Boeing Technology
Phantom Works

Design, Fabrication, and Test of a 5 kWh Flywheel Energy Storage System Utilizing a High Temperature Superconducting Magnetic Bearing

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Boeing Phantom Works

Energy Storage Systems
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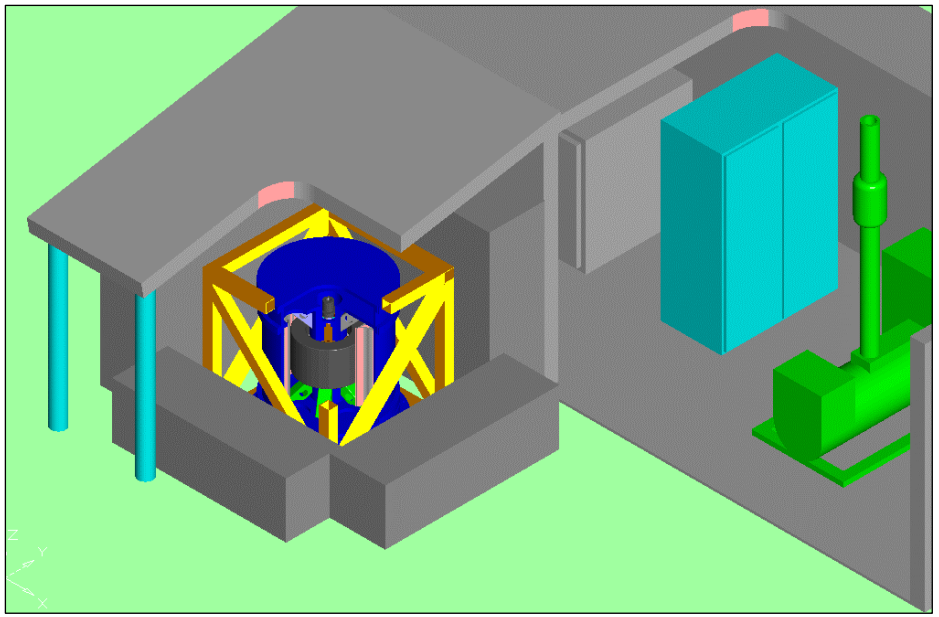
Flywheel Energy Storage Systems

Objective:

•Design, build and deliver flywheel energy storage systems utilizing high temperature superconducting (HTS) bearings tailored for uninterruptible power systems and off-grid applications

Goal:

•Successfully integrate FESS into multiple demonstration sites through cooperative agreements with DOE and contracts with Sandia National Labs



Deployment of a demo system, shown in relation to diesel genset and balance of system.

Status:

•The 1 kWh / 3 kW test was successful

•**The design upgrade of the 5 kWh rotor is complete**

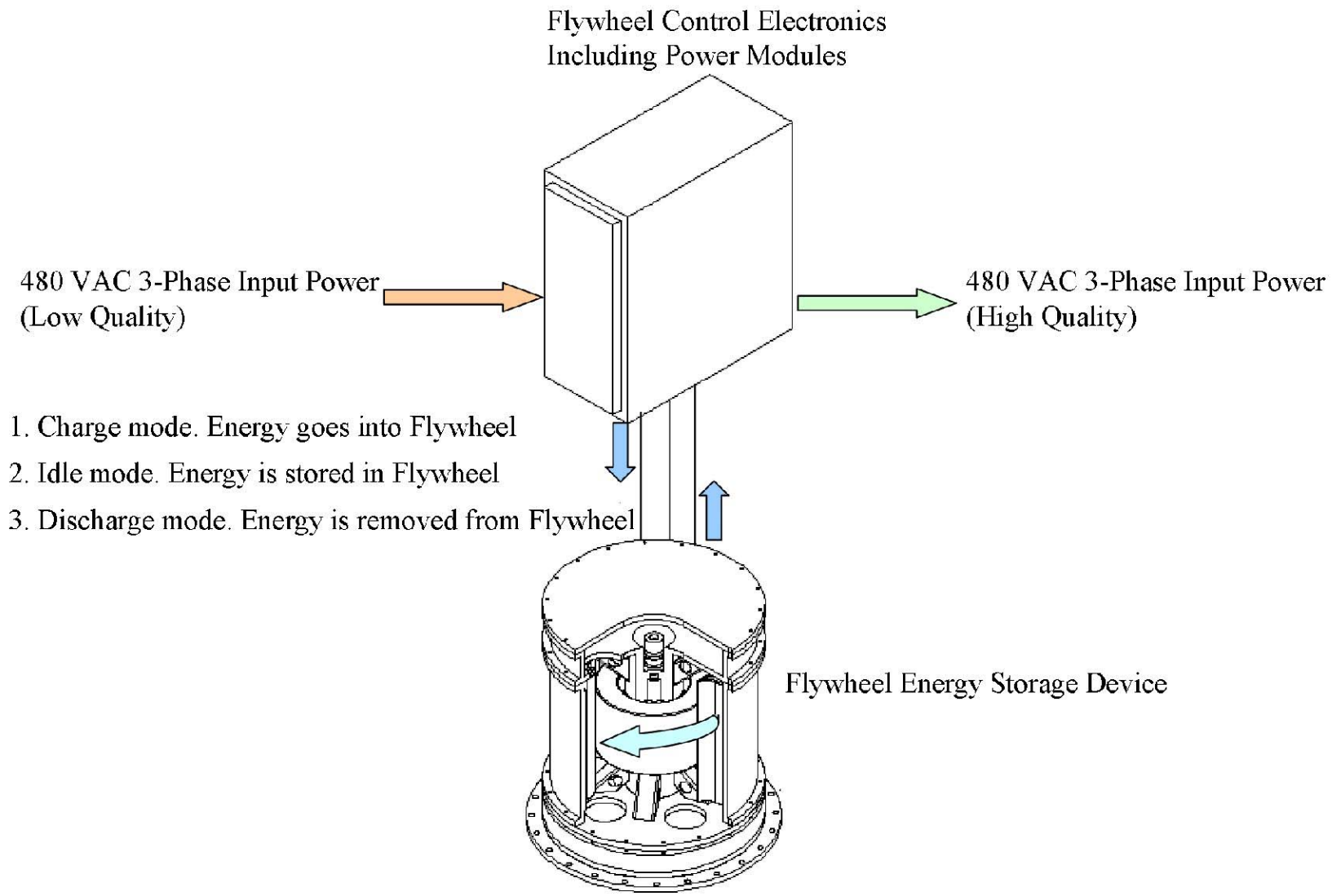
•**The 5 kWh / 100 kW is currently in integration testing**

•The 10 kWh / 3 kW achieved many of the program design goals

•The design upgrade of the 10 kWh rotor is complete

•Preliminary designs started for 30 kWh / 100 kW system

Flywheel Energy Storage Systems Basic Operation

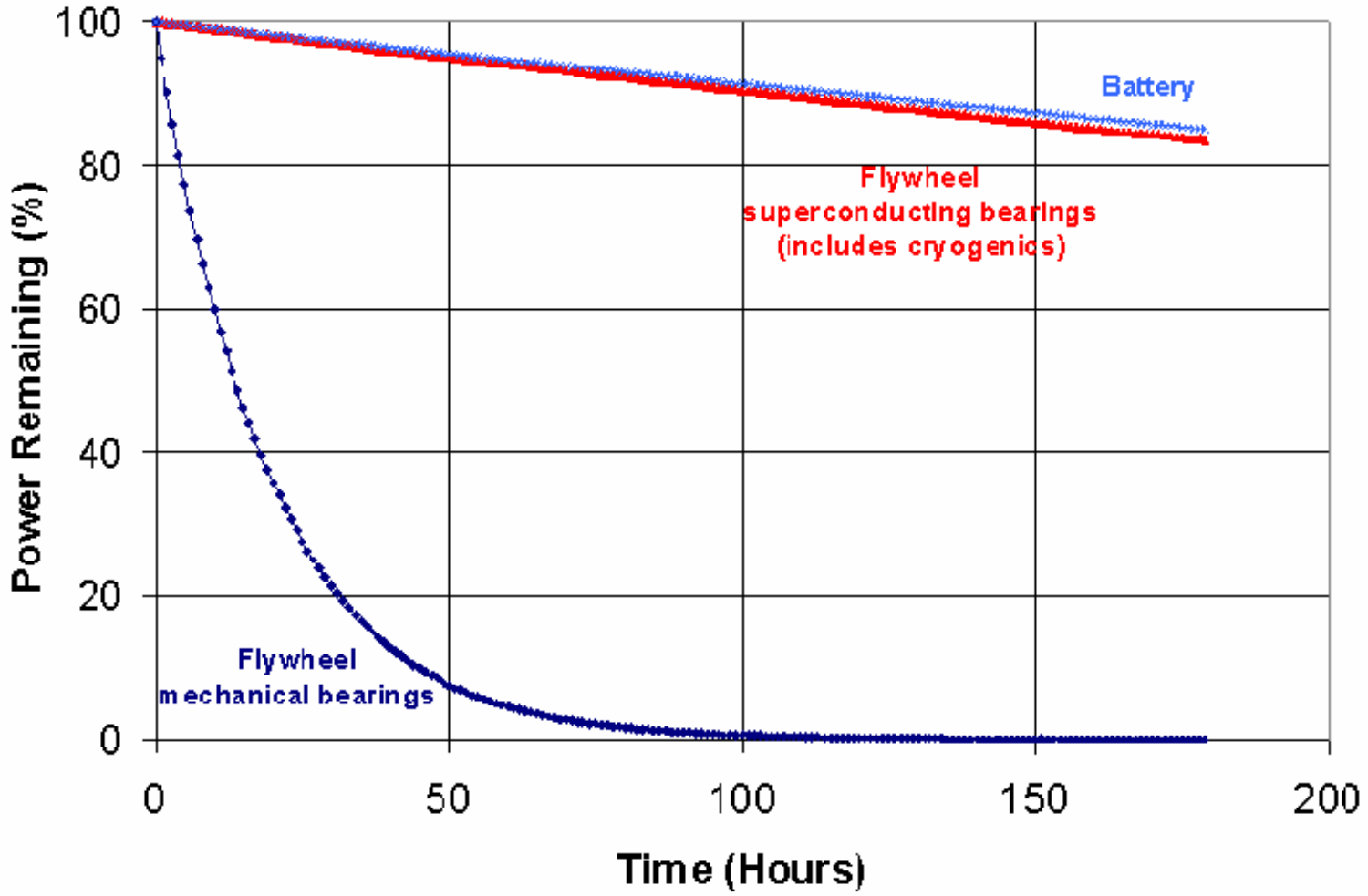


Flywheel Energy Storage System

- **Why Pursue Flywheel Energy Storage?**
  - Non-toxic and low maintenance
  - Potential for high power density (W/ kg) and high energy density (W-Hr/ kg)
  - Fast charge / discharge times possible
  - Cycle life times of >25 years
  - Broad operating temperature range

- **Why use high temperature superconducting bearings?**
  - Very low bearing losses to extend the idle mode
  - HTS bearings will support ultra high-speed flywheels
    - (Energy = (1/2) (Moment of Inertia) (Spin Speed)^2)

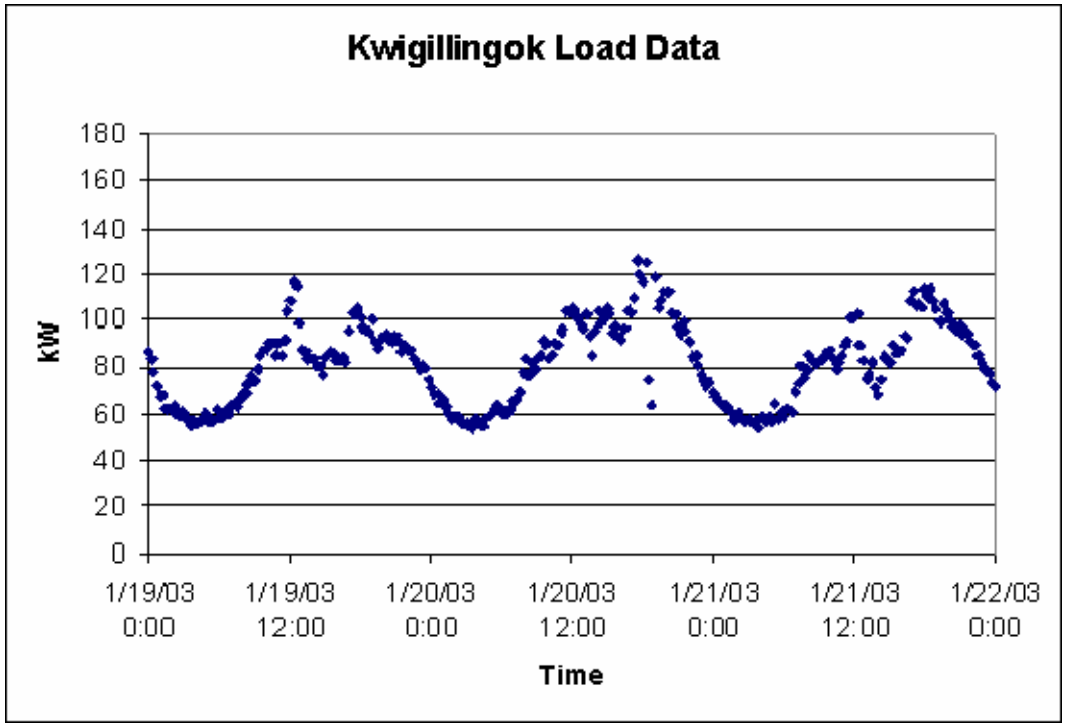
Charge Retention Comparison of Flywheels and Battery



Typical Load Profile for Remote Village in Alaska

Kwigillingok, Alaska (population 338)

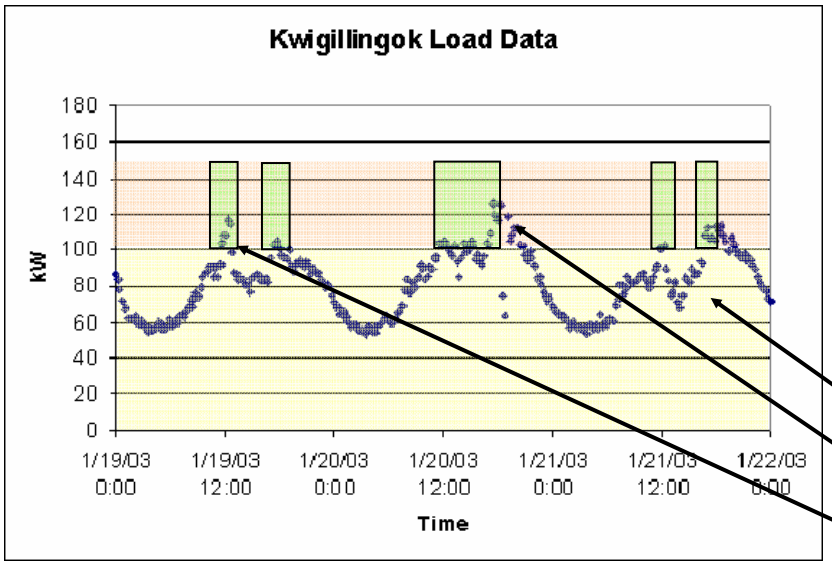
Photo and data credits Virtual Tourist.com & encyclopedia.thefreedictionary.com

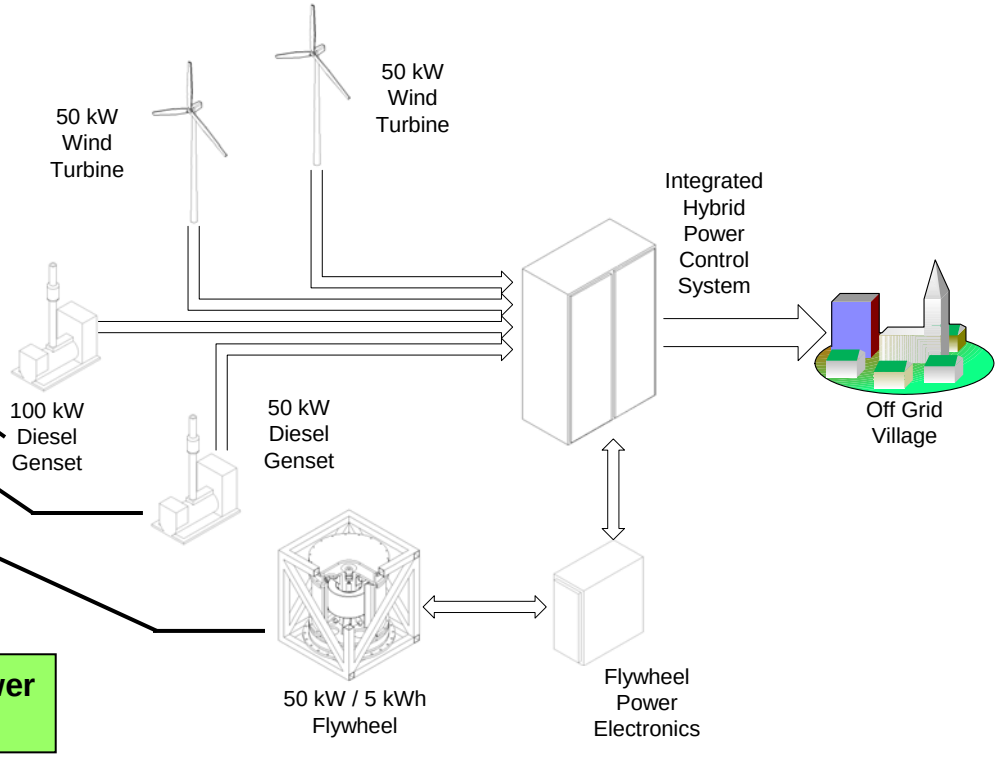


- Now served by multiple diesel systems
- Reasonable match for 50 kW FESS

- *Data provided courtesy of Alaska Energy Authority*

Proposed System Architecture for Deployment of a 5kWh / 50 kW Flywheel Energy Storage System





Flywheel Energy Storage System would supply power during short peak demand periods

<u>Benefits of using FESS instead of idling 2nd generator on standby</u>

- **Reduce generator maintenance by 50% (estimate)**
- **Reduce fuel costs by $80k/yr (estimate)**
- **Lower pollution (air and noise)**

Energy Storage Program 5 kWh / 50 kW Flywheel Energy Storage System Project Roadmap

6/99 – 9/99

Phase I: Application ID and Initial System Specification

- Applications
- Characteristics
- Planning

5/00 – 3/01

3/01 – 11/-01 (funding interruption)

1/04 – 05/-04 (funding interruption)

Phase I: Significant Outputs

- **Unit characteristics**
- **System specification document**

11/01 – 12/05

Phase II: Component Development and Testing

- Rotor/bearing
- Materials
- Reliability

Phase II: Significant Outputs

- **Prelim design complete**
- **HTS crystal array complete**
- **Material lifetime data**
- **Rotor upgrade complete**
- **Rotor qualification testing complete**

1/06 – 10/06

Phase III: System Integration and Laboratory Testing

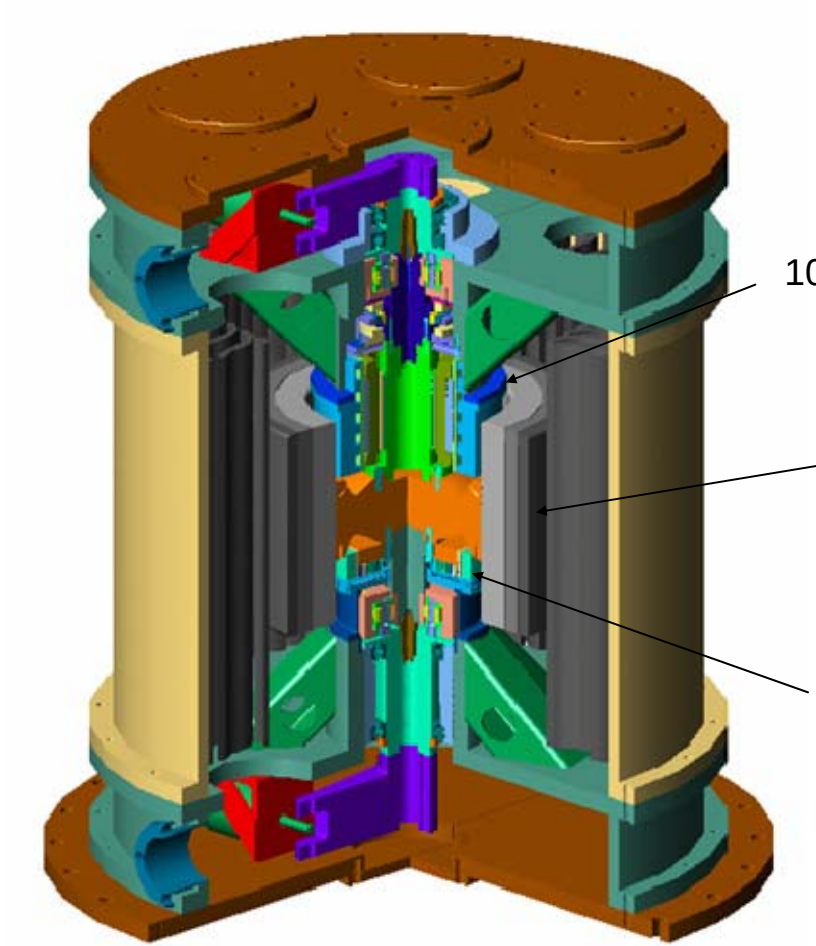
- Site selection
- Detail design
- Build/buy
- System test

10/06 – 9/07

Phase IV: Field Test

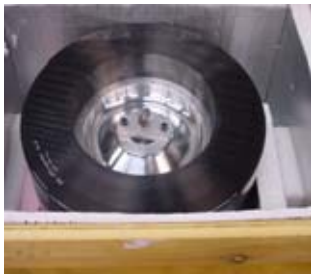
- Install
- Conduct field testing
- Post-test evaluation

Flywheel Energy Storage System Key Components

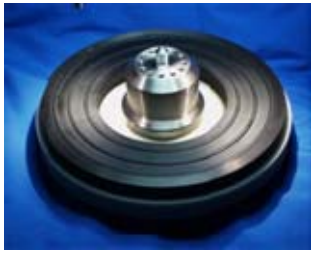


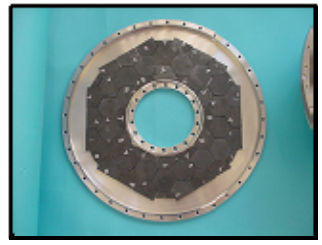
100 kW or 50 kW Motor Generator

5 kWh Rotor



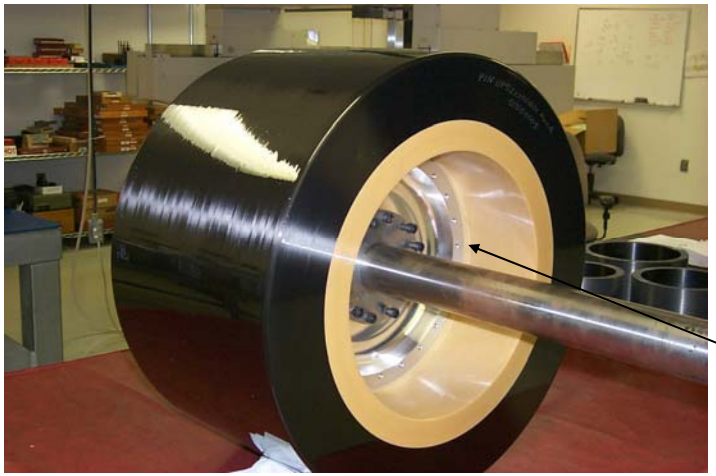
High temperature superconducting bearing





Hex YBCO

Energy Storage Challenges in Early 2004 Resolved in 2005



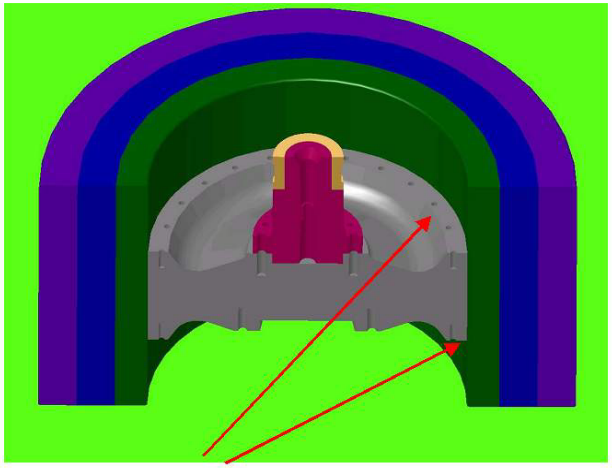
Crack appeared after clearcoat cure

- **2004**
  - Manufacturer's process had not accounted for the stresses related to the elevated temperature of the cure cycle for the clearcoat
  - Data revealed a nearly 40% reduction in strength at the peak clearcoat cure temperature.

- **2005**
  - **Problem is understood and corrected**
  - Improved rotor design has resolved this issue
  - New rotor has completed fabrication
  - High-speed spin qualification testing complete

High-Speed Quill Test of 5 kWh Rotor

Normal max operational speed is 22,500 RPM
Analysis complete and acceptable to 24,000 RPM
Quill tested at 105% or 23,675 RPM



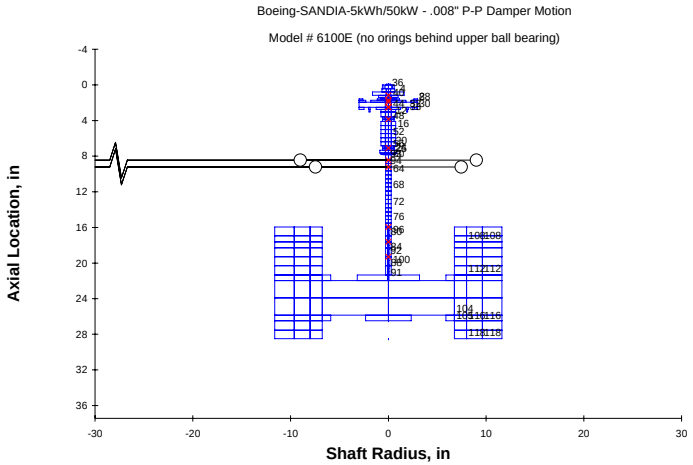
Balance Features

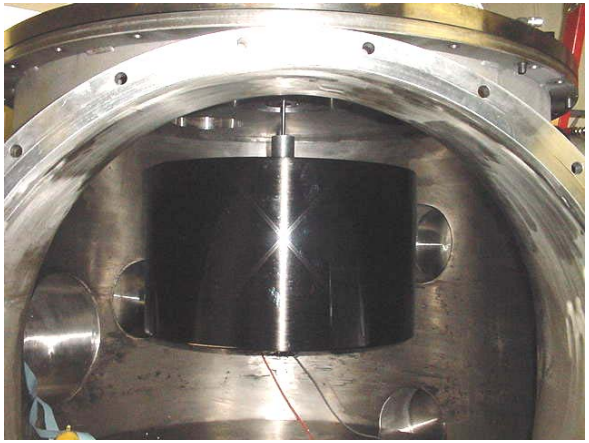
5 kWh rotor total indicated runout (TIR) held to 0.002” during fabrication

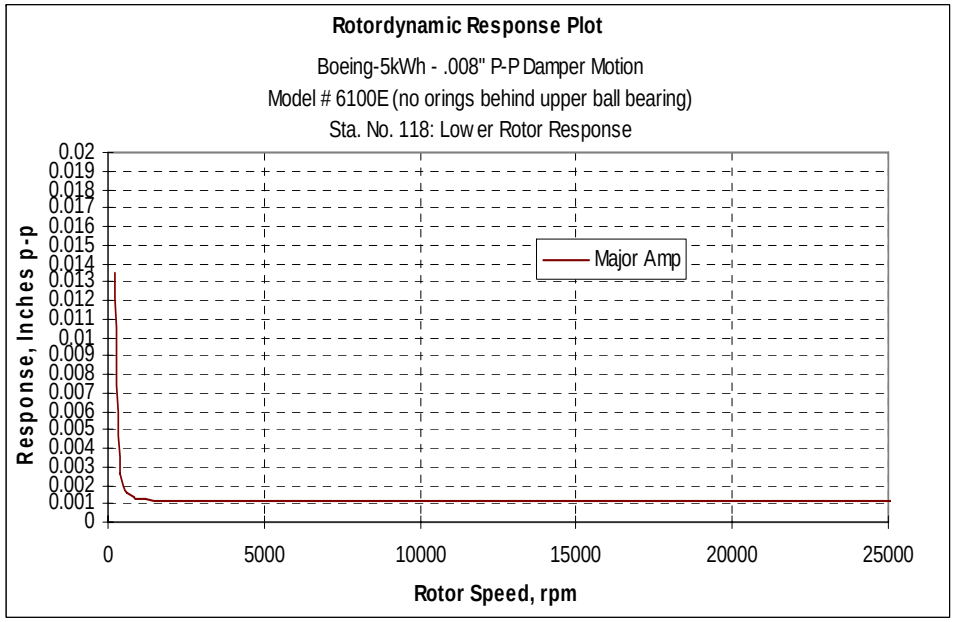
As such, the rotor did not require any balancing prior to or during quill testing

5 kWh Rotor inside of the Boeing Quill Tester

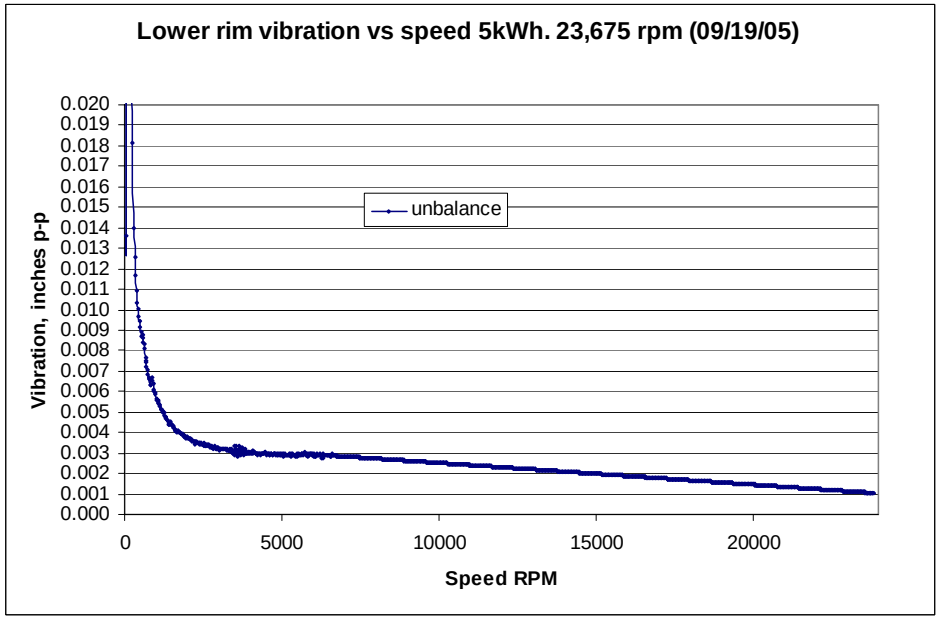
Quill Test Dynamic Model vs. Quill Test Data







xLrotor forced response plot showing the amplitude of unbalance vs rpm

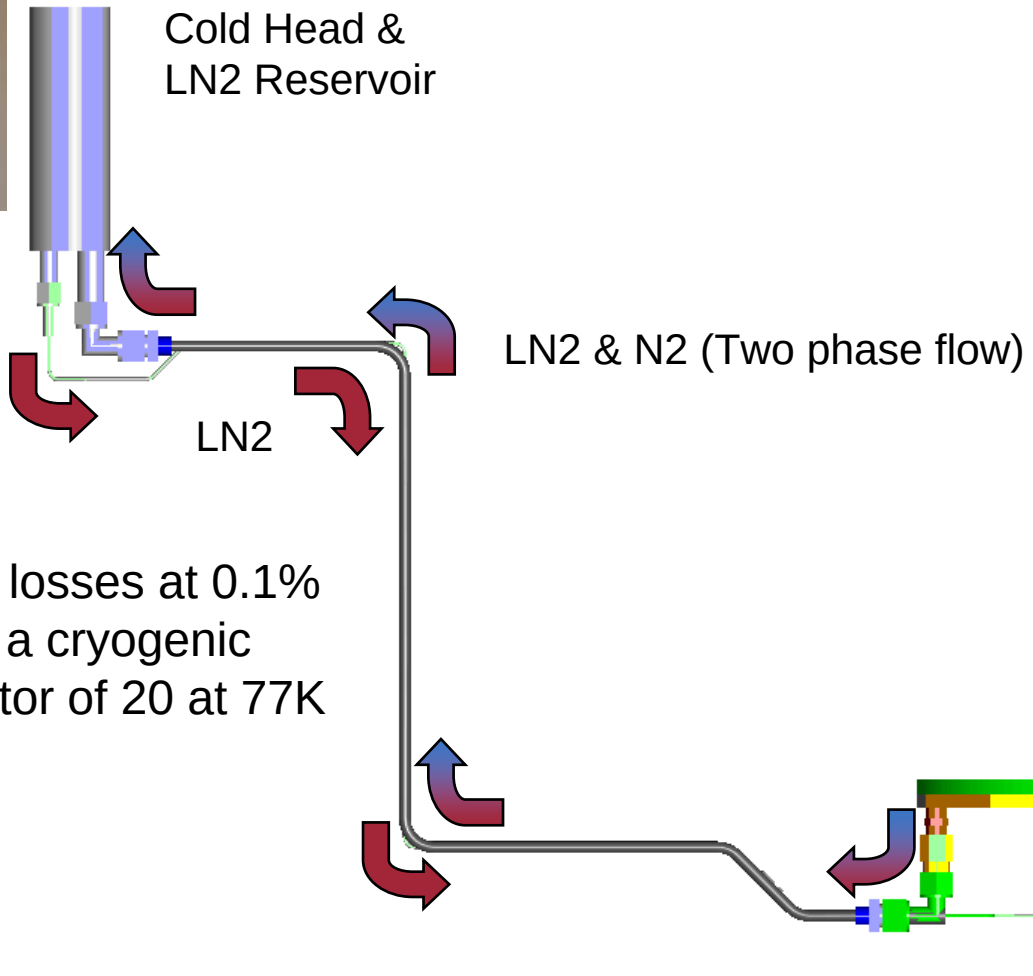


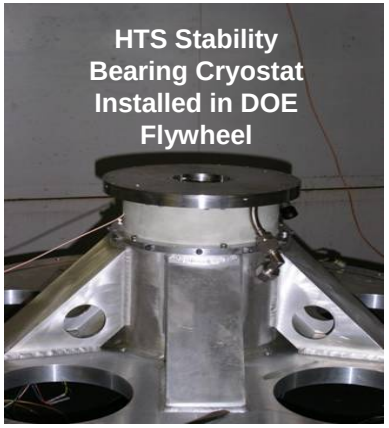
Lower Rim data from high-speed quill testing showing the amplitude of unbalance vs rpm

XLRotor Spreadsheet for Rotordynamic Analysis
© Rotating Machinery Analysis, Inc.

Current DOE/Boeing Flywheel Cryogenics

Thermosyphon Operation



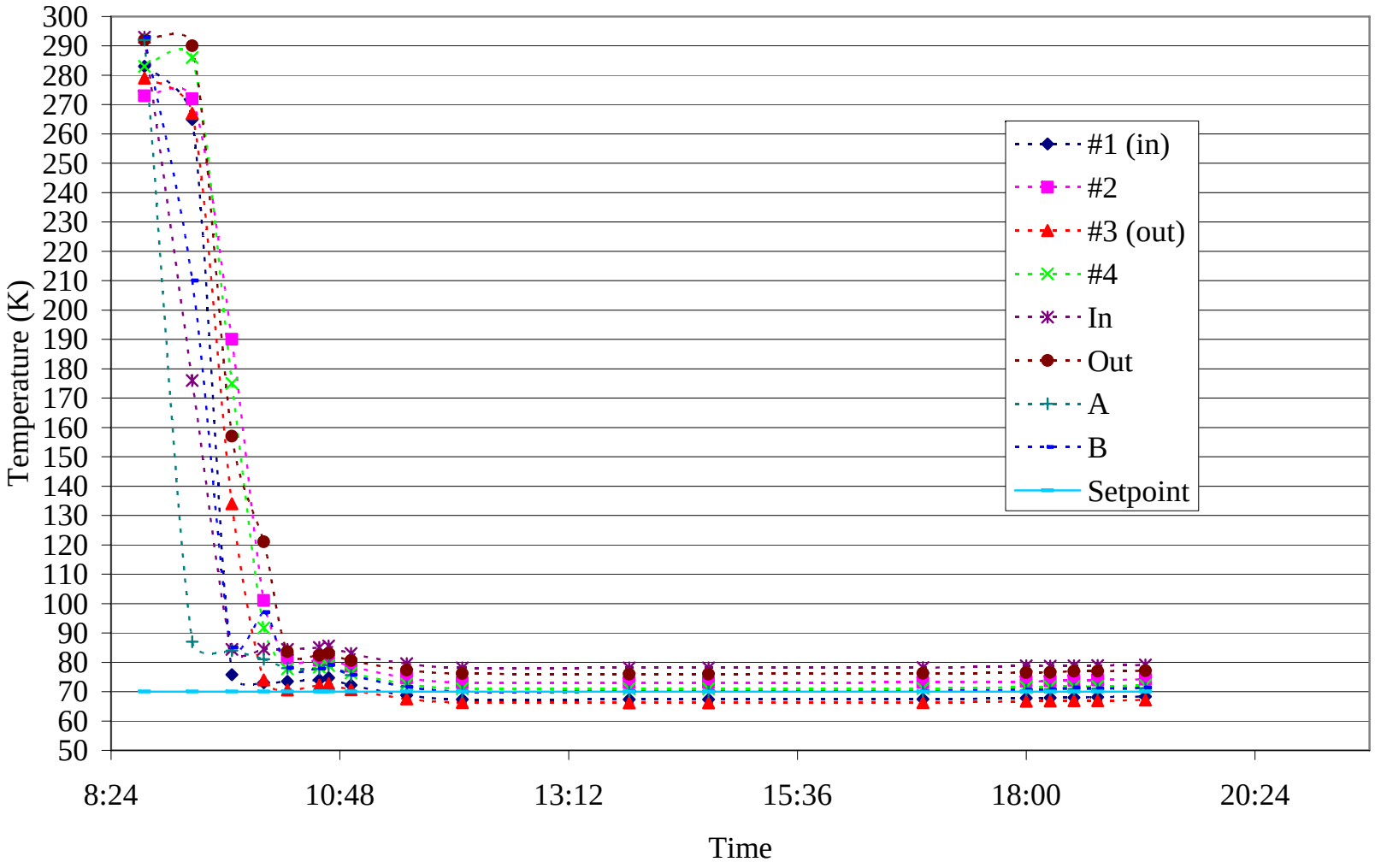


HTS Bearing losses at 0.1% / hr including a cryogenic overhead factor of 20 at 77K

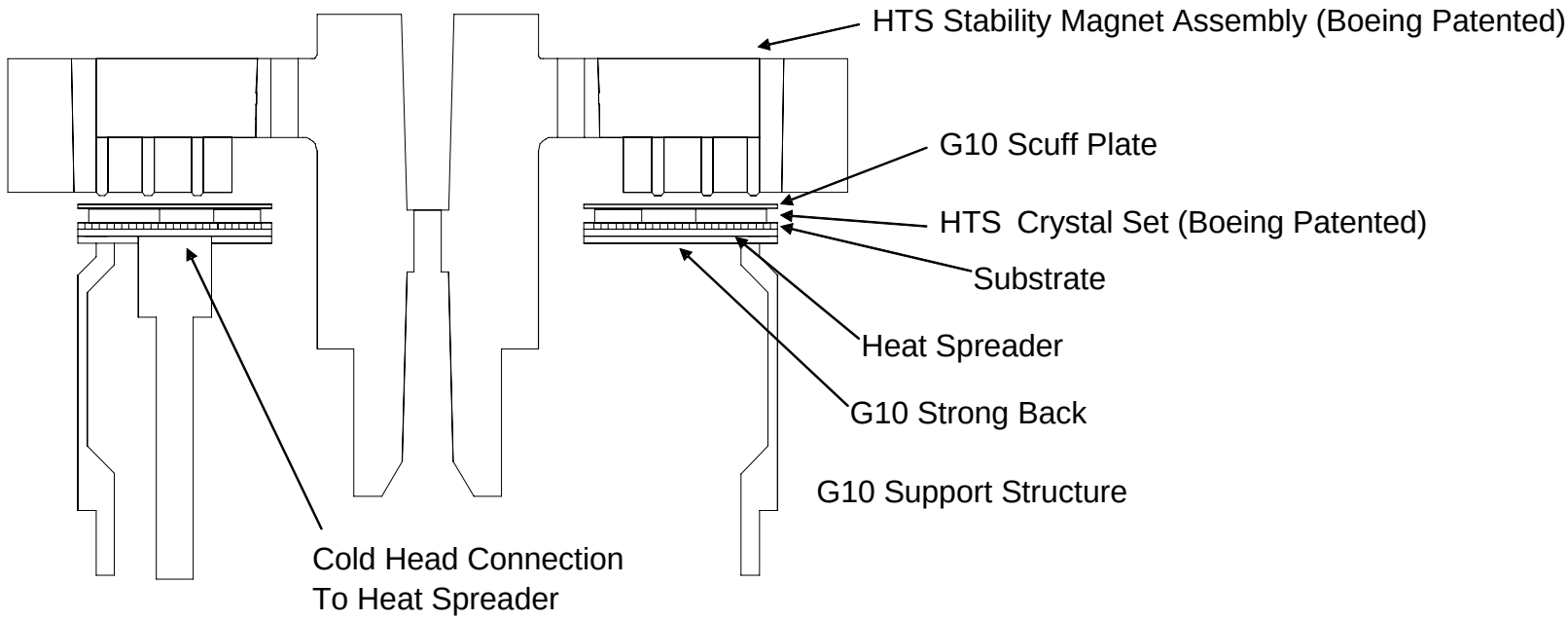
Cryostat (HTS)

Typical Cryogenic Data on HTS Bearing

22 April 05 Full Run Cryogenic Temperatures, 5 kWh / 100 kW FESS



Direct Cooling Approach on HTS Bearing Moving Forward



Benefits:
Fewer parts, lower power requirements
Eliminates the requirement for LN2
Reduces maintenance

Summary

- 1 kWh System
  - The 1 kWh / 3 kWh test was successful
  - Verified the HTS bearing approach and low losses

- **5 kWh Systems**
  - The 5 kWh / 100 kWh is currently in full system integration testing with all subsystems and components fully qualified
  - The high temperature superconducting bearing is performing very well
  - The design upgrade of the 5 kWh rotor is complete and validated by test
  - Direct cooling HTS approach for 5 kWh / 50 kW is moving forward into fabrication and test

- 10 kWh System
  - The 10 kWh / 3 kWh achieved many of the program design validation goals
  - The design upgrade of the 10 kWh rotor is complete and moving into fabrication

- 30 kWh System
  - Preliminary design started for 30 kWh / 100 kW system

- Boeing is committed to continue Flywheel Energy Storage System efforts

Acknowledgements

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  - **Dr. Imre Gyuk and Paul Bakke of the U.S. Department of Energy through the Energy Storage Program and Offices of Energy Efficiency and Renewable Energy**
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