superior performance. powerful technology.

2G HTS Materials for Rotating Machinery

Drew W. Hazelton
Principal Engineer, Applications

Superconducting Motor Workshop
Kleinheubach, Germany • October 22-23, 2012
From GE to Furukawa

• History
  – 1971: Superconductivity group spins out of General Electric and forms Intermagnetics General Corporation
  – 1987: following the 1986 discovery by Bednorz and Mueller, Intermagnetics forms a dedicated group to work on HTS
  – 2000: Intermagnetics forms SuperPower to develop 2G HTS technology for Energy Technology applications
  – 2006: Intermagnetics is acquired by Royal Philips Electronics for MRI magnet business
    • Holds SuperPower to build value
  – 2012: SuperPower is acquired by Furukawa Electric Co., Ltd.
Furukawa Electric Co., Ltd.

Founded: 1884

Net sales: ¥918,808 million (Consolidated) 3/31/12

Employees: 45,000

Head Office: Chiyodaku, Tokyo - Japan

Factories: 7
  Chiba, Nikko, Hiratsuka, Mie, Yokohama,
  Copper Tube Division and Copper Foil Division

Branch and Sales Offices: 10

Research Laboratories: 7
  Yokohama R&D Laboratories
  Metal Research Center
  Ecology & Electronics Laboratories
  Power & System Laboratories
  FITEL Photonics Laboratory
  R&D Center for Automotive Systems & Devices
  HTS Project Team
FEC Businesses

Three core materials across five business segments

- Metals
- Photonics
- Metal Polymer
- Telecommunications
- Light Metals
- Energy/Industrial Products
- Electronics/Automotive Systems
Company Structure

Y. Shirasaka – President & Treasurer

H. Sakamoto – VP and Director of Operations

T. Fukushima – Director of R&D and Applications (Houston/Schenectady)

A. Kazanjian – VP & Director of Finance & Admin.

T. Lehner – Sr. Director, Marketing & Govt. Affairs

~100 highly skilled employees in the US and Japan

HQ and Mfg: Schenectady, NY

R&D: Houston, Texas
SuperPower® 2G HTS wire: Thin film deposition on robust, flexible substrate

- Automated processes
- Reel-to-reel systems
- High throughput, fast processes

- Modular and scaleable systems
- Quality assurance throughout
- Rigorous testing, product certification with each delivery
Each layer serves a function....

- **Substrate** (Hastelloy® C-276) provides mechanical strength, electropolished base for subsequent layer growth
- **Buffer stack** provides:
  - Diffusion barrier between substrate and superconductor
  - IBAD MgO layer provides texture template for growing aligned superconductor, necessary for high current density
  - Final buffer layer provides lattice match between buffer stack and superconductor
- **HTS superconductor layer** – (RE)BCO superconductor with BZO based pinning sites for high current carrying capability in background magnetic field.
- **Ag layer** – provides good current transfer to HTS layer while providing ready path oxygen diffusion during final anneal.
- **Cu layer** – provides stabilization(parallel path) during operation and quench conditions.
2G HTS Wire Specifications

<table>
<thead>
<tr>
<th>Spec SF</th>
<th>Stabilizer Free</th>
<th>SCS = Surrounded Copper Stabilizer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SCS3050</td>
<td>SCS4050</td>
</tr>
<tr>
<td>Minimum (I_c)</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>Widths</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Total Wire Thickness</td>
<td>0.1</td>
<td>0.055</td>
</tr>
<tr>
<td>Standard Copper Stabilizer Thickness</td>
<td>0.04</td>
<td>n/a</td>
</tr>
<tr>
<td>Critical Tensile Stress</td>
<td>&gt; 550</td>
<td>&gt; 550</td>
</tr>
<tr>
<td>Critical Axial Tensile Strain</td>
<td>0.45%</td>
<td>0.45%</td>
</tr>
<tr>
<td>Critical Bend Diameter in Tension</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Critical Bend Diameter in Compression</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

• Robust, high-performance wire; several architectures, incl. variations of width, substrate thickness, stabilizer, and insulation
  – Insulated wire: Kapton wrapped - 30% overlap or butt-wrap available

• Two chemical formulations:
  – AP (Advanced Pinning) – for enhanced in-field performance in motors, generators, transformers, SMES, high field magnets, etc.
  – CF (Cable Formulation) – for cable or FCL
Addressing market requirements

- Fundamental principals:
  - Markets and customers have different needs

- Key requirements:
  - Proven success through device demonstrations and partnerships
  - Price, price, price (different approaches to get there)
  - Product attributes
    - Performance
    - Length
    - Uniformity
    - Mechanical properties
  - Performance certification/warrantees
  - Production capacity and ability to deliver (how much and how fast?)
  - Customer support, including engineering support
2G HTS offers excellent performance for all electrical device operating ranges

Normalized $I_c$ vs. Applied Field $\parallel c$

- Motors, generators
- SMES
- Cables, FCLs, transformers

$I_c (B/\parallel c, T) / I_c (self field, 77 K)$

Applied Field $B$ (T)
Critical current vs. temperature and magnetic field of recent AP production material
SuperPower 2G HTS wire has high tensile strength

4 K and 77 K data from NHMFL
SuperPower 2G HTS wire exhibits good fatigue strength

- **Ic & N** do not change under fatigue cycling if stress amplitude is below $S_{IcRL}$
- For stress $> S_{IcRL}$, $Ic$ & $N$ degrade with fatigue cycles
- Recommend a 98% reversible $Ic$ retention as “failure” criterion

Data from Ron Holtz, NRL
SuperPower is driving Price down on two fronts: Improving manufacturing process and increasing in-field performance

<table>
<thead>
<tr>
<th>Time</th>
<th>Performance at 77 K, zero field*</th>
<th>Lift Factor at device operating condition (30K, 2T)</th>
<th>Performance at device operating condition</th>
<th>Wire price ($/m)</th>
<th>Wire price ($/kA-m) at device operating condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Now</td>
<td>100 A</td>
<td>2</td>
<td>200 A</td>
<td>$ 45</td>
<td>$225</td>
</tr>
<tr>
<td>2 years</td>
<td>150 A</td>
<td>4</td>
<td>600 A</td>
<td>$ 40</td>
<td>$ 67</td>
</tr>
<tr>
<td>4 years</td>
<td>200 A</td>
<td>6</td>
<td>1200 A</td>
<td>$ 35</td>
<td>$ 30</td>
</tr>
</tbody>
</table>

* Based 4mm width

*Improving wire performance is key to success*
Strong history of price improvements achieved through technology advancements

- 10 m demo
- 100 m demo
- First year of pilot production
- 500 m demo
- R&D partnership with UH
- 1,000 m demo
- 2 to 4x higher throughput
- AP wire (Zr-doped) product introduction

Price ($/kA-m)

Year

2004 2005 2006 2007 2008 2009 2010

77 K, self field
30 K, 2 T
Moving toward large-scale production of robust, high-performance wire

- High critical current:
  - 100A standard; 110-120+ A premium (4 mm width)
- Uniform critical current over long lengths: +/- 10% standard deviation
- Single piece lengths of 50-300 m (without splices); up to 1 km and longer with high quality splices
- Excellent joints & solderability:
  - No degradation in Ic even when joint is bent over 1” diameter and thermal cycled
  - Joint resistance ~ 40 nohm-cm²
  - No issues with soldering to our 2G HTS Wire
- Manufacturing volume steadily increasing
superior performance. powerful technology.

Demonstration projects using SuperPower® 2G HTS wire
Office of Naval Research – HTS generator

Timeline:  Mar 2007 – June 2012
Objectives & Goals:
- SuperPower - 2G HTS coils, cooling system
- Baldor – Generator design/construction
- GD-Electric Boat – System integration studies
The project demonstrated a proof-of-concept 2G HTS-based generator rotor for use in the US Navy “All-Electric Ship”.
- Lighter weight / smaller footprint
- Improved operational costs
- Risk reduction studies on critical technology components
- Ship integration studies
- Sub-size rotor demonstration
Accomplishments:
- Rotor designed, fabricated and tested
- Cryogenic system designed, fabricated and tested
- Rotor cooled down and superconducting racetrack coils demonstrated
ARPA-E REACT (Rare earth alternatives for critical technologies) Program

Low-cost superconducting wire for future wind turbine generators

Partners:
- University of Houston – project lead, wire improvements
- SuperPower – wire manufacture
- NREL (National Renewable Energy Laboratory) – impact evaluation of enhanced superconducting wire on overall system performance
- Tai Yang Research Company – coil fabrication and test
- TECO Westinghouse Motor Company – development of device design

Budget: $3.1 million
Program Period: 3 years
Status: project underway
- work began Jan 2012
ARPA-E SMES development

• Funding: DoE ARPA-E $4.2 million (Total program = $5.25 million)
• Project timeline: 2011-2013
• Partners:
  – ABB, Inc.: project lead, power electronics
  – Brookhaven National Lab: SMES coil
  – SuperPower Inc.: 2G HTS wire, coil development
  – University of Houston, TcSUH: manufacturing improvements for wire cost reductions

  Objective: proof-of-concept of modular, scalable SMES system by integrating an advanced power conversion concept with superconducting magnet coil
  – 20 kW UHF SMES device with capacity of up to 3.4 MJ
  – Field of up to 25 T at 4.2K
  – 2G HTS wire with high critical currents (~ 800 A) to drive down price/performance
  – Capable of flexible connection to medium voltage distribution networks at 15-36 kV

• Relevance:
  – High power and high energy storage in a compact device with cost advantages in material and system
  – Modular units for both long (hours) and short term (seconds) storage requirements to help load leveling on the grid being fed by variable renewable sources
Army Research Lab – SMES for Micro-Grid

- Funding: US Army Research Laboratory $4.2 M of $7M funded to date
- Project timeline: 3 yrs., 2012 - 2015
- Partners:
  - SuperPower Inc: project lead, 2G HTS wire, coil development
  - Brookhaven National Lab: SMES coil
  - MTech Labs: power electronics
  - University of Houston, TcSUH: low ac loss material development

- Objective: Build upon the developments achieved in the ARPA E-SMES project with HTS superconductors and adapt those developments to the Army’s tactical Microgrid application.
  - Model, design and fabricate a 2.5MJ tactical Microgrid SMES
  - Modify 2G HTS MJ ARPA E-SMES coil to meet the tactical Microgrid requirements
  - Develop robust quench protection and switching components
  - Investigate methods to reduce ac losses through superconductor tape design

- Relevance:
  - High power and high energy storage in a compact device enables a power solution for remote areas.
  - Build on ARPA E investment in SMES technology to provide a practical application in real world environments.
## SFCL modular system design – components integration

### Module Design Specification and criteria

- **2G tape** – Jc, J/cm/tape, RUL Arms/tape, mechanical, thermal and electrical properties

- **Shunt Coils** – Zsh = Rsh + jXsh, X/R ratio, EM force withstand, thermal and electrical properties, connectors, size, weight, over-banding, ease of assembly and manufacturability

- **HTS assembly** – Tape per element, RUL per element, element energy capability, connectors, size, cooling orientation, failure mechanisms and mitigation, losses and their effects on cryogenics design

- **HV design** – LN2 and GN2 design stress criteria, spacing between tapes, elements and modules, stress shield dimensions, using solid barriers or not, bushings and assembly integration, assembly supporting structure (post insulators), overall assembly to cryostat spacing and integration

- **Cryogenics** - LN2 flow control, LN2 and GN2 interface, pressurizing, safety issues, thermal handling of fault and steady state losses

### Complete Transmission / Distribution System Design Boundaries

- Instrumentation, control and condition monitoring of SFCL system

- **Systems issues** - SFCL device testing, systems study and utility interfaces
2G conductor for SFCL shows consistent, excellent performance

**High-power SFCL test**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prospective current</td>
<td>90 kA*</td>
</tr>
<tr>
<td>Limited current</td>
<td>32 kA</td>
</tr>
<tr>
<td>Peak current through element</td>
<td>3 kA</td>
</tr>
<tr>
<td>Response time</td>
<td>&lt; 1 ms</td>
</tr>
<tr>
<td>Element quality range</td>
<td>Uniform</td>
</tr>
</tbody>
</table>

*Quench speed around 0.5 ms*
DoE Smart Grid SFCL transformer demonstration

- Funding: DoE Smart Grid Demo $10.7M (Total Program = $21.5M)
- Partners:
  - SuperPower (project lead)
  - SPX I Waukesha Electric
  - University of Houston
  - Southern California Edison
- Project objective:
  - Design, develop, manufacture and test SmartGrid-compatible SFCL Transformer
    - 28 MVA 3-phase FCL Medium Power Utility Transformer (69 kV / 12.47 kV class)
    - Testing on So. California Edison Smart Grid site in Irvine, CA – plan min 1 year of grid operation
    - First transformer to use significant amounts of 2G HTS wire
- Benefits
  - Greater efficiency
  - Smaller, lighter, potentially quieter
  - Safety: no oil for cooling
  - Can run indefinitely above rated power without affecting device life
- Add FCL feature …
  - Compatibility with Smart Grid requirements
    - Incorporation of FCL feature to rapidly detect and limit surges at high power levels that can be handled by downstream equipment
      - 30-50% reduction of prospective fault current
      - Low ac loss conductor development at UH
- Relevance:
  - Smaller footprint than conventional transformers, enabling existing substations to increase distribution capability without expanding into limited or expensive real estate
2G HTS has been used in multiple high field insert coil demonstrations

SuperPower: 26.8 T, 27.4 T / 20 T
NHMFL: 33.8 T, 35.4 T / 31 T
BNL: various HF coils to 16 T (500 A/mm²)
NIMS et al: 24.0 T / 17.2 T

NIMS 24 T
NHMFL 35.4 T
SP 26.8T
BNL 2G HTS Coil
superior performance. powerful technology.

Selected ongoing R&D areas
R&D Area: Advanced pinning continues to progress

Microstructure of production MOCVD HTS wires with standard 7.5% Zr doping

5 nm sized, few hundred nanometer long BZO nanocolumns with ~35 nm spacing created during in situ MOCVD process with 7.5% Zr
R&D area: Multifilamentary 2G HTS tapes for low ac loss applications

- Filamentization of 2G HTS tapes is desired for low ac loss applications.
- Techniques for tape striation demonstrated
- Scale-up to a cost-effective, robust manufacturing process continues

5-filament tape, 4 mm wide (produced up to 15 m)

32-filament tape, 4 mm wide (difficult to make even 1 m lengths)

![Graph showing ac loss vs. B_{ac rms} for 100 Hz with striated and unstriated samples.](image)
R&D area: Alternative configurations demonstrated for compact, high amperage windings

- Compact cable - ACT
- ROEBEL cable – IRL, KIT
- Bonded conductors for kA class conductors
2G HTS is ready to serve a diverse range of applications

<table>
<thead>
<tr>
<th>Energy</th>
<th>Defense</th>
<th>Transportation</th>
<th>Industrial</th>
<th>Medical</th>
<th>Science/Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>• FCL</td>
<td>• Motors</td>
<td>• Maglev</td>
<td>• Induction heaters</td>
<td>• Current leads</td>
<td>• HF magnets</td>
</tr>
<tr>
<td>• Cable</td>
<td>• Cables</td>
<td>• Motors</td>
<td>• Motors</td>
<td>• NMR</td>
<td>• Space exploration</td>
</tr>
<tr>
<td>• Generators</td>
<td>• Directed energy weapons</td>
<td>• Rail engines</td>
<td>• Generators</td>
<td>• MRI</td>
<td>• SQUIDS</td>
</tr>
<tr>
<td>• Transformers, incl. FCL</td>
<td></td>
<td></td>
<td>• Magnetic separation</td>
<td></td>
<td>• High energy physics</td>
</tr>
<tr>
<td>• Storage</td>
<td></td>
<td></td>
<td>• Bearings</td>
<td></td>
<td>• Electronics</td>
</tr>
<tr>
<td>– SMES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Cell tower filters</td>
</tr>
<tr>
<td>– Flywheels</td>
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</table>

Key:
- **Near-Term addressable**: 1-5 years
- **Mid-Term**: 3-7 years
- **Longer term**: 5-10 years

Courtesy of SuperPower and Furukawa

Oswald Workshop on Superconducting Motors - Kleinheubach, Germany - October 22, 2012
Thank you!

• Visit us at:  www.superpower-inc.com