superior performance.

powerful technology.

Development of 2G HTS Wire for Demanding Electric Power Applications

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enermat
NEW MATERIALS FOR ENERGY
www.enermat.eu
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SuperPower Inc. is a subsidiary of Royal Philips Electronics N.V.
Topics

- The HTS market application and device opportunity
- Critical Success Factors to accelerating market adoption
- SuperPower’s wire manufacturing program
- Continuing technology development
- Looking ahead
HTS Market Sizing Model & Analysis

**Definitions**

- **Sizing**
- **Drivers-Metrics**
- **Trends**

**Conventional Markets**
- Replacing Technology
- Aggregate Estimate: $150 to $250 Billion

**Emerging Markets**
- New Technology
- Aggregate Estimate: $50 to $100 Billion

**Segments:**
- Energy/Utility
- Industrial
- Science-R&D

**Devices:**
- Cable
- Generators
- Transformers
- FCL
- Motors
- MRI - High field magnets
- etc.

**Segments:**
- Renewable Energy
- Energy Storage
- Environmental

**Devices:**
- Wind Generators
- SMES
- Oil & Gas Exploration
- Space Exploration
- etc.

**HTS Addressable**
- 1 to 10%
- Driven by Adoption Rate

**Market Sizing**
- Conventional: 1-5%
- Emerging: 5-10%

**Combined Conventional & Emerging Markets**
- Addressable Market Size — HTS Devices/Products
- Low $4.0 to $7.5 Billion ↔ High $12.5 to 22.5 Billion

*HTS Represents ~ 20-25% of Device/Product Value*
HTS device portfolio - What are the winning devices?

<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>• Cable (ac, dc)</td>
<td>• Motors, propulsion</td>
<td>• Maglev</td>
<td>• Induction</td>
<td>• Current leads</td>
<td>• HF magnets</td>
</tr>
<tr>
<td>• FCL</td>
<td>• Cable, degaussing</td>
<td>• Motors, Marine propulsion</td>
<td>heaters</td>
<td>• MRI</td>
<td>• Space exploration</td>
</tr>
<tr>
<td>• Generators</td>
<td>• Directed energy weapons</td>
<td>• Rail engines</td>
<td>• Motors, industrial</td>
<td>• NMR</td>
<td>• SQUIDS</td>
</tr>
<tr>
<td>– Wind</td>
<td></td>
<td></td>
<td>• Generators</td>
<td></td>
<td>• High energy physics</td>
</tr>
<tr>
<td>– Utility</td>
<td></td>
<td></td>
<td>• Magnetic separation</td>
<td></td>
<td>• Electronics</td>
</tr>
<tr>
<td>– Hydro</td>
<td></td>
<td></td>
<td>• Bearings</td>
<td></td>
<td>• Cell tower</td>
</tr>
<tr>
<td>• Transformers, incl. FCL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>base station</td>
</tr>
<tr>
<td>• Storage</td>
<td>• Motors, Marine propulsion</td>
<td></td>
<td></td>
<td></td>
<td>filters</td>
</tr>
<tr>
<td>– SMES</td>
<td>• Directed energy weapons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Flywheels (Bearings)</td>
<td></td>
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</tr>
</tbody>
</table>

Key:
• Near-Term addressable by 2G HTS - 1-5 years
• Government interest/funding - Mid-Term 3-7 years
• Longer term/other - 5-10 years
What does it take to accelerate the HTS adoption rate toward commercialization?

**Technology advancement**
- **Wire**
  - Meet performance parameters
  - Achieve competitive price
  - Increase throughput / supply
- **Providing a robust product portfolio**
  - Market / device-driven
- **Continuing device demonstrations**
  - Government funding
  - Strategic partners

**Reduced business risk**
- **Price must be competitive with alternative technologies**
- **Meet or exceed customer expectations**
  - Supply
  - Quality
  - Performance
- **Provide superior customer support**
Driving Demand

SP has a proven track record in cost-price performance on a cost per $/kA-m.
Driving Demand

Rapidly Decreasing 2G Wire Costs 2008-2012

Drives Demand and Production Volume
Technology roadmap to realize large market potential

- Large market potential outside the capability of LTS wire
- Wide range of applications with broad operating conditions & unique requirements – need highly sophisticated & engineered wire
- Abundant opportunity to lead market capture through technology to improve wire performance and cost-profile
Application-specific requirements for HTS wire: Superior performance in operating conditions

<table>
<thead>
<tr>
<th>Application</th>
<th>Operating Field (Tesla)</th>
<th>Operating Temperature (K)</th>
<th>Additional requirement</th>
<th>Wire needed per device (kA-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cables</td>
<td>0.01 - 0.1 (ac)</td>
<td>70 - 77</td>
<td>Low ac losses</td>
<td>40,000 - 2,500,000</td>
</tr>
<tr>
<td></td>
<td>0.1 - 1 (dc)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind/Off-shore oil platform generators</td>
<td>1 - 3</td>
<td>30 - 65</td>
<td>In-field Ic</td>
<td>2,000 - 10,000</td>
</tr>
<tr>
<td>Transformers</td>
<td>0.1</td>
<td>65 - 77</td>
<td>Low ac losses</td>
<td>2,000 - 3,000</td>
</tr>
<tr>
<td>Fault current limiters</td>
<td>0.1</td>
<td>65 - 77</td>
<td>Thermal recovery</td>
<td>500 - 10,000</td>
</tr>
<tr>
<td>SMES</td>
<td>20 - 30</td>
<td>4.2 - 10</td>
<td>In-field Ic</td>
<td>36,000 - 500,000</td>
</tr>
<tr>
<td>Automotive motors</td>
<td>2 - 5</td>
<td>30 - 65</td>
<td>Low ac losses</td>
<td>500 - 1,000</td>
</tr>
<tr>
<td>Aerospace</td>
<td>2 - 5</td>
<td>30 - 50</td>
<td>Light weight</td>
<td>1,000 - 2,000</td>
</tr>
<tr>
<td>Magnets/coils</td>
<td>5 – 30+</td>
<td>4.2 - 40</td>
<td>Long lengths, persist joints</td>
<td>200 - 2,000</td>
</tr>
</tbody>
</table>

SuperPower is well positioned to service these markets.
Collaborations are Key

Government

Research Institutes and National Laboratories

Industry - Utility

Academia

etc.

etc.

etc.

etc.

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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
DoE Smart Grid SFCL Transformer Demonstration

• Funding: DoE Smart Grid Demo $10.7M (Total Program = $21.5M)
• Partners:
  – Waukesha Electric Systems
  – SuperPower
  – University of Houston
• 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 – expecting 2 years of grid operation
  – First transformer to use significant amounts of 2G HTS wire
• Relevance:
  – Smaller footprint than conventional transformers, enabling existing substations to increase distribution capability without expanding into limited or expensive real estate
• 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
SuperPower’s Wire Architecture and Production Methods
Thin film-based 2G HTS

- 2G HTS wire is produced in an automated, continuous process
- Cost-effective materials architecture:
  - 95% of the structure of 2G is comprised of inexpensive nickel alloy substrate and copper
  - Only 3% of 2G is made of silver, compared to 70% in 1G
  - About 40 times less HTS in 2G than in 1G
SuperPower manufacturing approach

Strong, concentrated emphasis on manufacture of high quality, long length 2G HTS wire to satisfy market demand
SuperPower manufacturing approach

- State-of-the-art, novel equipment
- Modular processing for maximum flexibility
- Integrated quality systems
- Designed to scale for high throughput to meet market demand
- Skilled and dedicated workforce
2G HTS wire offers superior mechanical properties

- 5 times higher yield stress than RABiTS-based wire
- Higher critical tensile stress
- Higher tensile strain
- Higher bend strain
2G HTS wire allows operation at higher temperatures and in higher magnetic fields

![Graph showing non-Cu Jc (A/mm²) vs. Applied Field (Tesla)](image)
Product offerings

**Wire Architectures:**
- SF3050, SF4050, SF6050, SF12050
- SCS3050, SCS4050, SCS6050, SCS12050
- SF12100
  i = insulation

**Wire Formulations:**
- CF = Cable Formulation
- AP = Advanced Pinning
Expanding manufacturing operations to meet customer demand

**Increasing annual capacity:**

<table>
<thead>
<tr>
<th>Improving manufacturing efficiency &amp; effectiveness:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
</tr>
<tr>
<td>Throughput</td>
</tr>
<tr>
<td>Quality assurance</td>
</tr>
<tr>
<td>On-time delivery</td>
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<tr>
<td>Cost improvement</td>
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</tbody>
</table>

**Product engineering/application support**

<table>
<thead>
<tr>
<th>Product engineering/application support</th>
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</thead>
<tbody>
<tr>
<td>Quality certification</td>
</tr>
<tr>
<td>New product development</td>
</tr>
<tr>
<td>Technical support</td>
</tr>
<tr>
<td>Coil design, engineering and fabrication</td>
</tr>
</tbody>
</table>
### SuperPower Wire: Competitive Assessment

<table>
<thead>
<tr>
<th></th>
<th>SuperPower</th>
<th>Others</th>
<th>Advantage for</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coil</td>
<td>FCL</td>
<td>Cable</td>
<td></td>
</tr>
<tr>
<td>Performance at 77 K,</td>
<td>100 to</td>
<td>80 to</td>
<td>SP</td>
<td>SP</td>
<td>SP</td>
<td></td>
</tr>
<tr>
<td>zero field (4 mm</td>
<td>150 A</td>
<td>100 A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wide)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>‘Lift Factor’ in</td>
<td>2.6</td>
<td>1.2</td>
<td>SP</td>
<td>---</td>
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<td></td>
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<tr>
<td>magnetic field</td>
<td></td>
<td></td>
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<tr>
<td>(at 30 K, 2 T)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ac losses</td>
<td>Medium</td>
<td>High</td>
<td>SP</td>
<td>SP</td>
<td>SP</td>
<td></td>
</tr>
<tr>
<td>Engineering current</td>
<td>2x</td>
<td>1x</td>
<td>SP</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td>700 MPa</td>
<td>250 MPa</td>
<td>SP</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>High</td>
<td>Medium</td>
<td>---</td>
<td>SP</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>“Stiffness”</td>
<td>Medium</td>
<td>High</td>
<td>---</td>
<td>---</td>
<td>Others</td>
<td></td>
</tr>
<tr>
<td>Production volume</td>
<td>~ 300 km/yr</td>
<td>10 to</td>
<td>---</td>
<td>---</td>
<td>Others</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;300 km/yr</td>
<td></td>
<td></td>
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</tbody>
</table>

*We continue to widen our advantage in performance, lift factor and ac losses through our continuing technology development program*
superior performance.
powerful technology.

Technology Update and Outlook

SuperPower Inc. is a subsidiary of Royal Philips Electronics N.V.
SuperPower R&D operations at U of Houston

- SuperPower scientists at U of Houston fully focused on R&D
- Research-scale deposition systems in place for trial runs
- SuperPower staff work with research students and university staff
- Enables clear focus on next generation of technology advancements
Technology development goals

Achieve higher amperage

<table>
<thead>
<tr>
<th></th>
<th>Today</th>
<th>2 yrs</th>
<th>5 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_c$ at 77 K *</td>
<td>100-130 A</td>
<td>200 A</td>
<td>300 A</td>
</tr>
</tbody>
</table>

* 4 mm width

Increase in-field performance

<table>
<thead>
<tr>
<th></th>
<th>Critical current (A/4 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard 2G HTS wire</td>
<td>Blue line</td>
</tr>
<tr>
<td>New enhanced 2G HTS wire</td>
<td>Orange line</td>
</tr>
<tr>
<td>Goal</td>
<td>Red line</td>
</tr>
</tbody>
</table>

Develop low ac loss wire

Improve throughput and reduce cost

New MOCVD Reactor Design

Silver Electrodeposition
SuperPower 2G wire program strategy

- SuperPower’s technology operations consolidated in Houston, allowing total focus on manufacturing in Schenectady.

**Manufacturing objectives**
- High yield, high volume operation
- On-time delivery of high-quality wire
- Incorporate new technology advancements

**Technology objectives**
- High performance wires
- Highly efficient, lower cost processes
- Advanced wire architectures
- Successful transition to manufacturing

**Best of both worlds:**
Strong, concentrated emphasis on manufacturing AND technology development
Planning ahead: Specialty Products Facility in Houston

- New SuperPower facility at UH Energy Research Park – opening August 2011
- Bridge between R&D and Manufacturing
- 5th MOCVD system procured by UH being installed at SPF
- Post-HTS processing and test equipment to also be installed
Huge progress in wire performance in 2010

### Lift factor from 77 K, zero field $I_c$

<table>
<thead>
<tr>
<th></th>
<th>65 K 3 T</th>
<th>40 K 3 T</th>
<th>18 K 3 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our standard (undoped) wire</td>
<td>0.27</td>
<td>1.02</td>
<td>2.13</td>
</tr>
<tr>
<td>Advanced pinning (AP) wire</td>
<td>0.73</td>
<td>1.99</td>
<td>3.50</td>
</tr>
</tbody>
</table>

### Lift factor of AP wire is higher by

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.7</td>
<td>1.9</td>
<td>1.6</td>
</tr>
</tbody>
</table>

### 77 K zero-field $I_c$ of 2009 wire = 100 A

### 77 K zero-field $I_c$ of 2010 AP wire = 130 A

### Lift factor of AP wire (including higher zero field $I_c$) is higher by

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.5</td>
<td>2.5</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Lower cost to customer ($/kA-m) while maintaining wire price ($/m) - our approach for increasing sales

<table>
<thead>
<tr>
<th>Time</th>
<th>Performance at 77 K, zero field (4 mm width)</th>
<th>Lift Factor at device operating condition</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>100-130 A</td>
<td>2</td>
<td>260 A</td>
<td>$40</td>
<td>$150 +</td>
</tr>
<tr>
<td>2 years</td>
<td>160 A</td>
<td>4</td>
<td>640 A</td>
<td>$35</td>
<td>$  55</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>

*Improving wire performance is the key to the success of our approach*
Significant price improvements projected through technological advancements

- Price reduction due to improvements in zero-field critical current, retention of in-field critical current, and cost reduction ($/m)
- Applications that involve magnetic field benefit from the additional improvement factor of in-field $I_c$ retention
- Increasing market opportunities with decreasing price at operating condition
Looking ahead: SuperPower’s primary areas of focus

- Scaling up manufacturing operations to ensure supply
- Further advancing the technology
- Working with customers to understand and meet their needs
- Collaborating to ensure success
- Participating in device demonstrations
- Meeting the price / performance challenge
- Working closely with all of our stakeholders

Thank You!

www.superpower-inc.com