LEGAL STATEMENT

The purpose of the information in this presentation is to guide ICA programs and provide members with information to make independent business decisions.
The following guidelines with respect to compliance with antitrust laws of the United States, Japan and European Community\(^1\) are intended to govern the conduct of participants in copper industry trade association meetings, both at the meeting itself and in informal discussions before or after the formal meeting.

**Price:** Competitors should not discuss future prices (including terms of sale) of their products. There is no blanket prohibition against the mention of or reference to current or past prices but limits must be observed. Such references or mentions should occur only when necessary in connection with the development of association programs. For example, reference to a particular price level in comparing the cost of a copper product to a competing product is permitted. Whenever possible, such references should be discussed in advance with legal counsel.

**Competitive Information:** Competitors should not discuss the market share of a particular copper producer or copper fabricator’s products. Furthermore, nothing should be said at a meeting which could be interpreted as suggesting prearranged market shares for such products or producer production levels. The overall market share of copper products may be discussed with regard to competition with non-copper products and general market acceptance.

**New Products:** Competitors should not encourage or discourage the introduction of a new product by another competitor or reveal a particular copper company’s plans to change the production rate of an existing product or to introduce a new product. No company should disclose to another company whether it is in a position to make or market a new product. New products may be discussed in a technical manner or from the standpoints of competition with non-copper products and general market acceptance. In addition, proposed methods for and results of field and laboratory testing can be considered.

**The Role of Legal Counsel:** Legal counsel attends association meetings to advise association staff and other meeting attendees regarding the antitrust laws and to see that none of the matters discussed or materials distributed raise even the appearance of antitrust improprieties. During the course of a meeting, if counsel believes that the discussion is turning to a sensitive or inappropriate subject, counsel will express that belief and request that the attendees return the discussion to a less sensitive area.

A paper entitled ‘Copper Industry Trade Associations and Antitrust Laws’ is available upon request.

10/92, 5/93, 10/10

1. Other foreign competition laws apply to International Copper Association, Ltd. (ICA)’s activities worldwide.
Competing High Technology Conductors

High-Temperature Superconductors (HTS), Carbon Nanotube Yarns, Copper Nanocomposites

Dr Richard Collins, Dr Nilushi Wijeyasinghe, Dr Khasha Ghaffarzadeh
Threats to Copper

Copper is the standard for conductive material in bulk applications.

However, copper is not immune to changing threats and markets.

IDTechEx have been asked to investigate the status and technology readiness level of emerging conductive materials. Many are at the stage of university research only. These include:

- Pure Nanocarbon material
- Copper nanocomposites
- High-Temperature Superconductors (HTS)
Carbon Nanotubes
Introduction to Carbon Nanotubes (CNT)

Since their inception in the early 1990s CNTs have had a large amount of promise.

<table>
<thead>
<tr>
<th></th>
<th>CNT</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>0.1-1</td>
<td>8.9</td>
</tr>
<tr>
<td>Tensile Strength (GPa)</td>
<td>&lt;100</td>
<td>0.2</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK)</td>
<td>&lt;3500</td>
<td>400</td>
</tr>
<tr>
<td>Electrical Resistivity (μΩ•cm)</td>
<td>&gt;1</td>
<td>1.7</td>
</tr>
<tr>
<td>Charge Carrying Capacity (A/cm²)</td>
<td>10⁶-10⁹</td>
<td>10⁶</td>
</tr>
</tbody>
</table>

These are some of the best reported values for a variety of individual CNTs.

Other benefits:
- Higher flexural strength, lower temperature coefficient of resistance (TCR), lower coefficient thermal expansion (CTE), improved corrosion resistance, and cost stability (at very high volumes)

But the problems are:
- Translating to the macroscale
- Different forms (SWCNTs – MWCNTs)
- Chirality optimisation

Source: Sao Paulo University and University of Oregon
Not all CNTs are equal

Each box corresponds to the size range of CNTs supplied by a different company

There was a rapid rise in capacity expansion between 2006 and 2011, this was then followed by a correctional period. Across this time frame utilisation rate went up.
Progression of CNT fibres

The progression to macroscale CNT wires/yarns/tapes has been challenging, but there have been significant advancements over the past 10-years.

![Image of CNT fibres]

Progression of best resistivity results for CNT yarns

This line represents the historic advancements in this field and the progression if this continues. The blue line represents CNT yarn and orange line copper. Note that this does not take into account the emerging improvements to copper conductivity.

But are the hardest steps still to come?

Source: Nanocomp Technologies
# Formation of CNT fibres

Tunability vs Scalability are the main challenges for this industry

<table>
<thead>
<tr>
<th>1-step CVD</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Resistivity (μΩ-cm)</th>
<th>Density (g/cm²)</th>
<th>Tensile Strength (GPa)</th>
<th>TRL Level (1-5)</th>
<th>Main player(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-step, scalable process, long length yarns, proven process.</td>
<td>Impurities, low conversion, cannot refine CNT feedstock.</td>
<td>50-500</td>
<td>0.5-1.0</td>
<td>1-3</td>
<td>2-4</td>
<td>Nanocomp Technologies, Q-Flo, Shanghai Jiao Tong U, Cambridge U.</td>
</tr>
<tr>
<td>Wet Spinning</td>
<td>Tuneable CNT usage, good alignment</td>
<td>Superacid used and capacity limited by chamber size.</td>
<td>15-100*</td>
<td>1.5-2.0</td>
<td>1-3</td>
<td>3</td>
<td>RICE University (Dexmat), RIT</td>
</tr>
<tr>
<td>Dry Spinning</td>
<td>Tuneable CNT, facile drawing process.</td>
<td>Poor resistivity through worse interconnects and alignments</td>
<td>1500-2000</td>
<td>0.5-1.0</td>
<td>1-3</td>
<td>3</td>
<td>Hamamatsu Carbonics and Murata Machinery</td>
</tr>
<tr>
<td>Electrospinning</td>
<td>Targets interconnects, electrospinning facile</td>
<td>High energy source for interconnects, not scaled.</td>
<td>~200</td>
<td>0.5-1.0</td>
<td>N/A</td>
<td>1</td>
<td>Surrey U.</td>
</tr>
</tbody>
</table>

*Note that due to the process used these fibers made via this route can have some acid dopants as a residuum from the CSA used.*
Dopants and specific conductivity

- Proof-of-concept stage, but many dopants struggle with stability.
- The industry still requires an innovative leap to compete with copper.
- The undoped yarn can outperform Cu for specific ampacity.
- Does the yarn have to reach copper in order to displace it?
Early CNT yarn applications

- High frequency data cables, particularly in defence applications. When above 20 GHz there is a significant pay off from the skin effect.

Main Driver: Skin effect and lightweighting
Timeline: Already in use

- Roles in military jets both as EMI shielding outer conductors and power cables.

Main Driver: lightweighting
Timeline: Non-critical roles within 5-10 years.

Following applications will be electric motors (10-15 yrs) and low power electronic applications (15+ yrs)

Source: Nanocomp Technologies and DexMat
Graphene
Graphene: ideal vs reality (I)

Ideal graphene = wonder material

Superlative properties:
- 2D sheet of carbon atoms → Thinnest imaginable material
- Higher conductivity than silver at room T (1 uOhm.cm)
- Record thermal conductivity (outperforming diamond)
- Highest current density at room T (106 times of copper)
- Highest intrinsic mobility (100 times more than in Si)
- Largest surface area (~2,700 m² per gram)

Commercial graphene = more down to earth

Properties of commercial graphene
Graphene: ideal vs reality (II)

Idea graphene: 2D, pristine, large-area defect-free single-crystalline flake or film

Towards commercial type

Platelet or powder type

- Variety of graphene powders covering a large range in later size and thickness (see opposite)
- Not all are equal: property and thus application depending on specific properties changes
- Numerous production processes for powder type

Film type

- Simple R2R CVD growth on Cu foil possible but challenge is how to transfer without damaging material & reducing yield?
- Polycrystalline structure thus not as good as ideal single-crystalline 2D graphene
Approaches towards graphene-based conductors

General approaches towards graphene-based conductors

Using film type graphene
- Cu-graphene film laminates
  - TCS 2
- Transferred CVD film
  - TCS 3

Using powder type graphene
- Graphene Metal composite
  - TCS 2
- Graphene polymer composite
  - TCS 5
- Conductive Graphene Ink
  - TCS 7

Potential to bridge performance gap with Cu
- Extremely Low
- Extremely High

Technology Commercialisation Scale (TCS)

Proof of concept
- Maturity

KEY
Copper Nanocomposites
Comparison of copper nanocomposites

Sometimes called nanocomposites, nanoalloys, or ultraconductive copper but all refer to the inclusion of conductive material into a Cu matrix.

The additives are usually CNTs or graphene and can be included in a range of volume percentages.

The properties range are shown on the left-hand side, but is important to also consider:

- Impact on ampacity
- Density (important for high %)
- Thermal conductivity
- Temperature coefficient of resistance (TCR)
- Usability of material
Production on copper nanocomposites

- The key is to introduce these nanoparticles without damage to their structure, without agglomeration, and a strong interaction with the metal matrix.
- Many have common challenges in reproducibility, poor metal wettability, scale, cost effectiveness, upstream supply chain and the ability to make a usable wire.

<table>
<thead>
<tr>
<th>Types of procedure</th>
<th>Mechanical</th>
<th>Chemical</th>
<th>Electrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder metallurgy, ball milling, casting, hot extrusion</td>
<td>Molecular level mixing, \textit{in situ} growth</td>
<td>Co-deposition, electroplating</td>
<td></td>
</tr>
<tr>
<td>Advantages</td>
<td>Easy scalable process, tuneable raw material</td>
<td>Good homogeneity, no dependence on raw material</td>
<td>Can make multi-phase, can be continuous</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Damage of nanoparticles, usually low vol %, not yarn</td>
<td>Often multi-step, small scale</td>
<td>Typically poor infiltration, small scale, inconsistent distribution</td>
</tr>
</tbody>
</table>
**Copper nanocomposites**

Highlighted here are three particularly notable processes, there are many more that have been reported to IDTechEx that provide results over 100% IACS or with specific benefits.

**Shanghai Jiao Tong University, China**
**Key outcome:** 118 % IACS.

**Ohio University, USA**
**Key outcome:** 104 % IACS and performance at high temperature.

**National Institute of Advanced Industrial Science and Technology, Japan.**
**Key outcome:** 100-fold increase in ampacity relative to copper.

Source: AIST, Shanghai Jiao Tong University, Ohio University
High-Temperature Superconductors (HTS)
High-Temperature Superconductors

Properties of superconductors

Conductor v. Superconductor

- Superconductivity at $T < T_C$
- 100x current capacity of copper. Zero resistance & zero heat loss until critical current ($I_C$) flow.
- External magnetic fields excluded. Applied field & angle affects $I_C$

Critical Temperature ($T_C$)

- Low-T superconductor (LTS): liquid He cooling to 4 K; metallic
- High-temperature superconductor (HTS): liquid N cooling to 77 K; ceramic, oxide
- Magnesium diboride ($\text{MgB}_2$): $T_C = 39$ K
- Liquid H cooling or He gas cryocooler

1st & 2nd Generation HTS

- 1G = bismuth based, BSCCO
  - Silver matrix: high raw materials cost
- 2G = rare-earth metal based, ReBCO
  - Re = yttrium (Y), gadolinium (Gd)
  - Most common: YBCO, $T_C = 93$ K
- Both 1G & 2G are copper oxides

Image source: Ural University

Popular demo of the Meissner effect: magnet levitating above superconductor cooled below $T_C$.

Image source: IOP Publishing

Ag matrix of 1G HTS wire stabilizes (electrically & thermally) & couples BSCCO filaments.
Applications of HTS materials

- **Wire (tape) – commercial** (not building wiring)
- **Electric power grid – demos**
  - High-voltage cable: underground transmission
  - Medium-voltage cable: underground distribution
  - Superconducting fault current limiter (SFCL); transformer
- **Rotating machine (compact, high power)**
  - Generator: wind turbine (AMSC SeaTitan, 10 MW)
  - Motor: ship propulsion (Northrop Grumman and AMSC, 36.5 MW)
- **Other applications** include: Degaussing system (US Navy, AMSC), Magnetic energy storage (Boeing), Low-voltage cable: data center (AMSC), RF circuit: receiver & amplifier (HYPRES), Current lead (ITER fusion project), Tokamak: nuclear fusion reactor, Medical: MRI and NMR, MagLev vehicles
**Advantages of HTS underground cables:**
- HTS cable transmits 3-5x power of Cu cable with equal cross section: minimize land use in dense urban areas.
- Transmit power at higher current & lower voltage: fewer transformers.
- Zero resistance: minimize power loss from remote renewables (long cables) & no heating of soil.
- Low magnetic field generation; self-shielding cable.

**Challenges in HTS cable technology adoption:**
- 1 km cable requires >100 km HTS wire: process yield & production capacity.
- 2G wire production is dominated by process cost (80%), not raw materials cost (20%).
- HTS wire cost is 20-25% of cable cost: cooling system cost dominates.
- Target wire cost: $20-30 /kA m for large-scale adoption.
- Many utility companies lack cooling expertise.
- New tech = investment risk and inertia
### Main Players:
- 30+ HTS wire suppliers & integrators
- Most use ReBCO (▲ = BSCCO) 
  \[\text{MgB}_2 \quad \text{– Columbus Superconductors HyperTech Research, Nexans, STI}\]

### Cost of 2G HTS wire (without cooling):
- Average product = $100 /\text{kA m}
- Lowest quote = $30-80 /\text{kA m}
  \[\text{MgB}_2 \approx $10 /\text{kA m}\]

### 2G HTS wire production capacity:
- 300-1000 km /year (width = 4 mm)
- Limits: process, end-user demand

<table>
<thead>
<tr>
<th>Europe</th>
<th>North America</th>
<th>Asia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nexans (France)</td>
<td>Southwire (USA)</td>
<td>Sumitomo (Japan) ▲$</td>
</tr>
<tr>
<td>BASF (Germany) acq.</td>
<td>Bruker (USA) acq.</td>
<td>LS Cable &amp; System (S. Korea)</td>
</tr>
<tr>
<td>Deutsche Nanoschicht $</td>
<td>Oxford Instruments OST $</td>
<td></td>
</tr>
<tr>
<td>Siemens (Germany)</td>
<td>AMSC (USA) $</td>
<td>Fujikura (Japan) $</td>
</tr>
<tr>
<td>Innogy subs. RWE</td>
<td>SuperPower (USA)</td>
<td>Furukawa (Japan) acq.</td>
</tr>
<tr>
<td>(Germany – utility)</td>
<td>subs. Furukawa $</td>
<td>SuperPower $</td>
</tr>
<tr>
<td>Billfinger Noell (Germany)</td>
<td>STI: Superconductor Technologies, Inc (USA) $</td>
<td>Shanghai $ Superconductor (China)</td>
</tr>
<tr>
<td>SuperOx (Russia) $</td>
<td>ComEd (USA – utility)</td>
<td>SuNAM (S. Korea) $</td>
</tr>
<tr>
<td>THEVA (Germany) $</td>
<td>MetOx (USA) $</td>
<td>SCSC (China) $</td>
</tr>
<tr>
<td>OXOLUTIA (Spain)</td>
<td>HYPRES (USA)</td>
<td>InnoST (China) ▲$</td>
</tr>
</tbody>
</table>

### R&D institutes and associations:
- Center for Advanced Power Systems – Florida State University (USA)
- National High Magnetic Field Laboratory – Florida State University (USA)
- Texas Center for Superconductivity – University of Houston (USA)
- CERN (Europe); Conectus consortium (Europe); CCAS coalition (USA)
High-Temperature Superconductors

HTS projects: present status & future prospects

**HTS Projects**
- AmpaCity 2013-2016: Nexans & RWE/Innogy
- Resilient Electric Grid 2014 – present: AMSC & ComEd.
- Eurotapes 2012-2017: Bruker & Nexans
- Fast Grid 2017 – present: H2020 with 12 partners
- Siemens HTS R&D 2015 – present: Siemens & Australia Defence Science and Technology Group

**Industry Outlook**
- “No significant impact on the Cu industry within the next 10 years.”
- “Displacing 1% of Cu cables is the ultimate goal.” (upper limit)
- “HTS wire can be cost competitive with Cu wire if production is scaled up to 100,000 km/year.” (>2030)

Source: Nexans
Outlook
Conclusions and Outlook

- Continued research has displayed a range of promising results, but is still a long way off being competitive with copper (or aluminium) in terms of properties and cost.

- High-Temperature Superconductors continue to improve with most efforts going into reducing the processing costs.

- Nanomaterials show ever more promise:
  - CNT yarns have had resistivity improvements, but they have now reached a limit that is dependant on the raw material production and improved post-yarn processes.
  - Copper composites have shown mixed results with CNTs and graphene. Of late advancements with graphene have proved the most promising. This will help keep copper ahead of the curve.