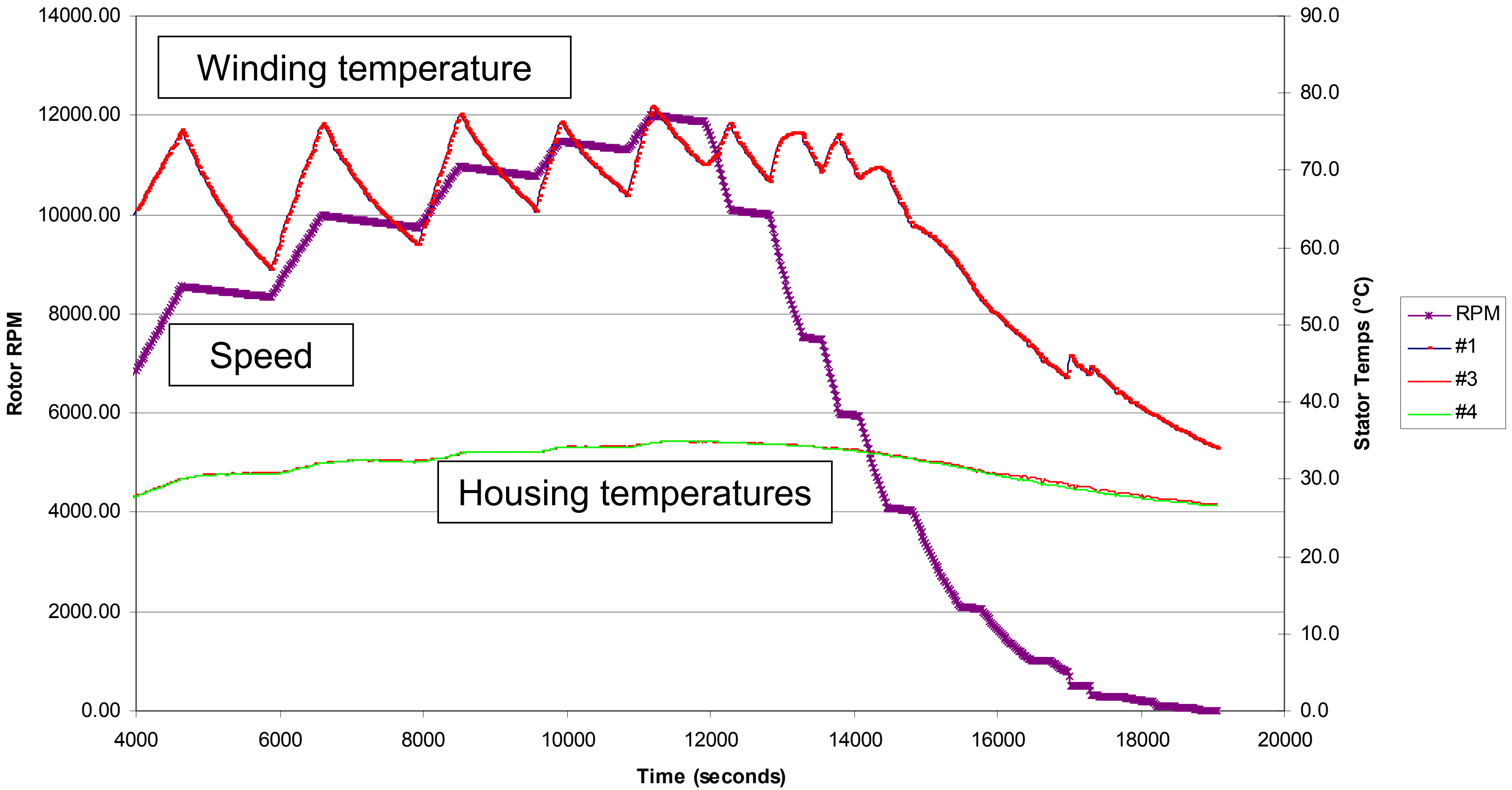

Run of June 6, 2002 with M/G on 1-kWh Flywheel: Establishing power-handling, heat-transfer capabilities

Power Output of Flywheel

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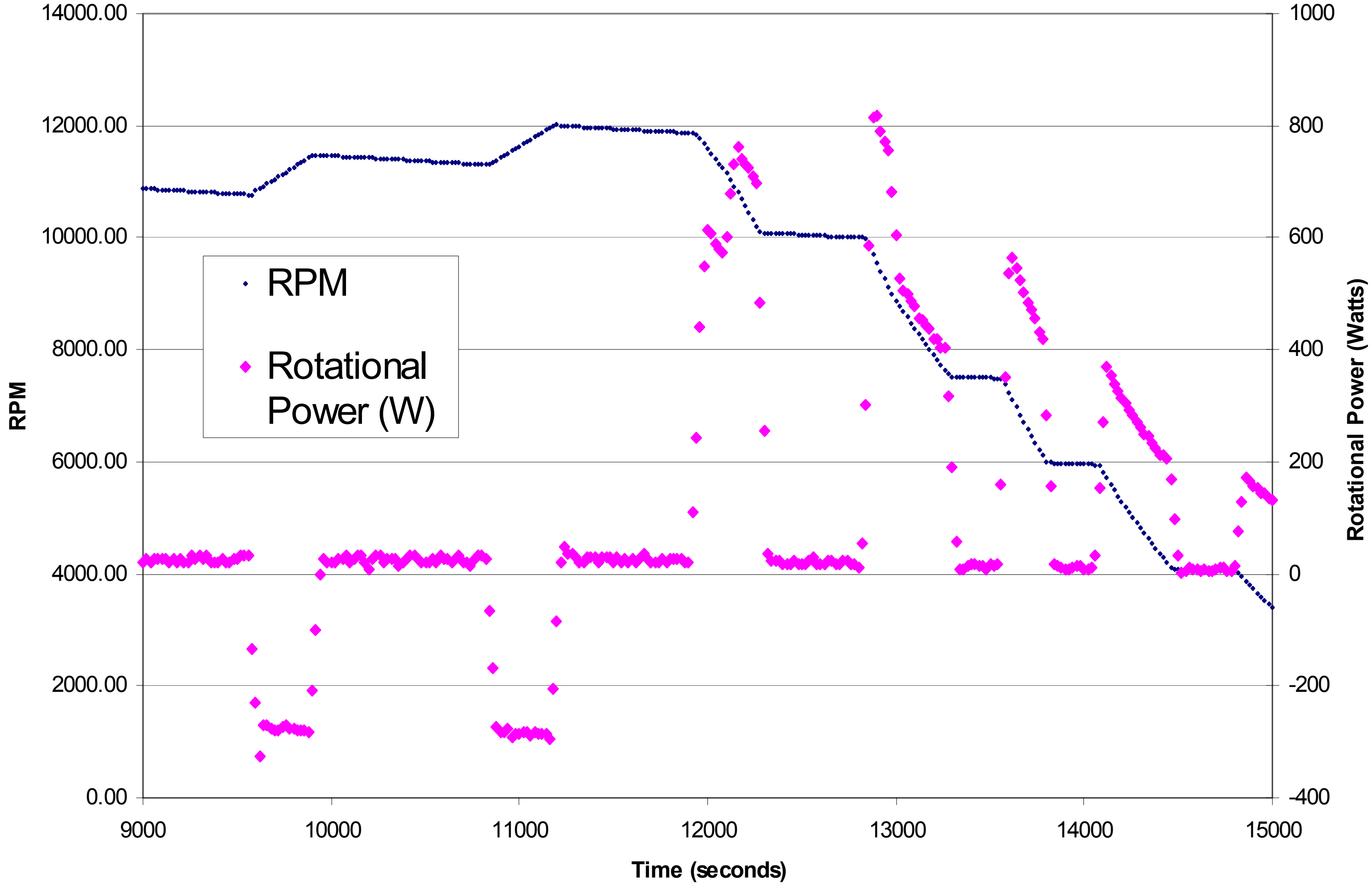
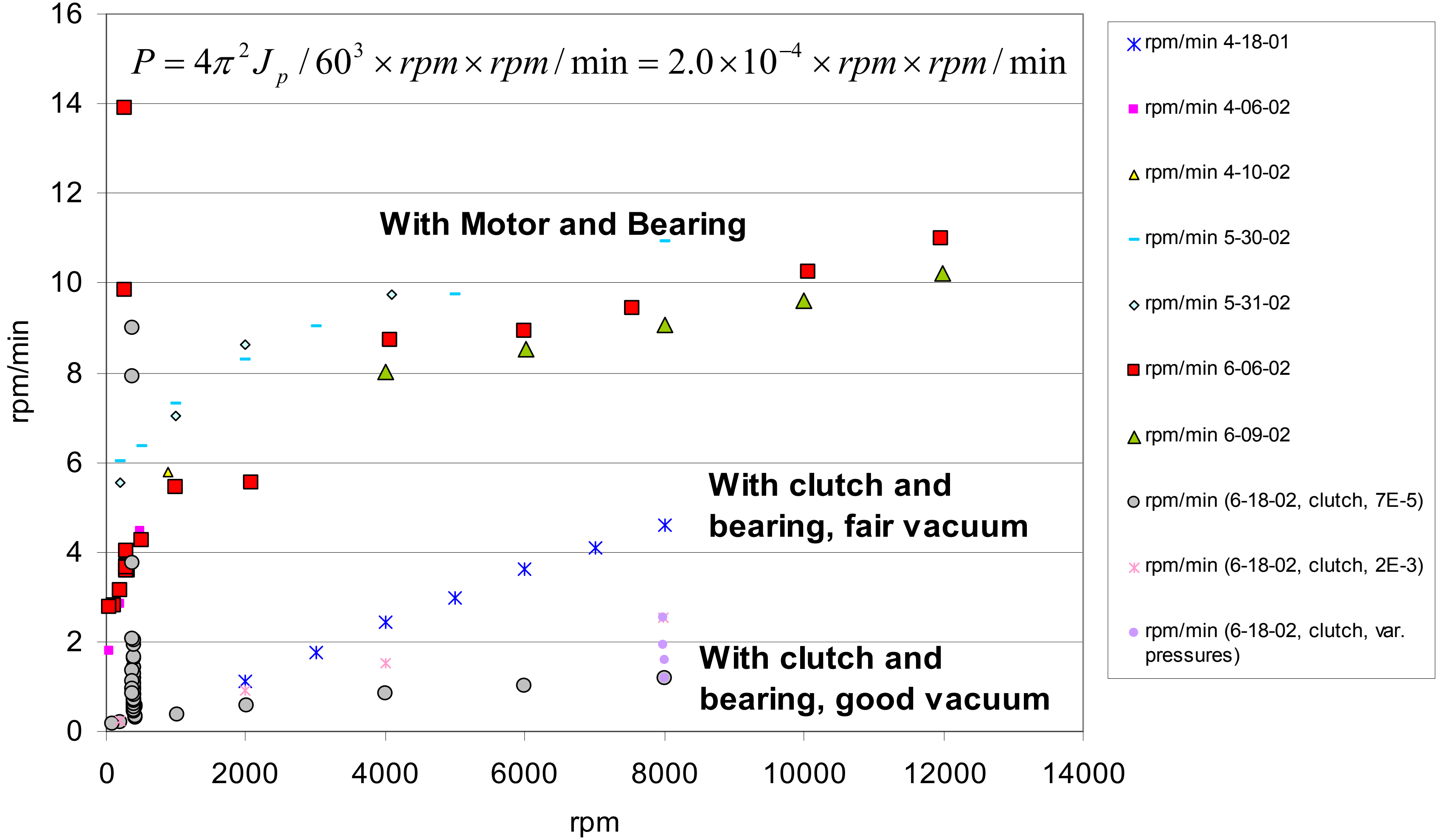


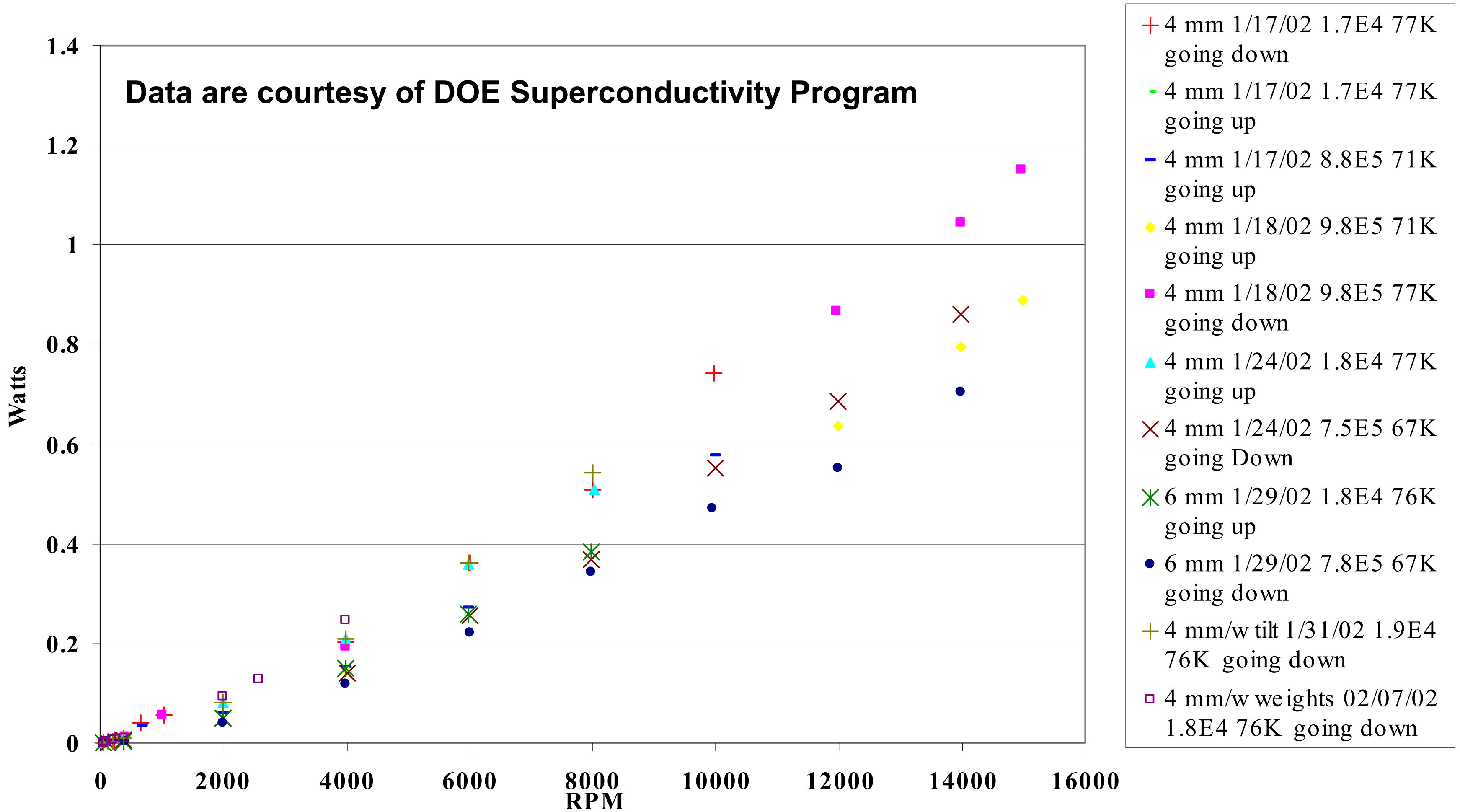
Run of June 6, 2002 with M/G on 1-kWh Flywheel:
First power output, approx. 800 W (load limited)

Flywheel Idling Losses: Motor, Pressure, Bearing

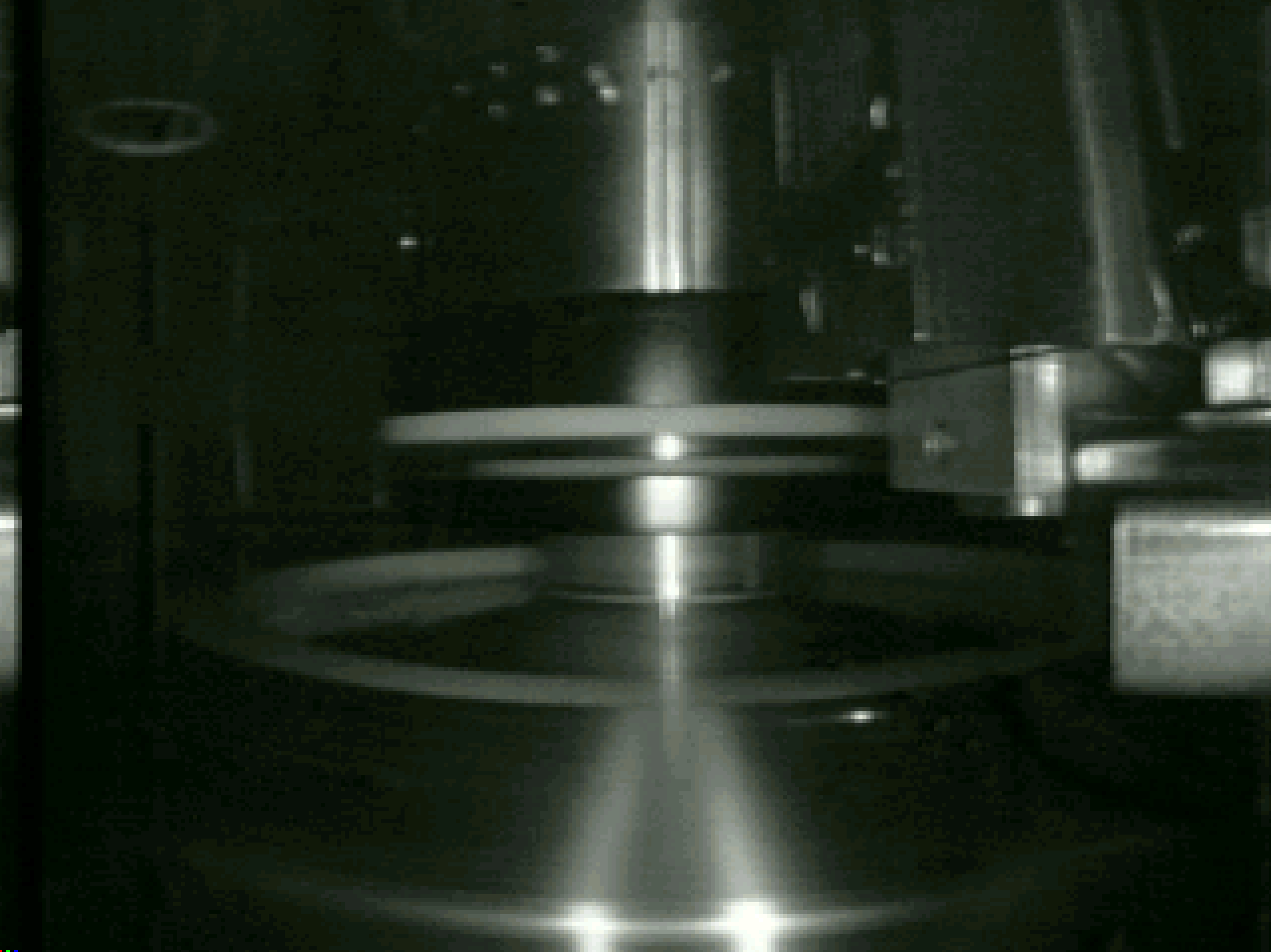


For the 1 kWh flywheel as tested, the motor backiron dominates losses unless pressures are quite high (~ 10^{-2} torr)

HTS Bearing Losses, 0 – 15,000 rpm



Direct bearing losses will be on the order of 1 – 2 Watts. Typical refrigeration penalties are 20 – 30X; parasitic losses will be highly design-dependent.



Related Activities

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- Cooperative Agreement DE-FC36-99G010825 (SPI) carries out basic work in HTS bearings and other hardware
- Laboratory can support multiple test operations

390-lb. rotor (10 kWh) between tests on DOE/SPI program. Bearing achieved fully stable operation

A busy day – side-by-side setups prepare for tests

Unintended Consequence

- Improper adjustment of magnet spacing led to contact at high speeds, but part is cheap and replaceable

Plastic strain-accommodation ring took brunt of high-speed contact

Some abrasion on underside of lift magnet preventer ring

Potential Test Sites: Solar, Wind

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Application attributes:

- Both place high value on 4 – 8 hour storage / sometimes longer
- Power conversion: strongly favor proven units (typ. 50 VDC to 120 VAC)
- 3 – 10 kWh modules are useful size

PV Shack as seen on site visit to STAR Center, Ocotillo Power Plant, Arizona.

Kotzebue Electric: Low- to high-penetration wind sites

Design Evolution to Demo Unit

System attributes:

- Useable capacity ~3.5 kWh (total wheel energy ~5 kWh)
- Power out 3+ kW continuous, 8 kW peak at 120 VAC

Magnetic bearings:

- Will adapt low-loss SPI design for rotor but try alternate lift magnet approach

Low-cost hub/rim shows promise:

- Structural analysis underway; rotordynamic analysis pending
- Backup approach is 5 kWh SPI design

Motor/generator:

- 4 – 8 kW, approx. 50 VDC. Brushless PM, probably lower-loss variant

Power electronics:

- Inverter likely to be Xantrex SW5548 or near-equivalent (44 – 66 VDC)
- Lower bus voltage will require modifications to motor controller design

Near-term goals (Jan. ’03) are to: 1) complete rotor analyses; 2) procure hub/rim; 3) complete System Definition document

Development of Standards and Qualification Procedures

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DRAFT

MARKED-UP COPY(August 27-28, 2002)

ANSI/AIAA
S-0XX-200X

Standard

Space Systems – Flywheel Rotor Assembly Certification

Sponsored by

American Institute of Aeronautics and Astronautics

Approved XXXX-XX-200X

American National Standards Institute

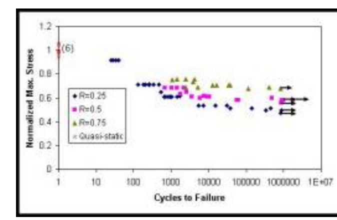
Abstract

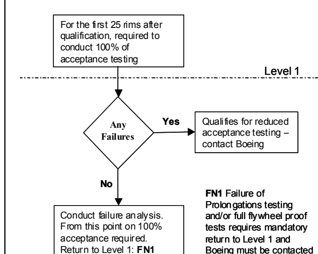
This standard establishes baseline requirements for the design, fabrication, test, inspection, ~~operation, and maintenance~~ storage, and transportation of flywheel rotor assembly used in a spaceflight flywheel system for energy storage and/or attitude control. These requirements when implemented on a particular system will assure a high level of confidence in achieving safe and reliable operation.

Flywheel Rim Material Testing and Qualification Plan

Karl Nelson and Charles Bakis

Draft – September 24, 2002





Boeing Document D-XXXXXX

New Methodology for Transverse Strength

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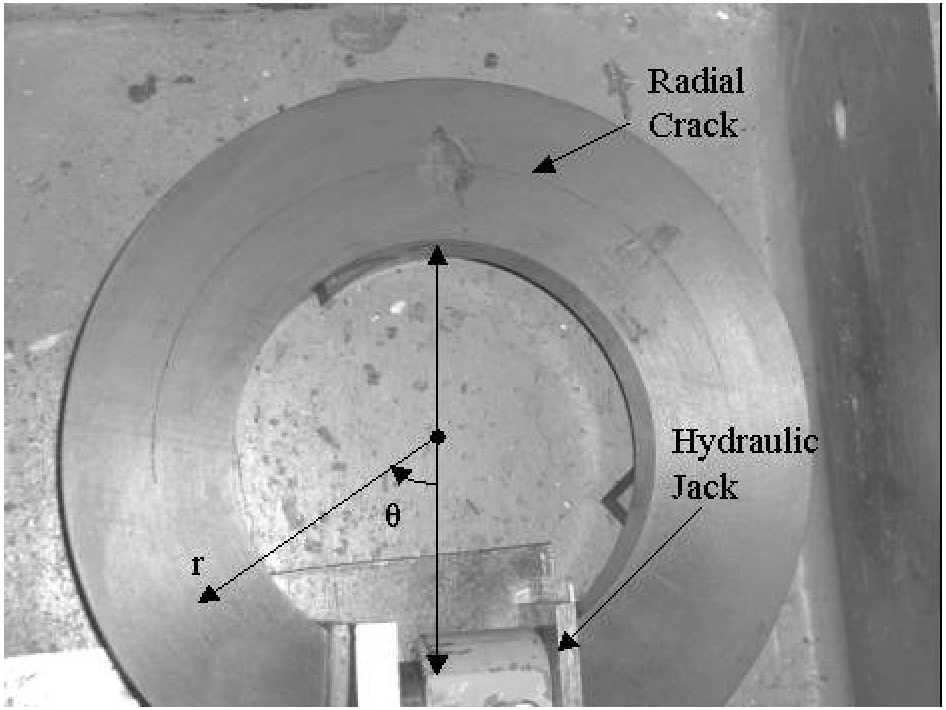
- *Problem:* Most flywheels are hoop-wound but have low transverse strength. It is difficult to make transverse coupons; the results are often non-representative.
- *Solution:* PSU is developing a test method based on expansion of a hoop-wound C-ring.
- *Progress:* Closed-form equations for stress and strain fields were developed. A test was carried out to prove theory. Measured strains were within 5% of theory.
  - For T700/RF007 measured:
    Transverse tensile strength = 5.7 ksi
    Radial strain at failure = 3530 $\mu\varepsilon$.



Photograph of first radial crack (shown after test).

Reducing the Design-dependence of Fatigue Data

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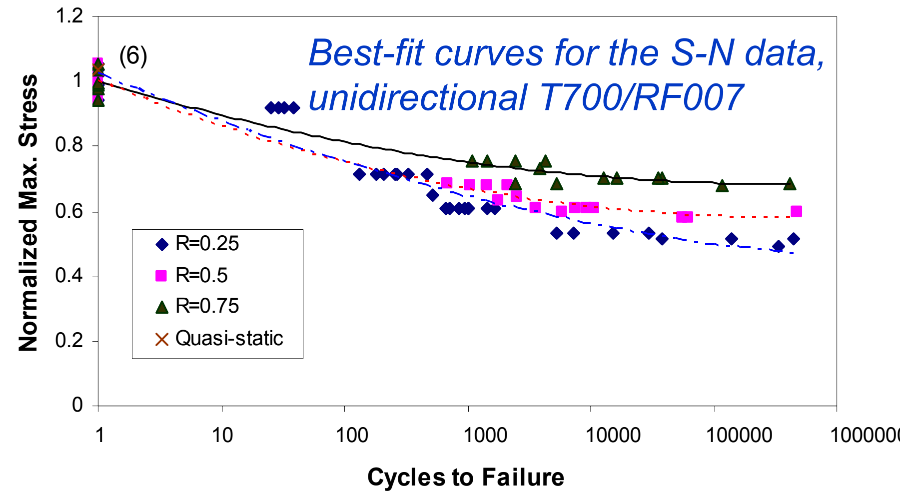
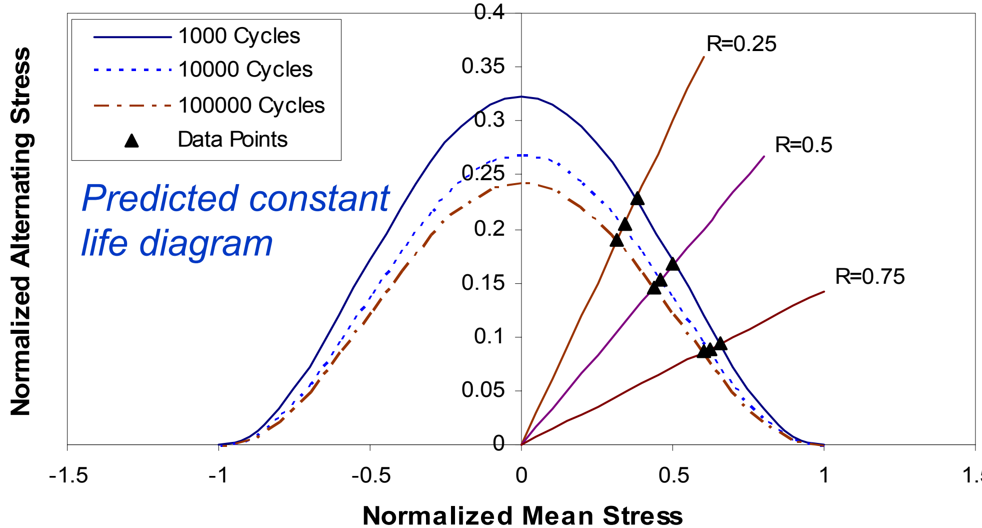
- ***Problem:*** **fatigue life depends on stress σ, stress ratio $\sigma_{min}/\sigma_{max}$, and temperature. A new design can require a large amount of testing to validate.**
- ***Solution:*** **use predictions from constant-life diagrams (built from limited data sets) to generalize behavior to new conditions.**
- ***Progress:*** **Boeing/Toray/PSU obtained initial stress ratio data; will add temperature effects soon.**



Damage growth prior to failure, cyclic loading at 70% of ultimate, R = 0.75

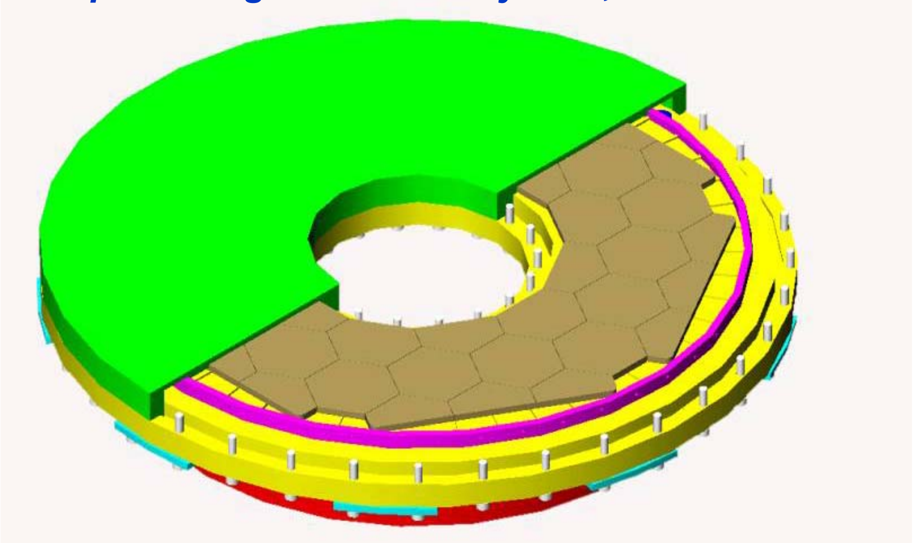


Gathercole, N., H. Reiter, T. Adam, and B. Harris, 1994, "Life Prediction for Fatigue of T800/5245 Carbon-Fibre Composites: I. Constant Amplitude Loading," *Fatigue*, 16:523-532.

Fabrication of HTS for Deliverable Demo Unit

- A full set of high-quality HTS crystals has been prepared to populate the main bearing for a 5 kWh unit.
  - Crystals grown
  - Sliced to wafers (~ 50 pc.)
  - Trimmed
  - Quality check (B-field)

Improved process gives flatter crystals, better utilization



Typical cryostat construction showing wafers in cutaway

Summary of FY2002 Results

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1) Extend low-cost rotor/bearing work ✓

- Speeds to 12,000 rpm with motor/generator

2) Downselect application ✓

3) Develop preliminary design ✓

4) Qualification planning / safety and reliability ✓

- Rim qualification plan, AIAA Standard work
- Supporting materials testing at PSU

5) Fabricate superconductors for demo unit ✓

6) Initiate build of flywheel rotor ✓

7) Communicate results ✓

- EESAT presentation and paper, ASC2002

↑Top

←Agenda

No-cost extension should allow for completion of all contacted tasks