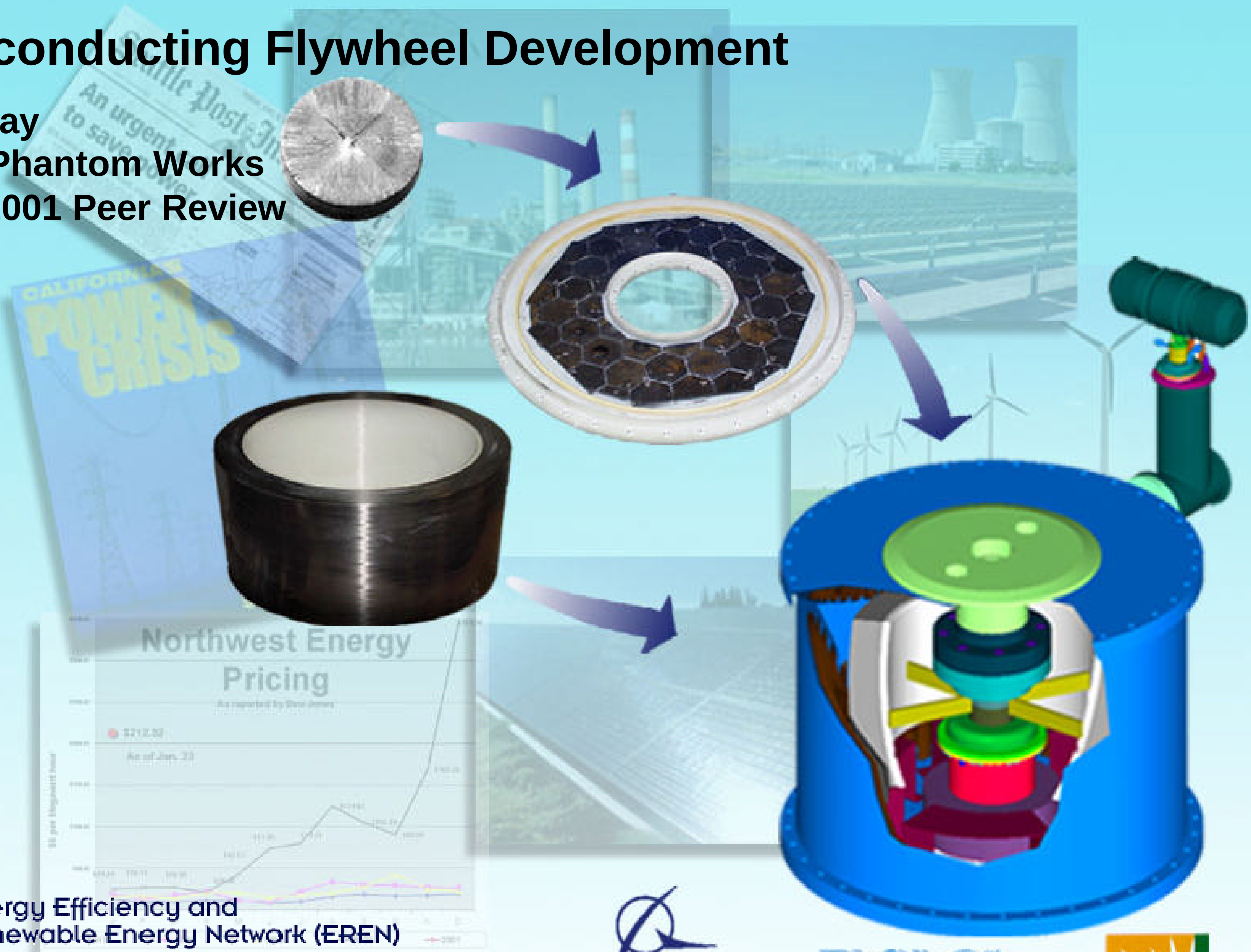
Superconducting Flywheel Development

Arthur Day
Boeing Phantom Works
ESS FY2001 Peer Review



Energy Efficiency and Renewable Energy Network (EREN)

Sandia National Laboratories

ARGONNE NATIONAL LABORATORY

Mesoscopic Devices

BOEING

IGC

PRAXAIR

Ashman Technologies

SOUTHERN CALIFORNIA EDISON

Project Roadmap

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 - 3/03

Phase III: System Integration and Laboratory Testing

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

4/03 - 4/04

Phase IV: Field Test

- Install
- Conduct field testing
- Post-test evaluation

Objectives for Past Year's Work

1) Develop low-cost rotor/bearing approach

- Identify scaleable approaches
- Build sub-scale unit
- Initiate spin testing

2) Determine & enhance system reliability

- Materials: composites, magnetics
- Qualification plan

3) Communicate results

- EESAT presentation and paper

Timeline for Past Year's Work

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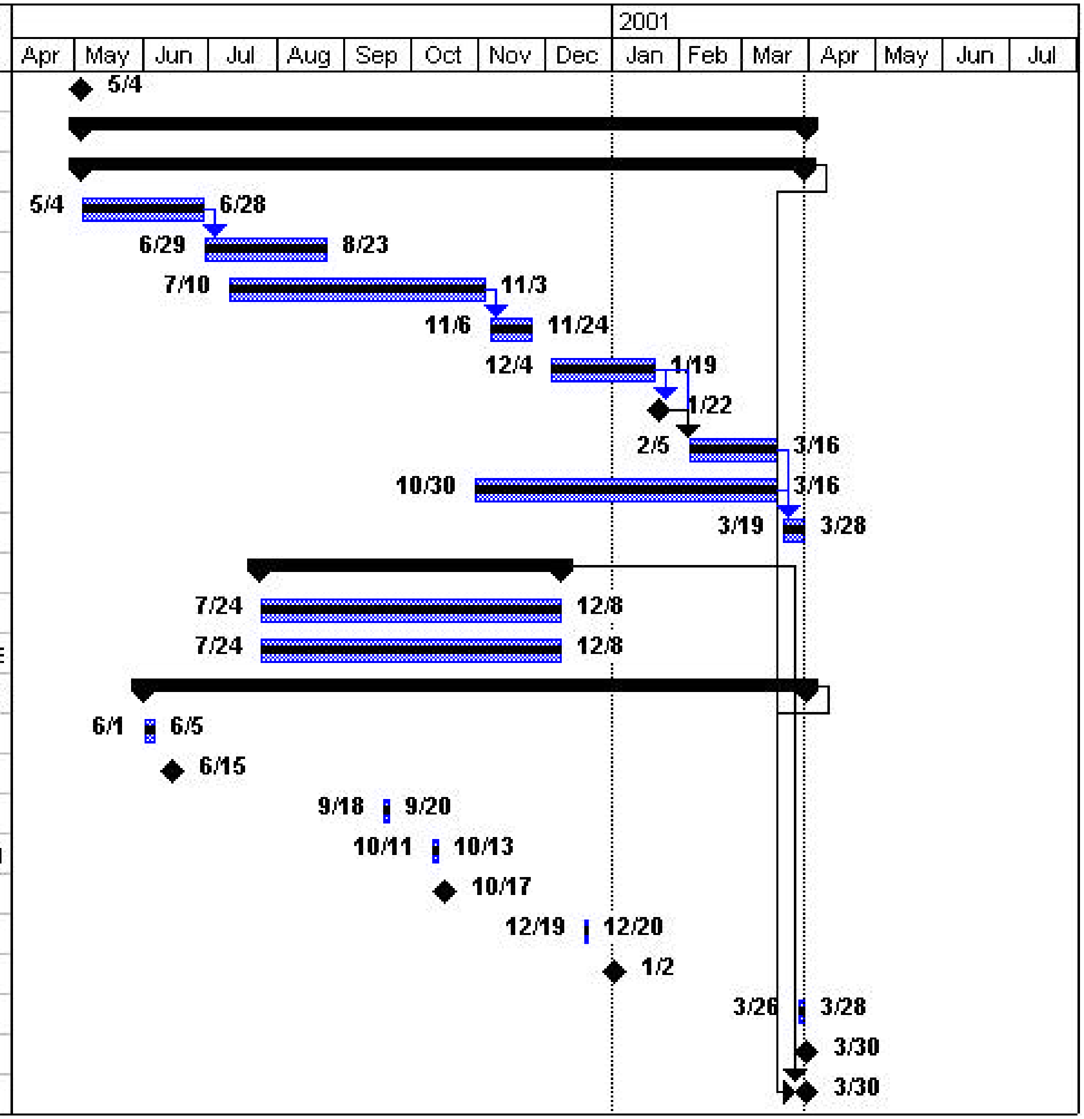
ID	Task Name
1	Start of Phase II (received Work Authorization)
2	**Total effort Phase II**
3	**Develop low-cost rotor/bearing approaches**
4	Identify 10 - 50 kWh wheel approaches
5	Investigate alternate materials
6	Generate sub-scale design
7	Evaluate rotordynamic behaviour
8	Build/buy rotor components
9	Toray rotor on-dock
10	Integrate with subscale bearing unit
11	Prepare test instrumentation and plans
12	Initiate test in vacuum
13	**Determine & enhance materials reliability**
14	Measure fatigue properties of rim materials
15	Measure fatigue properties of bearing magne
16	**Communication and program management**
17	Prepare status report #1
18	Status report #1 delivered
19	Travel - EESAT Conference
20	Prepare status report #2 (Fiscal year report)
21	Status report #2 delivered
22	Prepare status report #3
23	Status report #3 delivered
24	Prepare Final report
25	Report delivered to customer
26	Phase II complete



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

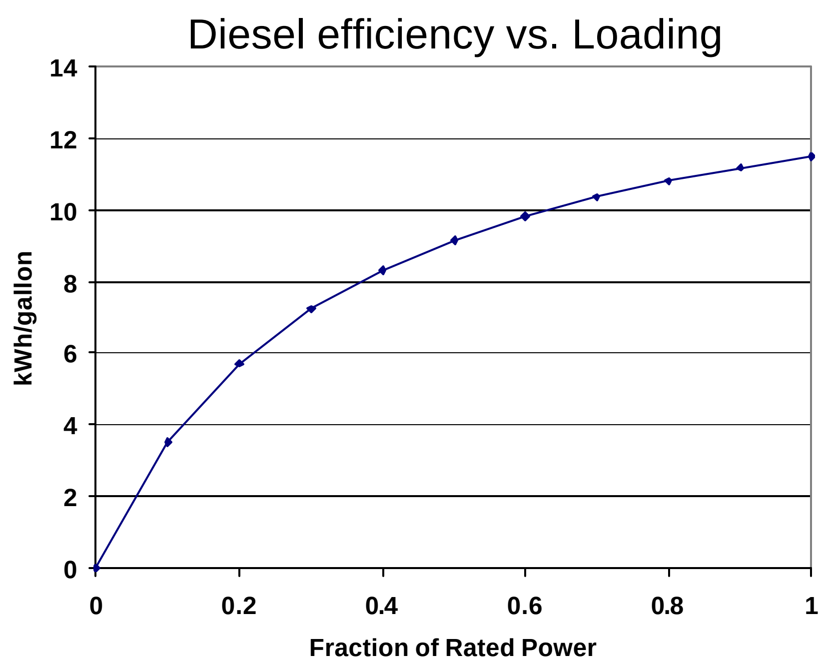
Remote Application Example: Wind Site in Alaska

- Kotzebue Electric: low-penetration wind generation

– 660 kW from Atlantic orient wind turbines.

– Primary power is from large diesel generators, approx. 5 MW total capacity.

– Multi-100 kWh storage highly desirable



Power Conversion for Flywheels - UPS Example

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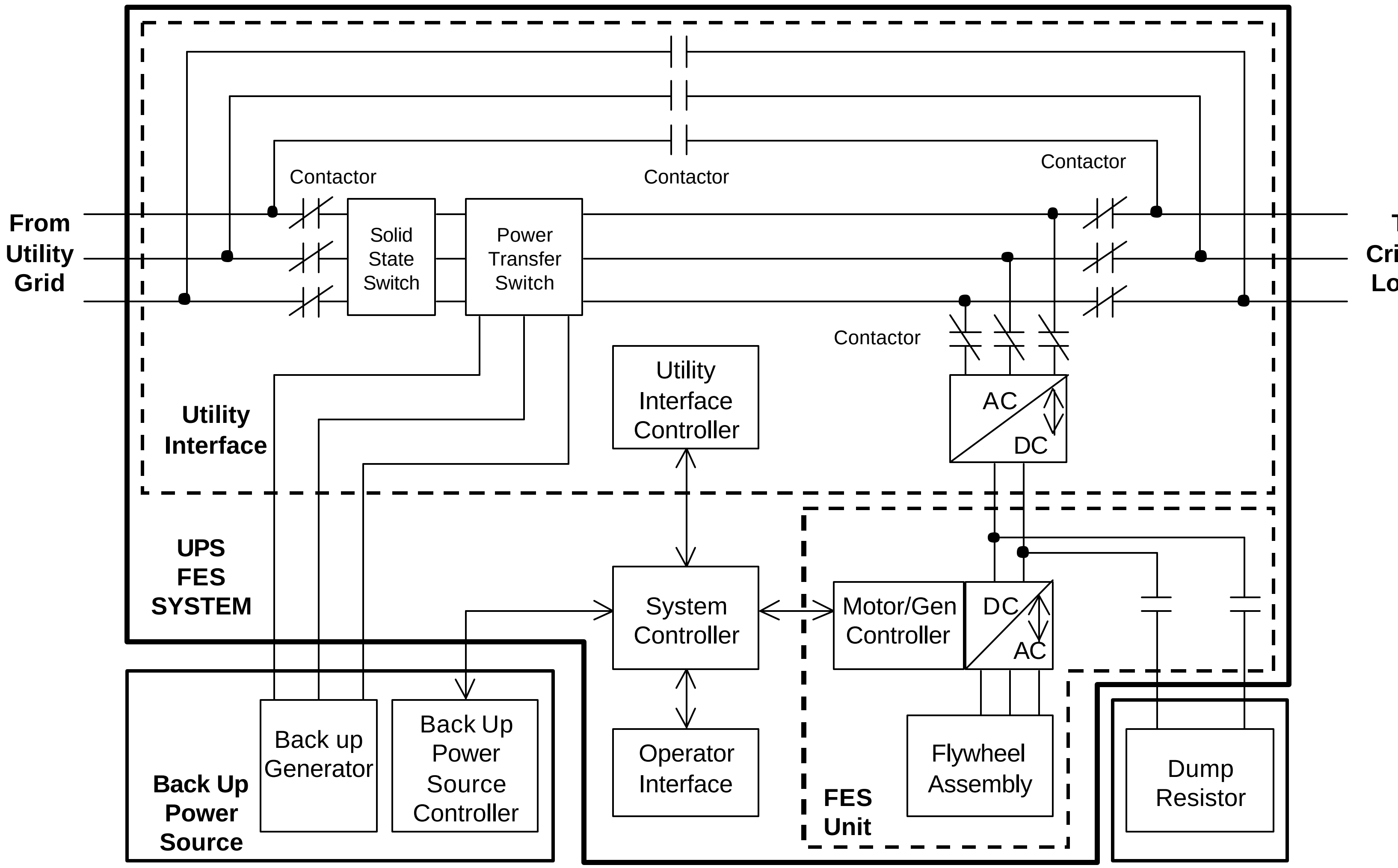
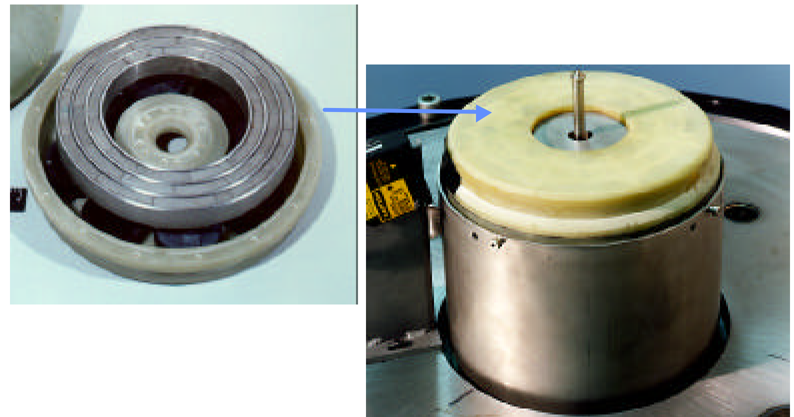


Features and Benefits of Boeing's Design Approach

Active Magnetic Bearings

Complex, Inefficient, Large, Expensive System

Superconducting Bearings



Simple, Passive, Efficient, Self-Centering System

Advantages of Superconducting Bearings

- Much lower frictional losses than active magnetic bearings or mechanical bearings
- No electronic bearing controls required
- Simple bearing design vs. 3 or more active control circuits for active bearings
- Passive control for greater reliability and life times
- Lower weight, cost, and maintenance

Flywheel Sizing: 1 kWh vs. 45 kWh

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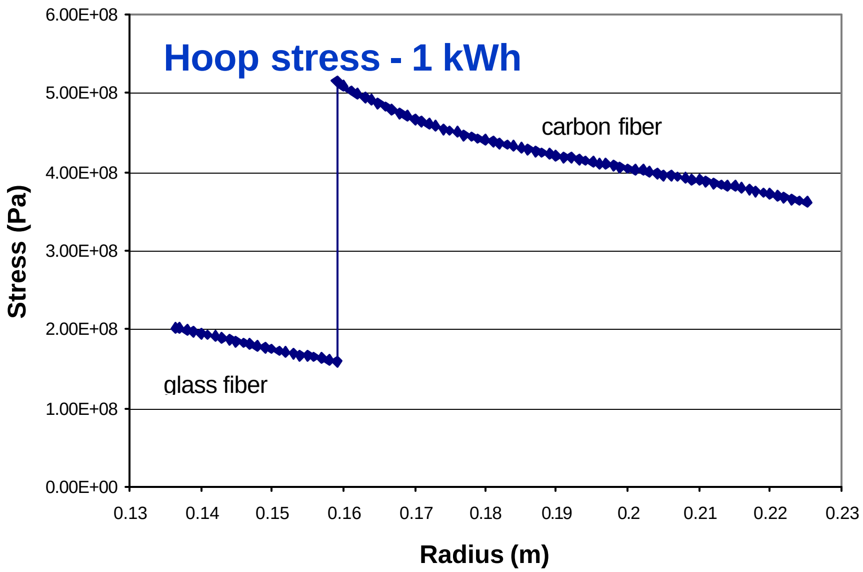
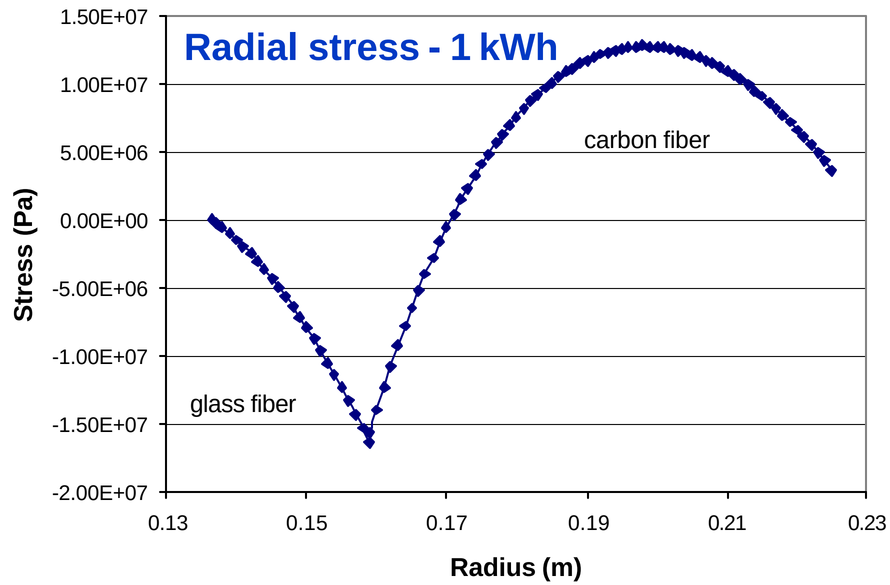
- **Developed spreadsheet design tool for initial sizing and stress distribution**

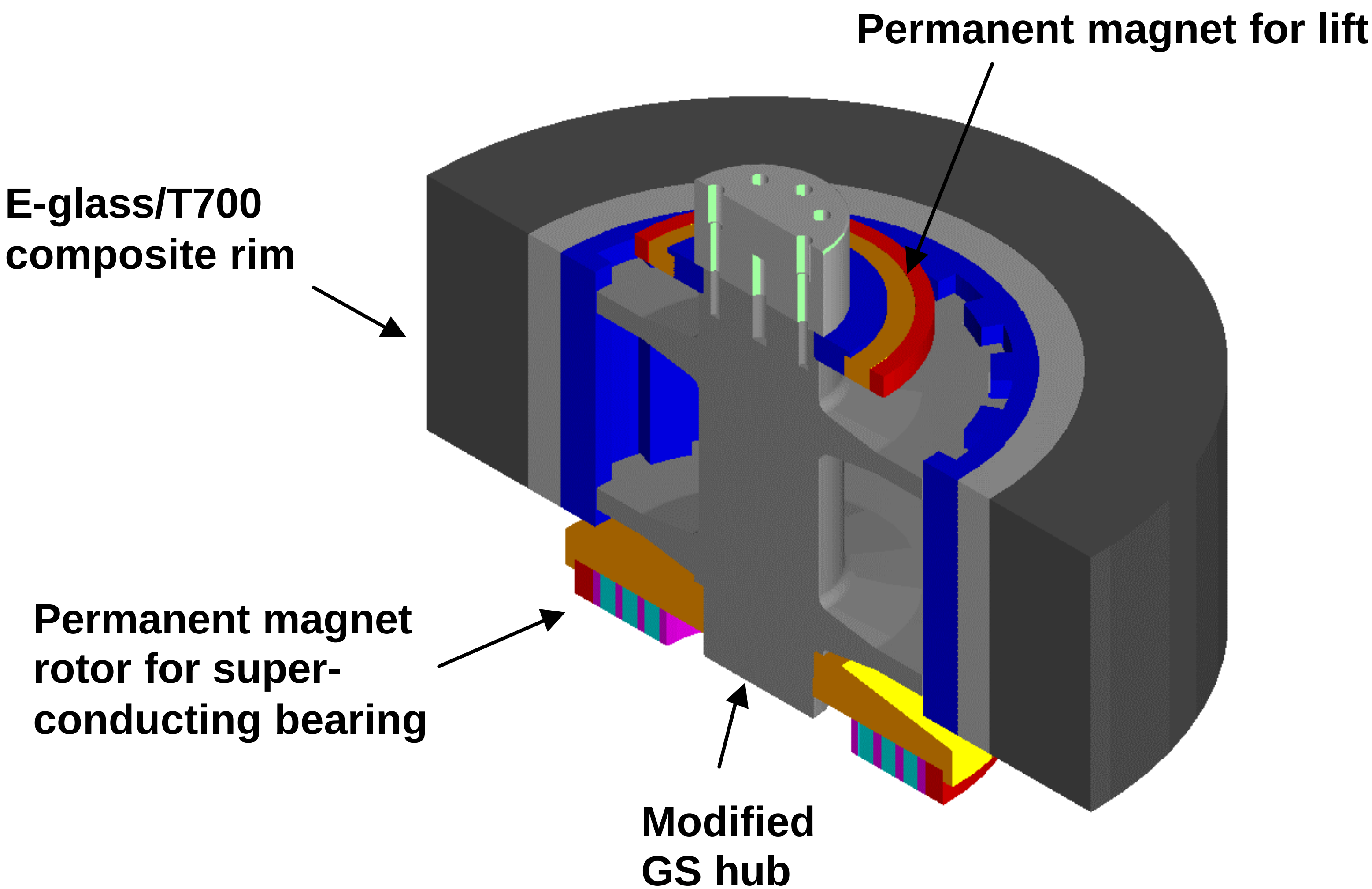
Initial sizing: 1 and 45 kWh rotors with F.S.(hoop) > F.S.(radial) > 2.0

	ID (inches)	OD (inches)	Height (inches)
1 kWh	10.75	18.0	6.0
45 kWh	33.1	49.6	23.6





Features of 1 kWh Rotor Design

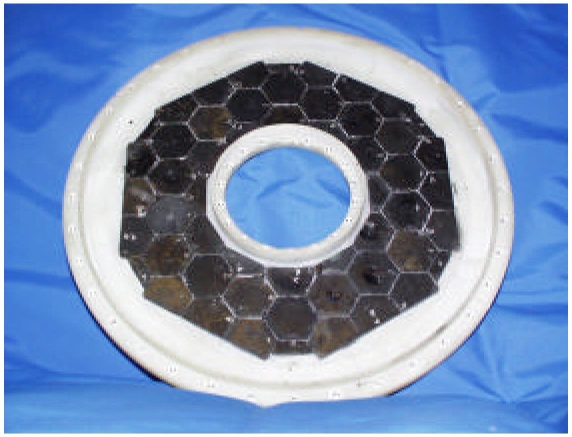


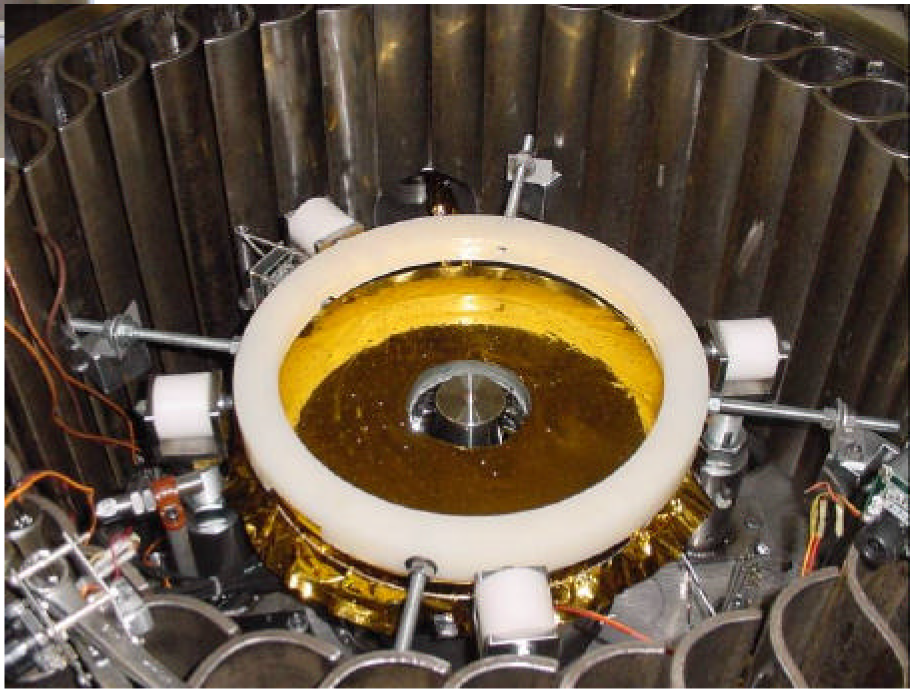
1 kWh Flywheel Rotor and Bearing

Underside of rotor
with magnet array

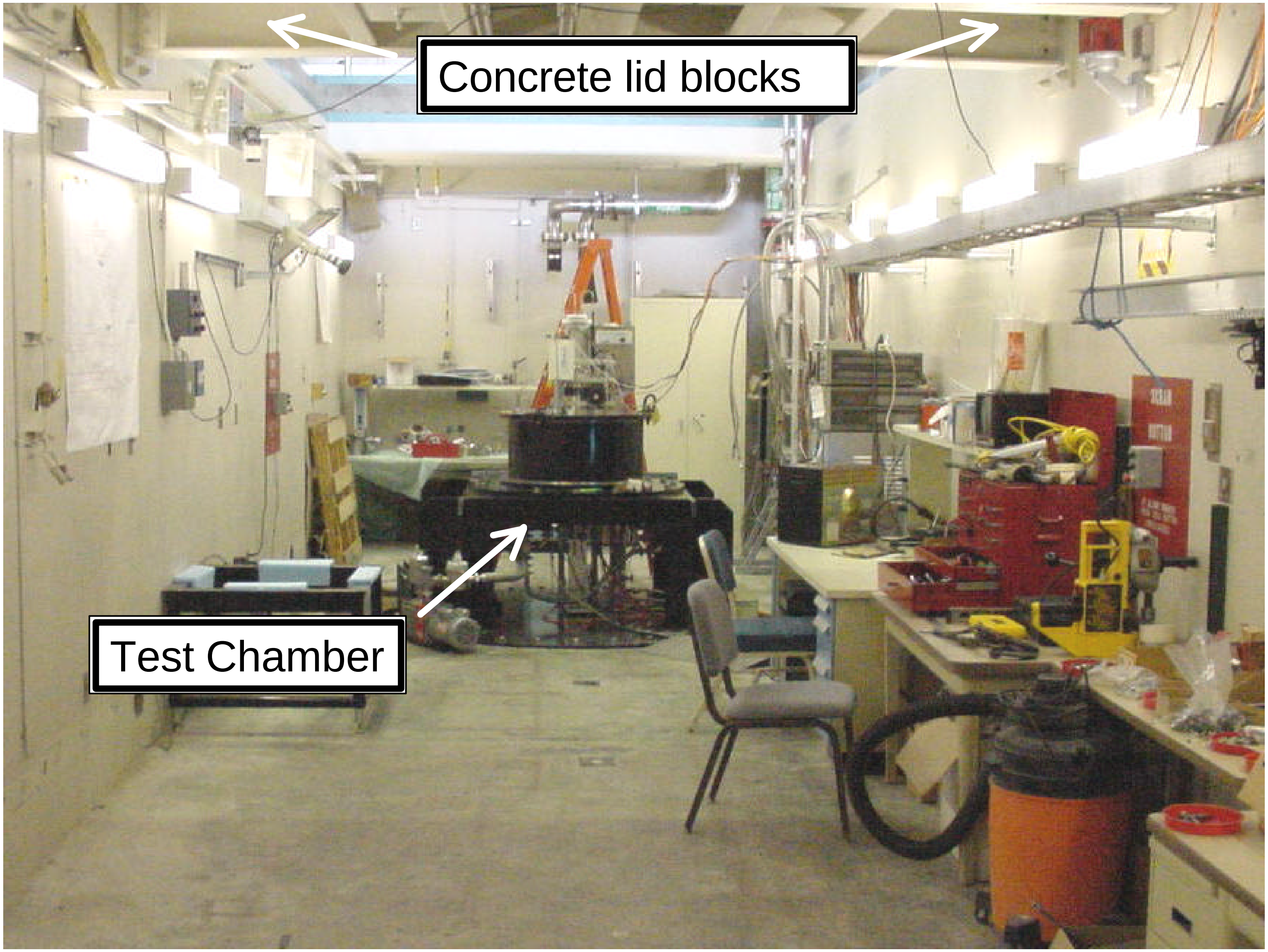
Cryostat in test chamber

YBaCuO wafers





Boeing Spin Test Laboratory



1 kWh Flywheel Rotor and Bearing

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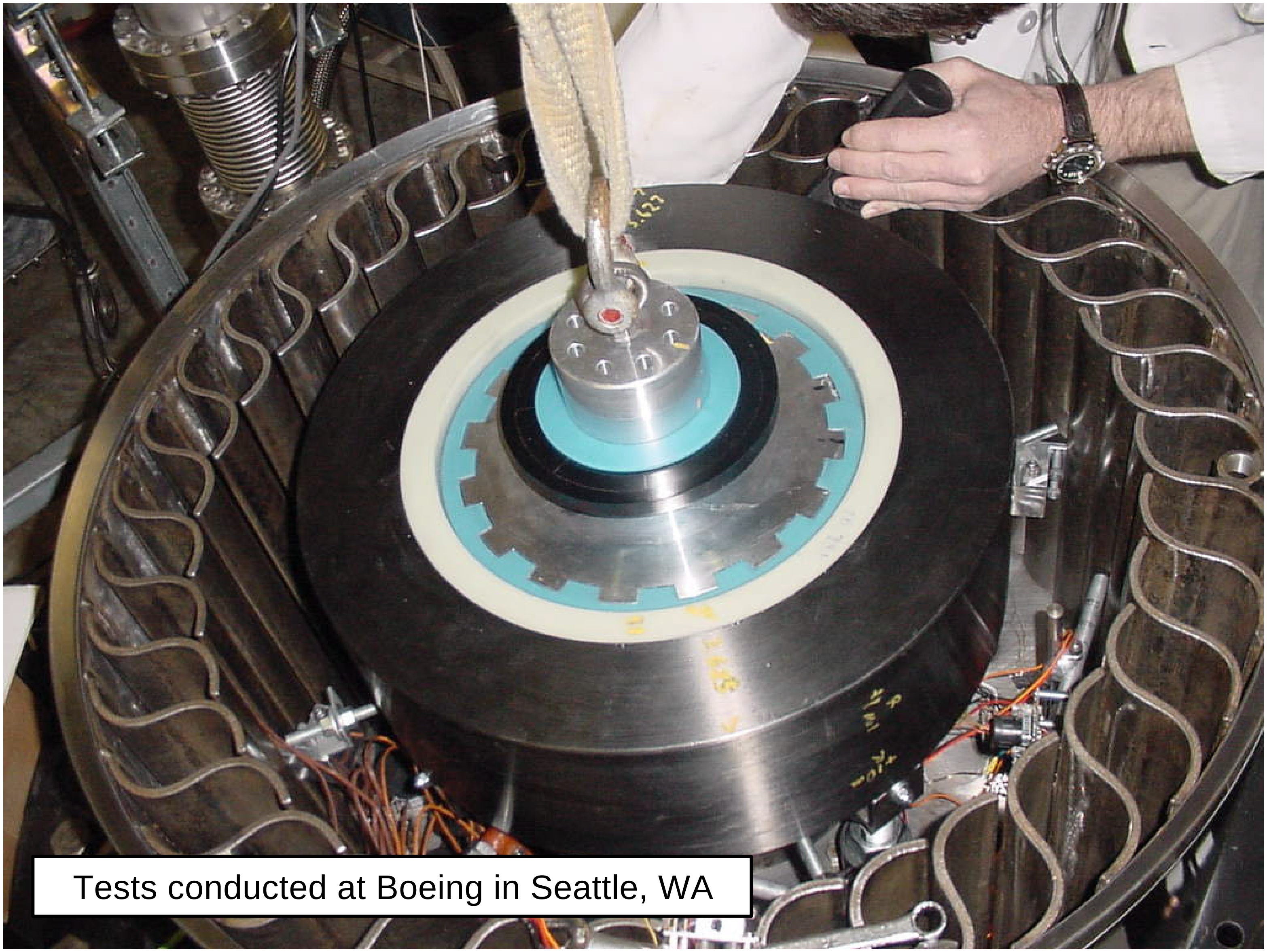
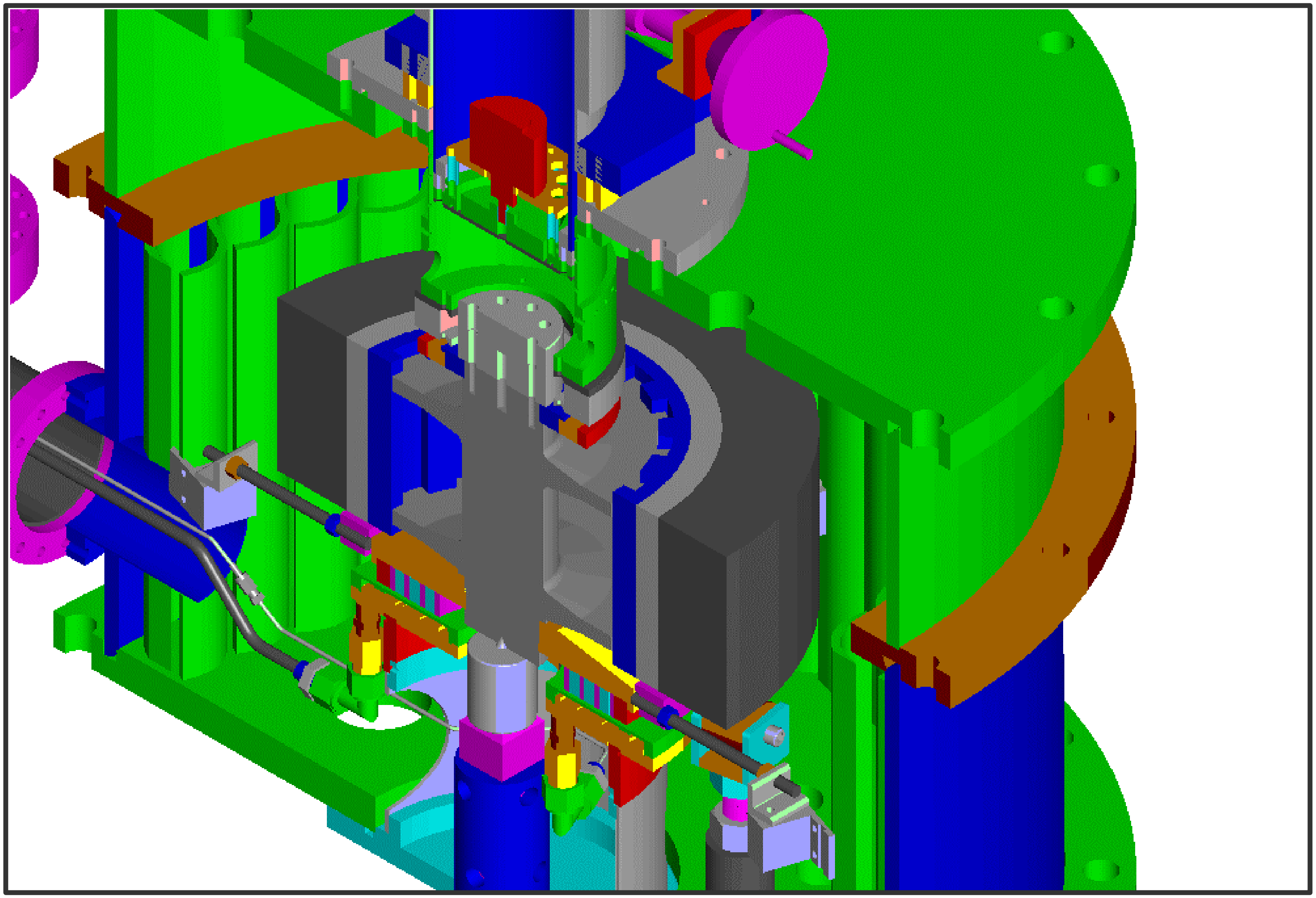


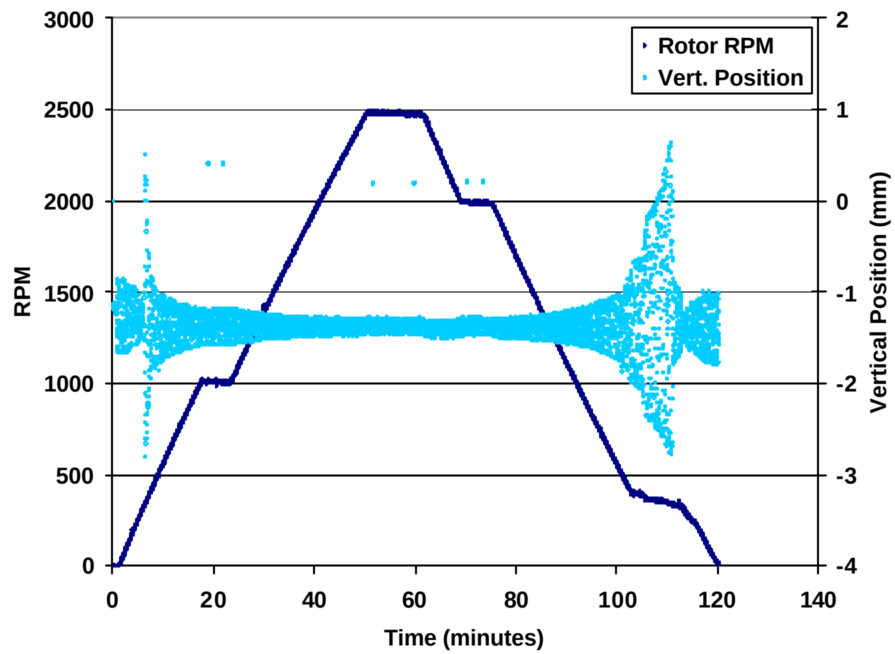
Tests conducted at Boeing in Seattle, WA

Testing of 1 kWh Flywheel: Cutaway View in Test Chamber



Spin-down Results

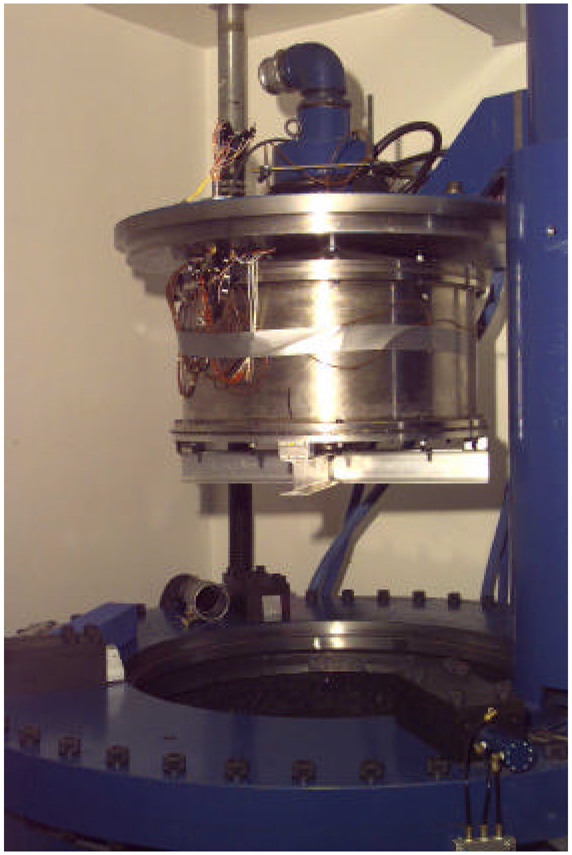
- In series of spin runs, rotor achieved 350 - 2500 - 8000 rpm
- At 8000 rpm, max spin-down at 4.6 rpm/min → 6.8 Watts, windage dominated (3 mTorr)
- In separate bearing tests losses have been lower even at much higher speeds



Magnet/Cryo Gap	Bearing Raw Power Loss, 20,000 RPM	AC Loss Contribution (estimate)	20 x P(AC) (72K penalty)	Bearing Net Power loss, 20,000 RPM
6 mm	1.54 Watts	0.26 Watts	5.2 Watts	6.5 Watts
4 mm	4.80 Watts	0.67 Watts	13.4 Watts	17.5 Watts

Flywheel Rotor Safety Activities

- Initiated composites test program with Penn State
- Carried out magnet test and analysis program with WSU
- Member of NASA/AFRL rotor safety study group

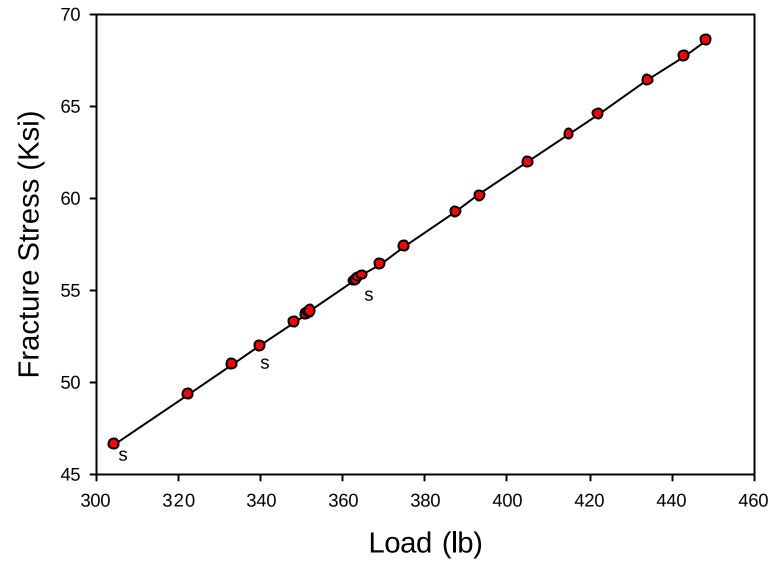


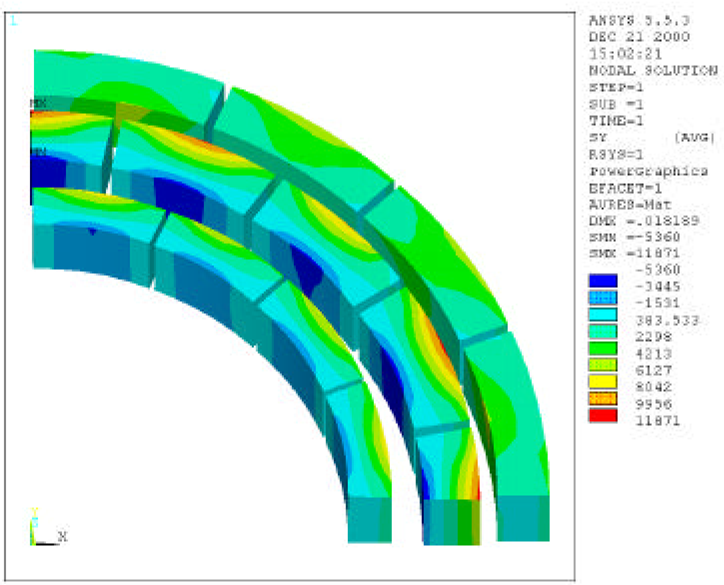
Test of flywheel container-in-container

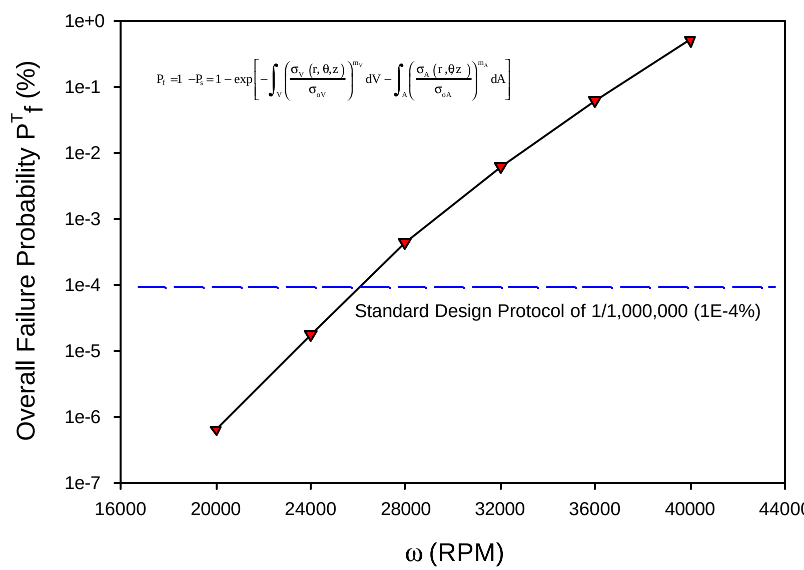
Rotor Safety: Magnet Failure Prediction

Initial study of magnet reliability:

- **Search for properties, test methods**
- **Obtain samples for fracture testing**
- **Initial test lot to obtain Weibull modulus**
- **ANSYS for probabilistic analysis**







Composite Materials Fatigue Measurements

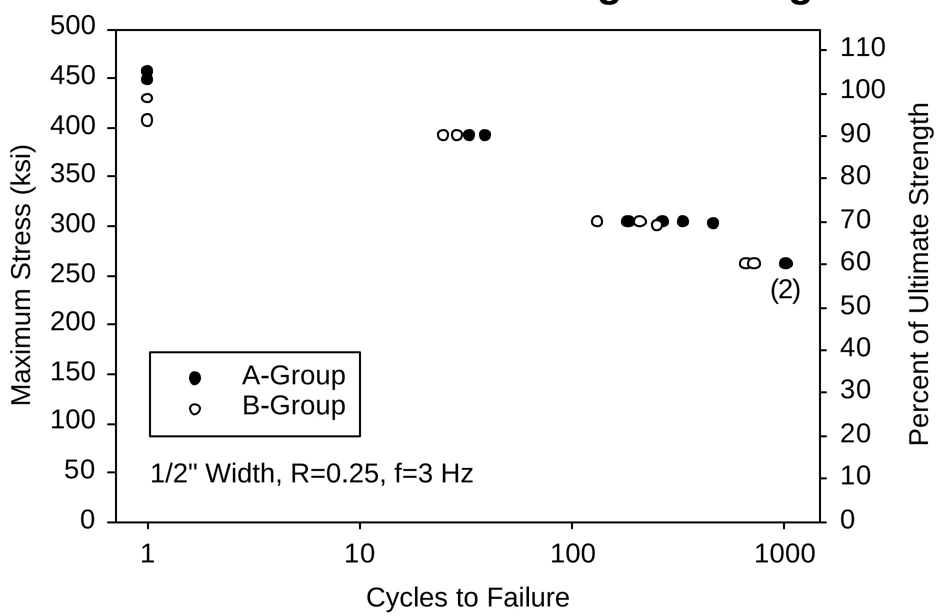
Initial study of composite fatigue:

- **Loading ratio effect studied**
- **Specimen width effects underway**

PSU assisting with qualification plan development; also participates in NASA/AFRL working group

T-700 composite coupon in grips

S/N curve for T-700 fatigue strength



Summary of Past Year's Results

1) Develop low-cost rotor/bearing approach ✓

- Identify approaches for up to 50 kWh ✓
- Build sub-scale unit: 1 kWh ✓
- Initiate spin testing: 8,000 rpm ✓

2) Determine & enhance system reliability ✓

- Materials: composites, magnet test & analysis ✓
- Qualification plan v 0.1 / NASA safety group ✓

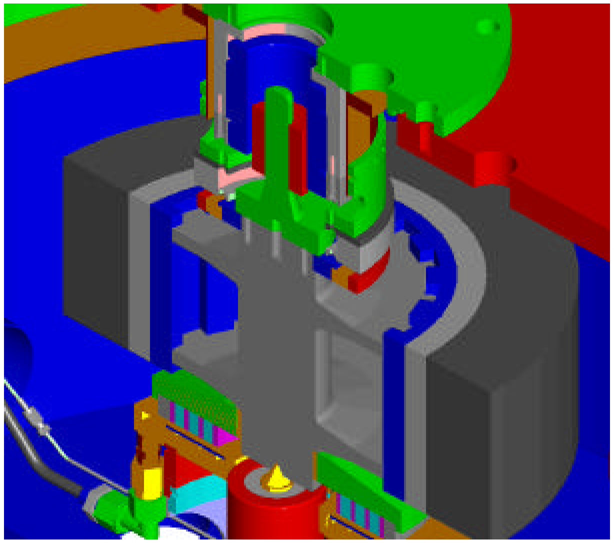
3) Communicate results ✓

- EESAT presentation and paper ✓
- PASREG presentation and paper ✓

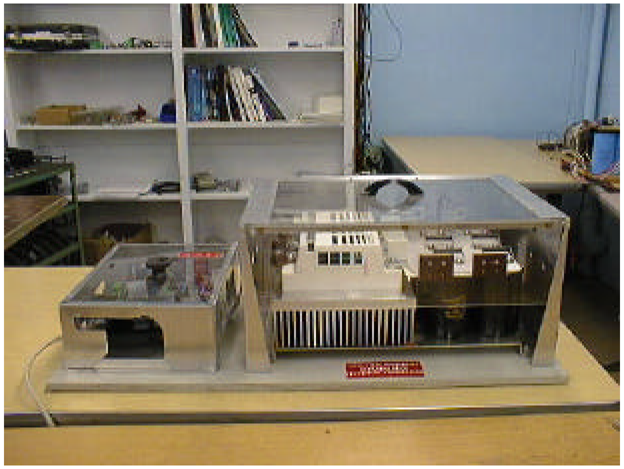
Plans for Current Year

1) Extend low-cost rotor/bearing work
2) Select site for field test
3) Develop system design
4) Develop rim qualification plan
5) Fabricate superconductors
6) Initiate build of field demo unit
7) Communicate results

Cutaway of rotor with M/G



Motor drive electronics



Boeing Flywheel Project Milestones

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Date	Event	Power	Energy
Aug 1997	Boeing submits Phase I proposal as Superconductivity Partnership Initiative (SPI) - under Jim Daley/EERE		
May 1998	Phase I SPI starts. Utility/UPS emphasis, component design.	3 – 100 kW	10 kWh
Nov 1998	Boeing and Argonne National Lab initiate CRADA		
May 1999	Sandia Energy Storage Program issues Advanced Storage RFQ		
Jun 1999	Sandia/Boeing Phase I starts. Selects off-grid emphasis, develops program plan, estimates system costs.		
May 2000	Boeing conducts site visit in Israel for potential IEA project		
May 2000	Sandia/Boeing Phase II starts. Low-cost rotor/bearing development and rotor qualification work are major tasks.		1 kWh
Jun 2000	Boeing opens discussions with Trace, L3 Communications		
Jul 2000	Conduct full-speed test of Ashman motor/generator and controller.	3 kW	
Aug 2000	Conduct drop test of rotor in Boeing containment chamber		1 kWh
Sep 2000	Penn State begins collaboration with Boeing for rotor qualification and materials testing		
Sep 2000	Phase II SPI starts. Objective is to complete design and test of UPS unit at Southern California Edison in 2002.	100 kW	3 kWh
Nov 2000	Optimized High-Temperature Superconducting (HTS) Bearing achieves first levitation and spin		
Jan 2001	Low-cost flywheel rotor and hub completed by Toray Composites for Boeing		1 kWh
Mar 2001	Flywheel rotor and HTS bearing are integrated and successfully levitated and spun to 8,000 rpm.		1 kWh
Mar 2001	Boeing innovator team submits flywheel project for possible spin-out through Boeing's "Chairman's Innovation Initiative"		
May 2001	Boeing submits new SPI proposal for Commercial Entry system	50 kW	35 kWh
Jun 2001	NASA Rotor Safe Life Program kick-off. Boeing attends and agrees to participate w/ aerospace expertise.		
Jul 2001	HTS Bearing reaches 15,000 rpm. Raw bearing power loss (before cryogenics) projected to 5 Watts at 20,000 rpm.		
Aug 2001	10 kWh rotor and hub receive first test in spin pit, achieve 13,600 rpm.		
Aug 2001	Sandia/Boeing Phase III to start. Objectives are to complete SDR, PDR, and initiate system build-up for on-site demo.		>3 kWh
Aug 2001	Boeing and Argonne National Lab renew CRADA		
Sep 2001	Penn State to begin detailed materials investigations		