Copper Applications Technology Roadmap

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CONTENTS

Executive Summary

Background

Three years ago, the copper industry published a far-reaching plan for future endeavors, the *Copper Technology Roadmap*, which addresses “upstream” copper production — from mine planning to electrowinning/refining. Led by AMIRA International Ltd., the industry made a comprehensive examination of copper’s extraction, production costs, and status in the context of economic, environmental, and social factors. As described in the roadmap, the industry prioritized actions to reduce technological risk; improve safety, health, and industrial hygiene; and increase energy efficiency by 10% through the implementation of better technology.

The new *Copper Applications Technology Roadmap* focuses on finished products and end uses for this ancient yet cutting-edge metal. It suggests paths for increasing the value of copper in its applications, and does so with full understanding of copper’s place in society and its relationship with issues such as energy efficiency, health, environmental benefit, and sustainability. The roadmap aims to guide collaborative, pre-competitive research efforts among copper producers and fabricators, copper-using industries, universities, government programs, entrepreneurs, and independent technologists.

New Directions

Copper has a “remarkable uninterrupted record as an integral part of human life and civilization.”[1]

It is a metal that helped drive the industrial revolution, has been irreplaceable in the advancement of information technology and communications, has helped provide clean, safe drinking water to millions of families, and has aided in the reduction of microbial infections. The fundamental properties of copper have enabled it to meet society’s needs throughout history, and it is these characteristics that the industry must continue to investigate in order to uncover new ways copper can drive innovation. Chapter 1 describes the fundamental properties of copper and examines the ways these attributes can best help society progress in the future.

In the course of developing this roadmap for future collaborative technology development, the industry set priorities for evolving copper use in existing applications and advancing copper use in emerging applications. Chapter 2 describes the criteria for selecting priorities and provides details on the trends and recommended pursuits specific to each area. The top evolving/existing opportunities include:

- **Electric Energy Transmission Opportunities** — *Copper is unsurpassed as a transporter of electricity and heat.* The implications for more efficient global energy consumption are clear, and copper can lead meaningful progress on this crucial front. The demand for high-ampacity, high-efficiency products used in utility transmission and distribution grids and large industrial facilities is rapidly growing in developing countries due to the massive expansion of energy infrastructure. It is a demand that copper’s high power-transmission capacity can help meet. Opportunities for copper lie in the market for high-voltage, sub-sea power cables, which are expanding to accommodate users such as offshore/gas production platforms, offshore wind farms, and electrical grids.

- **Data/Signal Transmission Opportunities** — *Copper cables and connectors are used for more than 80% of signal-carrying equipment interconnections in data centers. For runs of less than 100 meters, copper cables with bandwidth exceeding 10 Gbps are available at a fraction of the cost of other cables.* Industry can strengthen its competitive position by developing copper-based cables that have higher bandwidth, reduced power consumption, and offer easier installation and connection. Copper also has the key ability to deliver power and data over the same cable, and thus simplify connecting digital entertainment, communications, computing, and security equipment into high-speed networks in homes, businesses, and public infrastructure.

- **Automotive Wiring Opportunities** — *New copper cables can be stronger and thinner than current ones to meet automotive space limitations and also decrease vehicle weight for improved fuel economy*. Vehicles increasingly use electronic devices in performance, comfort, safety, and entertainment features. Wiring and connectivity demands, especially for wiring harnesses and associated connectors, will continue to influence the growth of copper usage in the automotive industry. Space limitations have driven automakers to downsize both harnesses and connectors. This trend towards miniaturization places higher demand on mechanical properties in the conductors and connector materials, principally higher yield strengths in conductors, and improved stress relaxation resistance in the copper alloys used in connectors.

- **Motor Driven Systems Opportunities** — *Motor-driven systems are the largest energy consumers accounting for about 40% of global electric energy consumption.* Even modest increases in motor efficiency can have enormous effects on electricity consumption. The International Copper Association, Ltd. (ICA)-supported development of the cast copper motor rotor (CMR) opened a large window of opportunity. Yet, more opportunities exist to further increase motor efficiency. Eddy current losses in stator windings can be further reduced and standards for super-premium motors have not been defined. CMR motors at high horsepower ratings can be optimized and the cost of production can be reduced. With those improvements, the CMR could become more economically viable for both manufacturers and users. Copper is the key to significant energy efficiency and performance advancements.

- **Electronic Interconnection Opportunities** — *Copper leadframes, plugs, terminal blocks, and other forms of connectors are widely used in electronic equipment.* Technology developments in electronic interconnection are currently being driven by miniaturization, cost-reduction, and inter-material competition. Miniaturization requires denser integration of dissimilar materials for mechanical reinforcement and higher performance. Advancements in leadframe connectors must continue in order to support high-frequency input/output (I/O) memory, computing, automotive, and portable digital products. The connector and leadframe industries, being reliant on innovation, present an ideal landscape for partnership and collaborative development programs.

- **Electronic Thermal Management Opportunities** — *High-power, compact electronic devices with higher-than-current heat fluxes will demand improved cooling technologies and thermal management, especially in aerospace equipment, high-power laser systems, and automotive electronics.* Today, copper is the heat-transfer material of choice for many electronics systems. However, copper will need to drive the development of next-generation heat transfer devices, such as ultra-compact, high-heat flux technologies to maintain its competitive edge.

- **Appliance Heat Exchange Opportunities** — *Copper's outstanding thermal conductivity, malleability, antimicrobial effect, and ease of joining are put to widespread use in producing heat exchangers for refrigeration, air conditioning, vending, and commercial food merchandising systems.* However, these systems could be more efficient, more compact, and less expensive to produce with the use of smaller-diameter or multi-port flat copper tubes. Achieving cost-effective solutions will require R&D in materials joining, metal fabrication, design engineering, applied heat transfer, and alloy development/optimization. The increasing use of environmentally friendly refrigerants presents both design implications and opportunities for copper that can be addressed by collaborative R&D.

Emerging applications are those that open entirely new markets for copper and thereby broaden as well as increase its use. Each area will require development of new and improved copper-based technologies. The top emerging opportunities include:

- **Electrical Propulsion Opportunities** — *The rail, marine, heavy construction, and automotive sectors comprise the largest markets employing electrical propulsion technology, of which copper is an integral component.* Automotive electrical propulsion systems are undergoing substantial development and moving away from relatively simple electric motor-based systems toward more highly engineered, compact, and efficient approaches. Additional opportunities include copper components for high current capacity and thermal management in power electronics, and the infrastructure to support the recharging of electrical vehicles. Promising developments are occurring in superconducting propulsion systems, including the construction of very large marine propulsion motors.

- **Renewable Energy Opportunities** — *Copper plays important roles in clean energy systems, particularly in generators, power electronics, cabling, controls and protective devices used in wind, tidal, biofuel, wave, geothermal, and solar thermal plants.* Solar photovoltaic systems need copper for power transport, grounding, switchgear, and control system components. Ocean-based systems can benefit from copper alloys' resistance to biofouling and corrosion. Newer systems will need to be even more efficient and have a low environmental impact.

- **Aquaculture Opportunities** — *Fish farming is a rapidly growing multi-billion dollar global industry.* Copper alloy marine aquaculture cages are emerging as a powerful solution to significant problems facing the industry. Typical cages constructed from synthetic materials with anti-fouling coatings become encrusted with marine organisms (i.e., algal films, various brachiopods) after several months of use. This fouling diminishes the flow of clean oxygenated water to the fish and provides an environment where parasites and pathogens can thrive. In addition, the nets do not provide a strong enough barrier to prevent attack by sea lions and seals. The combination of copper alloys' antifouling, antibacterial properties, and mechanical strength address these issues. Copper alloy cages remain free of fouling for years, thereby improving fish health, increasing the rate of fish growth, and eliminating the need to clean or replace the cages. Copper alloy cages may reduce or eliminate the need for antibiotics by eliminating the fouling environment. The mechanical strength and resilience of a copper alloy structure also prevents predator attack or the escape of fish. Unlike nets made from synthetic materials, copper alloy structures are completely recyclable at the end of their useful life. Significant advances in reducing the corrosion rate of copper alloys in seawater have been made, and advanced cage/platform/mooring systems are under development.

- **Hygienic Surfaces Opportunities** — *Copper-rich surfaces inhibit the growth of harmful pathogens and fungi.* This nearly unique and extremely valuable property offers application potential for copper and/or copper alloys as touch surfaces, in air conditioning systems, and perhaps for other uses. In particular, frequently handled medical equipment, furnishings, and touch surfaces in health care facilities and public buildings can be made from copper to reduce transmission of pathogens, including dangerous multi-drug resistant organisms. Air quality inside buildings can be improved by the incorporation of copper antimicrobial surfaces in air handling equipment.

- **Potential Future Applications Opportunities** — *The prioritized copper-related R&D topics described above are sound and defensible, yet the selection was based only on the information available at the time the roadmap was constructed.* The copper industry, acting through the ICA, funds pre-competitive research that can create or enable significant market applications for copper and for which a relatively rapid demonstration and/or development timescale can be realized. In exceptional cases, ICA may support activities to solve copper-related issues for an individual company or organization. Therefore, in addition to the opportunities above, the copper industry is interested in learning about other new concepts. Readers are invited to propose application-directed projects that could create a new copper application or enlarge an existing one. Such proposals should identify the breakthrough required, and describe a credible technical approach.

The *Copper Applications Technology Roadmap* will continue to evolve as industry reacts to societal trends, competitive pressures, related technical developments, and unanticipated opportunities. While the current roadmap does not cover all technological pathways to the future, it does focus on what we believe are the highest-priority pre-competitive needs of the copper industry and its customers. However, implementing the needed changes will involve the most difficult and complex steps toward achieving the desired results. To that end, Section 3 outlines plans for an industry-managed process to create, launch, and manage copper applications projects beyond those described in this roadmap.

This roadmap encourages organizations to participate in ways that will best capitalize on their distinct skills, capabilities, and resources for developing the opportunities described herein. As the industry looks to the future, the success of this roadmap will be measured by the number and scope of collaborative R&D projects that it inspires and the benefits those projects accrue. Complementary but equally important benefits will include the enhancement of the perception of copper as an environmentally friendly, advanced technical material.

1. Introduction

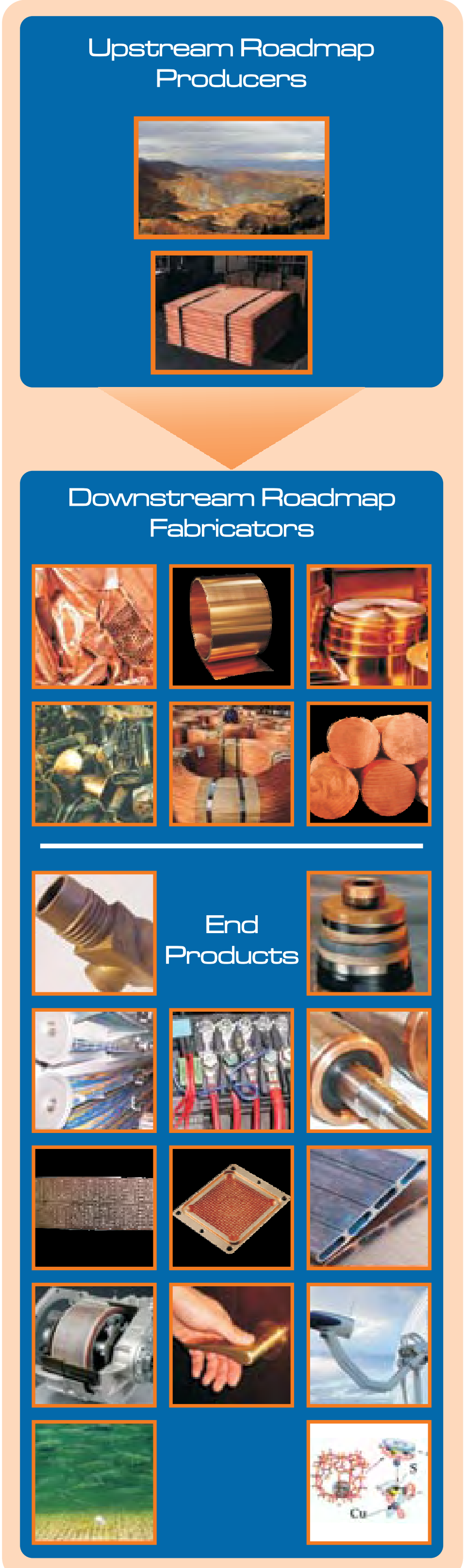
With the publication of this document, the copper industry continues a process begun several years ago; namely, to chart fruitful directions for responsible, sustainable growth in copper utilization over the coming decades. An earlier industry effort, the *Copper Technology Roadmap* (2004), focused on mining and extraction, how those technologies will (or could be induced to) change, and how they will interact with a variety of industrial, political, economic, societal, and technological driving forces. The development of the "upstream" roadmap was led by AMIRA International Ltd., the mineral industry research association. While it is too early to identify specific "eureka" events, the technical literature reports steady improvement in such areas as systems control, water utilization, robotics and automation, and in situ mining and processing — all of which were identified as research priorities in the 2004 publication.

Now, the industry's field of view broadens. The *Copper Applications Technology Roadmap* looks downstream from mines, mills, smelters, and refineries to fabricators, processors, and manufacturers, and also to specific disciplines and industries, as well as to specific applications, Figure 1.1. The objective here is to identify those areas in which technological research and development will most likely lead to a significant impact on the value of copper in evolving and emerging markets. This roadmap has been developed through the collective knowledge of copper producers and fabricators, copper-using industries, universities, government laboratories, entrepreneurs, and independent technologists with the expectation that the industry will use this combined knowledge to guide its future.

Copper has a remarkable uninterrupted record as an integral part of human life and civilization. It is a metal that helped drive the industrial revolution, has been irreplaceable in the advancement of information technology and communications, has helped provide clean, safe drinking water to millions of families, and has aided in the reduction of microbial infections. The fundamental properties of copper have enabled it to meet society's needs throughout history, and it is these characteristics that the industry must continue to investigate in order to uncover new ways copper can drive innovation.

As the industry moves forward, it must collaborate with its partners to examine the ways copper's intrinsic advantages can best help society progress in the future. In some instances, success will come through the development of new materials — alloys, composites, and compositions — and improved, more cost-effective ways to produce and process those materials. The electrical-connector and electronic-packaging industries are two examples out of many in which this approach is routinely utilized. There are also situations that call for optimizing the way copper is used or fabricated. The successful, International Copper Association (ICA)-sponsored development of cost-effective copper die-casting is a useful example of collaborative process R&D in the copper industry (see Appendix A). Lastly, there are developments that are needed to counteract potential

Figure 1.1 Copper Industry Value Chain



substitution by alternative materials; however, these issues can be overcome by innovation that takes appropriate advantage of the many attributes of copper.

Copper's Intrinsic Advantages

No other metal, alone or in alloy form, so effectively offers the amount and breadth of useful properties as copper. Foremost are high electrical and thermal conductivity, inherent corrosion resistance, antimicrobial efficacy, ease of fabrication, versatile alloying potential, and an aesthetically pleasing appearance. Technological progress over the coming decades will depend strongly on advanced materials: metals, alloys, composites, and other structures, many of which can potentially contain copper. These materials will not only have to perform well, they will also be required to bear favorably on, or at least not negatively influence, such issues as human health, energy efficiency, sustainability, and standards of living. Copper and copper-based materials clearly meet these criteria. Appendix B offers additional information on copper's useful properties. Appendix C offers insight into copper's role in meeting societal needs.

From Cathode to End Product: Engineering Design and Product/Process Development

Copper cathode and recycled copper are the starting materials for downstream copper applications. Semi-fabricating companies process these materials, often with alloying elements, to produce an intermediate form with properties suitable for fabrication and final end use. These value-added copper materials are then fabricated into the precise shape of the end product. Materials experts in the semi-fabricating companies and their customers' engineers and product specialists closely interact throughout the engineering design and development processes to ensure the composition and purity of copper alloys achieve the desired functionality and performance in the final application.

The copper industry, using its own representatives and those of 29 copper centers throughout the world, offers users a high level of support to assist in the selection of the most effective copper material solution. Chapter 2.1 provides additional details on the key issues, opportunities, and recommended pursuits for copper that will support future technical collaboration with product and process engineers.

Trends and Challenges Influencing Copper Use

Here, we describe a few influential trends that affect copper use, along with some of the properties of copper relevant to these issues. Appendix D contains information on the general trends of copper use.

- **Reducing processing cost** — To remain competitive, fabricators must continue to reduce their cost of manufacturing while maintaining high quality in their products. Copper is routinely processed by common manufacturing methods and is available in many forms and alloys that enable efficient production. Copper is also readily adaptable to net-shape processing techniques, and it is possible to semi-fabricate some copper products using the "upstream" electrowinning step in copper cathode production. The copper industry must continue to raise the level of sophistication in manufacturing and the accompanying materials processing technologies to produce high-quality and reliable products in an efficient and cost-effective manner.

- **Maximizing value-added use of copper** — Manufacturers naturally seek to utilize the least amount of material consistent with optimum functionality. Improvements in engineering analysis, design methods, and process simulations allow materials to be used only where needed. In copper's existing market applications, there is an opportunity to use less metal while maintaining or improving product performance. In addition, copper's value can be enhanced by collaborative material and process selection, in which the copper industry provides technical support and new application-specific alloys to the general industry. For example, an increasing number of electrical applications require new alloys because other properties, such as mechanical strength, are required in combination with conductivity. The same concept applies to aquaculture applications, where high mechanical strength is needed in combination with resistance to corrosion and biofouling.

- **Increasing competitive pressure from other materials** — Metals, composites, polymers, multi-layer systems, and other alternative materials have challenged many of copper's traditional markets. Yet copper, with its unique combination of useful properties, frequently offers potential systemic improvements and/or economies unachievable with other materials. In this case, the designer's challenge is to minimize, compromise, and make the most efficient use of an inherently better material. While the influence of high copper costs cannot be denied, copper has historically found applications in which it is uniquely suited, successfully removing cost-sensitivity from the purchasing decision.

- **Changing regulations, codes, and standards** — Energy efficiency and sustainability issues have rapidly climbed the policy agendas of businesses and governments. Copper is increasingly perceived as being energy-efficient, infinitely recyclable, and biologically essential. As a result, the metal has, in many cases, successfully held its ground.

- **Assuring performance of engineered copper products** — Computer simulation is increasingly applied to predicting and validating copper's performance in new applications. Few metal systems are as well understood (or as extensive) as the copper family of metals and alloys. The huge technical literature base on copper is freely available online, and is supported by more than two dozen national and regional copper development organizations.

- **Increasing use of complementary engineered materials** — Copper is rarely applied alone. It is most frequently used in combination with other engineering materials to tailor the final properties of a system to the needs of a specific application. Complimentary materials can, for example, provide thinner layers of electrical insulation, protection against rough handling and corrosion, or any number of desirable qualities.

- **Designing for recovery and re-use** — Designs that foster recyclability will preserve copper's value while benefiting the environment. Copper is among the most efficiently recycled metals in global commerce. It is 100% recyclable without any loss in performance; 34% of global copper demand is met through recycling.

2. Roadmap Priorities

This roadmap — combined with other initiatives — aims to guide collaborative, pre-competitive R&D programs that benefit the copper industry and society. Industry favors this collaborative and non-competitive approach, as costs are distributed among the parties that expect to gain benefits, and a range of expertise is available to project teams. The following general criteria for selecting priority activities were established by copper industry associations, semi-fabricated and fabricated product producers, and end-use manufacturers:

- Priority activities should result in a significant positive impact on the utilization of copper, and results of R&D efforts should show innovation or substantial improvement in the respective technology or market sector. For example, although the water distribution (plumbing tube, etc.) market represents a significant copper application, accounting for almost 13% of copper use today, it is not considered a priority area for R&D. This is because there is growth in the use of acceptable alternative materials, and market conditions suggest technical innovation is not the key to sustaining copper use in the water distribution application. On the other hand, copper is an important strategic energy metal with growth potential in renewable energy systems and automotive propulsion.
- Priority activities should have a high probability of commercial implementation within a reasonable (about five-year) timeframe from project initiation. Meeting this criterion is not inherently difficult, but it does require that activities be judiciously chosen, carefully planned, well organized, and tightly managed.
- Priority activities should enhance the positive environmental and societal posture of copper, where relevant. Copper is essential to health, its use promotes energy efficiency, and its recyclability is nearly unsurpassed among all engineering materials.

Uncertainties in markets, regulations, technology advancement, and competition require that the copper industry maintain a robust research portfolio that can respond effectively to a variety of plausible futures. It is difficult to predict the significance of each market over time. What seems significant today may change with shifts in fundamental issues that influence copper use. As the industry pursues the opportunities contained in this roadmap, it must review, assess, and adjust the mix of projects that will lead to success today and in the future.

Classification of Prioritized Opportunities

Prioritized opportunities described in this roadmap are grouped into three broad classifications: Cross-Cutting Applications, Existing/Evolving Applications, and Emerging Applications.

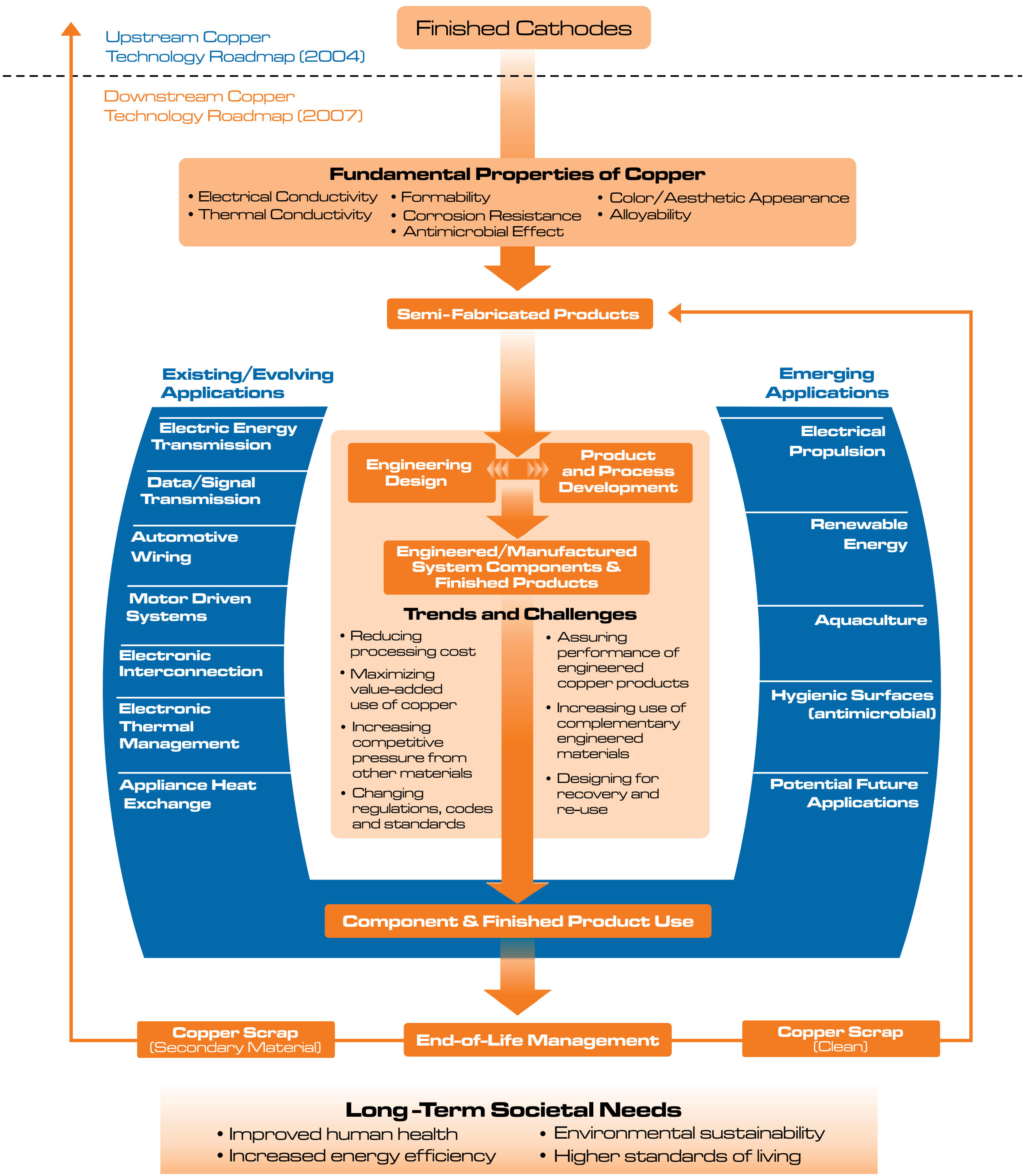
Cross-Cutting Applications support engineering design and product/process development to advance one or more uses of copper. The aim is to optimize the intermediate production processes of copper to achieve maximum value in the end product. For example, optimizing the semi-solid casting of copper alloys improves the manufacturer's ability to produce high-strength, complex-shaped components at reduced costs and environmental impact.

Existing/Evolving Applications maintain or expand upon current large-scale uses of copper. They are typified by cost pressure, inter-material competition, and design constraints (e.g., miniaturization), any of which can influence copper use in these applications. Here, the objective is to increase market share through the development of new or improved copper products, reinforcing copper's position. Development of improved copper-based heat transfer devices is a useful example of this approach.

Emerging Applications open entirely new markets for copper and thereby broaden as well as increase its use. The focus here is on the creative application of copper properties to solve new technology problems. The exploitation of copper's antimicrobial efficacy for touch surfaces is an example of this category. Considerable research has already been completed in this area, although a great deal of technology transfer, as well as fundamental market development/promotion, remains ahead.

The following summaries provide additional details on the applications listed in Figure 2.1. The summaries are broad, including only a few specific examples, with the aim of promoting discussion among potential collaborators on new ideas for copper innovation.

Figure 2.1 Research Priorities Along the Downstream Value Chain



2.1 Cross-Cutting Opportunity: Engineering Design and Product/Process Development

Material and process selection for a given component depends on its complexity and desired function, the product's quality and performance specifications, and the projected cost level. Both physical and mechanical properties play an important role in the selection of an appropriate alloy and its subsequent processing steps such as stamping, drawing, welding, etc.

Today, research in processing, manufacturing, and fabrication of materials is becoming more fully integrated with research on engineering design of components and structures. Increased sophistication in engineering design, manufacturing, and the accompanying materials processing technologies are necessary to produce high-quality, reliable products in an efficient and cost-effective manner. Innovation in materials processing techniques is needed to incorporate into products advanced materials such as high-strength, flexible copper connectors; composite heat exchange materials; and low-tarnish touch surfaces.

Increasingly, copper users are requiring technical support to gain maximum value from copper. Customers expect technical support in making decisions regarding issues such as optimizing the use of complex multi-material components, overcoming a specific obstacle, or obtaining a needed capability in a particular application. While the copper industry offers customers a high level of support to assist in the selection of the most effective copper material solution, additional activities are necessary to support technical collaboration concerning evolving and emerging applications for copper.

Trends, Issues, Drivers	• Increasing sophistication and performance requirements of copper components • Further miniaturization, complexity, and density of components • Constant pressure to save costs and use less materials • Higher level of composites vs. mono-materials required to meet application needs • Rising expectations as to the level of service and support from semi-fabricating companies
Opportunities and Recommended Pursuits	
Composition (Alloys)	• Develop alloys with excellent machining properties that do not contain toxic elements, such as lead and beryllium • Develop tarnish-resistant alloys, especially those that maintain anti-microbial properties • Develop high-strength alloys using environmentally benign elements • Design alloys to optimize specific application processes, such as semi-solid casting
Microstructure	• Clarify dynamics of the complex micro-structural mechanisms by which advanced copper materials deform, degrade, and fracture • Improve detection and characterization of defects developed in processing, manufacturing, and fabrication to trace the evolution of defects in new service applications • Determine simulation data required for alloy design and fabrication optimization
Shape	• Improve solidification models for simulating near-net-shape casting • Update milling data to include new cutting tool materials (e.g., diamonds, diamond-like coatings, ceramics) • Promote application of innovative shaping processes (e.g., hot gas forming, semi-solid processing, copper die casting)

Surface	• Improve understanding of interfaces to enhance the manipulation and control of the interfaces that separate various components of complex substances • Develop new self-healing coatings enabling controlled copper ion release
Joining Methods	• Study copper-to-dissimilar-material interfaces to predict durability of composite structures • Investigate new joining technologies • Establish an application network of advanced joining techniques (like electron beam, CuproBraze®, laser, etc.) to support manufacturers
Application	• Collaborate with copper-specific, other material-specific, and multi-metal organizations to optimize the application of copper composites • Improve methods for prediction and assurance of lifetime in service, including integrated engineering design to meet performance requirements combined with modeling of the processing, manufacturing, or fabrication steps necessary to apply copper materials • Improve understanding of the supply-chain issues when introducing a new copper material
Recycling	• Improve product design for copper recovery • Provide product life-cycle cost information about copper to product developers and material specifiers • Inform manufacturers about best practices for copper-related manufacturing processes

2.2 Existing/Evolving Opportunity: Electric Energy Transmission

A portion of copper's largest market — electrical wire and cable — comprises high-ampacity products used in utility transmission and distribution grids, as well as some large industrial facilities. Increasing demand for these products is accelerating due to expansion of energy infrastructures. In growing economies, limited capacity of existing grids will require upgrades and additions to existing distribution infrastructure. The construction of extended grids to service distributed or remotely located generation facilities such as wind and solar farms adds even more demand for power distribution cable. There is also growing interest in underground transmission and distribution cables for secure, uninterruptible power and a desire to avoid the higher maintenance and operating costs of overhead lines.

The market for high-voltage, sub-sea power cables is expanding to accommodate uses such as offshore oil/gas production platforms, offshore wind farms, and electrical grids. Requirements include cables with higher voltage (>275 kV) and higher power-transmission capacity. In addition to electrical conductors, opportunities for copper lie in copper water-tight sheathing of deep-sea and riser cables, which offer improved fatigue resistance over traditional lead-sheathed cables.

Additionally, copper is used as the thermal and electrical buffer in superconducting devices, a technology which has only begun to emerge as a source of substantial new applications for copper.

Trends, Issues, Drivers	• Concerns over reliability in sub-sea cables, coupled with rising demand for offshore electric energy transmission (especially from emerging marine-based generation technologies) • Rapidly expanding infrastructure • Increasing strain on existing infrastructure in growing economies • Increasing use of distributed generation and liberalization of energy markets in mature economies
Opportunities and Recommended Pursuits	
High Voltage	• Replace lead sheath with watertight, fatigue-resistant copper sheath in static (i.e., sea floor) and dynamic (i.e., sea to platform) sub-sea cables • Revisit economics of high-strength, high-conductivity, copper-base composites as alternatives for traditional cores in overhead transmission cables
Medium Voltage	• Develop thinner, more flexible insulation systems
Low Voltage	• Develop reduced-thickness insulation systems
Transmission and Distribution System Components	• Develop higher-packing-density transformer windings
Other Applications	• Develop cost-effective, copper-containing superconducting materials

2.3 Existing/Evolving Opportunity: Data/ Signal Transmission

Today, copper cables and connectors are used for more than 80% of signal-carrying equipment interconnections in data centers. However, industrial, commercial, and consumer computing installations continually demand higher bandwidth capacity from these interconnections. In many cases, copper competes successfully against optical fiber. For example, for runs less than 100 m long, copper cables with bandwidths up to 10 Gbps are available at a fraction of the cost of optical fiber, and bandwidths up to 100 Gbps have been demonstrated.

Using copper in place of fiber avoids the need for optical/electrical coupling devices, reducing both cost and complexity. However, the cost of fiber-based installations continues to decrease, and this market reality demands ongoing development of improved copper-based cable systems in order for the metal to remain competitive. In addition to providing adequate bandwidth, new copper-based cables should reduce power consumption and, preferably, should be simpler than existing systems with regard to installation and connectivity.

One of copper's key features is its ability to deliver power and data simultaneously, providing a reliable source of power that enables network devices such as Internet Protocol phones, wireless access points, and network jacks to operate without separate power adapters, cords or AC outlets.

Trends, Issues, Drivers	• Increasing performance requirements • Continuing inter-material competition, especially on the basis of cost • Improving reliability • Improving electrical efficiency, i.e., reducing power consumption • Increasing simplicity in wiring harnesses
Opportunities and Recommended Pursuits	
High Speed Copper Interfaces	• Develop method(s) to overcome signal degradation across 100 m, preferably in low-cost terminal devices • Promote development of industry standards applying the benefits of copper interfaces
Power to Remote Network Devices	• Develop the capability to deliver high power (e.g., 30W) with data transmission over communications cables • Promote the development of industry standards incorporating increased power delivery capabilities • Expand availability of products that take advantage of available power over data cables
Reduced Power Consumption	• Develop low-power signaling techniques to reduce data center/network power consumption

2.4 Existing/Evolving Opportunity: Automotive Wiring

Automobiles increasingly use electronic devices in performance, comfort, safety and entertainment features. Wiring for power and connectivity will continue to influence copper usage in the automotive industry, especially with respect to wiring harnesses and associated connectors.

In addition, the continuing trend toward more computer and microprocessor control will prompt higher demand for reliable, cost-effective sensor housings, which comprise a fertile and increasingly interesting market for brass and other copper alloys.

Space limitations are driving automakers to downsize both harnesses and connectors. This trend towards miniaturization places higher demand on mechanical properties in the conductors and connector materials, principally higher yield strengths in conductors, and improved stress relaxation resistance in the copper alloys used in connectors. To date, the thinnest copper cable for an automotive wiring harness is 0.13 mm^2 (cross-section). Automotive wiring harnesses could be lightened by 3.4 kg or 12% per 2 liter class luxury sedan by replacement of instrument panel harness and floor harnesses with newly developed 0.06 mm^2 copper cables.[2]

Persistent overcapacity in the highly capital-intensive auto industry means automakers face continuous pressure to reduce cost. Reliability will continue to be an issue to assure passenger safety. The under-hood temperature range is -40°C to 200°C and the maximum design temperature is expected to rise to around 220°C.

Copper's inherent corrosion resistance, formability, thermal stability, recyclability, and compatibility with many existing manufacturing processes provide many opportunities for it to grow and remain viable in the automotive wiring sector.

Trends, Issues, Drivers	• Miniaturization • Increasing number of electrical/electronic functions • Increasing need for quality, cost, and supply stability • Increasing under-hood temperatures • Higher bandwidth communications • Increasing environmental concerns (i.e., electrical and electronic equipment waste and restriction of the use of certain hazardous substances, such as lead, mercury, and cadmium)
Opportunities and Recommended Pursuits	
Wiring Harnesses/ Inter-connection	• Develop compact, copper data/signal cable with lower cost than current products • Develop fine flexible wires with increased tensile strength suitable for low power and/or short range data transmission • Integrate copper-based heat transfer techniques with wiring harness
Connector Alloys with Improved Elevated Temperature Properties	• Improve elevated-temperature strength • Increase stress-relaxation resistance • Enhance oxidation resistance
Terminals and Busbars	• Develop small terminals with increased strength, heat resistance, and stress relaxation • Develop relays and busbars with increased electrical conductivity • Improve bending workability of micro-mini terminals
Joining Methods	• Develop improved techniques for joining copper with dissimilar materials

2.5 Existing/Evolving Opportunity: Motor-Driven Systems

Motor-driven systems power applications from a few watts in personal devices up to 1000+ kW motors driving large manufacturing processes. These systems account for about 40% of global electricity consumption, making improved efficiency important. A 7% reduction in electricity consumption is possible if the EU-27 applies the best available motor driven system technology. The U.S. Department of Energy estimates that industrial motors consume 23% of electrical energy generation and that electricity use could be reduced 11-18% (62-104 billion kWh/year) if industrial facilities took advantage of all available efficiency measures.

Drivers in motor systems include more stringent regulations, rising energy costs, and wider acceptance of life-cycle cost considerations. The use of die-cast copper for the conductor bars and end rings of induction motors results in improvements in motor energy efficiency and reduced cost. The use of variable speed drives with motors containing copper rotors always results in a significant efficiency gain at partial-load conditions. However, while die-cast copper motor rotors (CMR) are an established product, a reduction in production costs would enable wider application. For applications requiring high torque to weight ratio, permanent magnet motors and water-cooled, high-frequency induction motors with copper rotors are increasingly applied. Designers are also looking to increase packing density in stator windings, the source of 60% of electrical losses in AC induction motors. Variable speed motor drive technology relies on copper in system components and thermal management of power electronics.

Trends, Issues, Drivers	• More stringent energy-efficiency regulations and standards • Rising energy costs • Increasing awareness of life-cycle cost of operation, replacing first cost as the primary driver in purchasing decisions • Increasing use of variable speed drives to raise motor-driven system efficiency • Reducing CMR production cost • Reducing motor weight and size in military and aviation applications
Opportunities and Recommended Pursuits	
Motor Efficiency/ Performance	• Design economical, single-phase CMR motors and production processes • Develop standards and test methods for super-premium efficiency motors • Optimize copper-specific designs for motor and conductor bar shape • Control slip; quantify effect of copper rotor on torque threshold (starting, breakdown, locked-rotor), especially in high power motors • Develop improved energy-efficient motor drive systems for continuously operating air conditioning equipment components
Thermal Management in Variable Speed Drive and Motors	• Advance the state-of-the-art in copper-based thermal management packaging of power semiconductors used in variable speed drives • Develop compact coolers for large air-cooled variable speed drives • Develop ultra-compact coolers and optimized thermal management technologies for smaller drives • Explore in-rotor cooling technologies
Manufacturing Efficiency	• Reduce the cost of production for die-cast CMRs • Increase die life for CMR die-casting, for example: cost-effective, replaceable die inserts; thermal barrier coatings; or high-temperature-resistant die-casting mould materials having thermal and thermoelastic properties conducive to minimizing thermally induced strain • Develop low-cost method to achieve higher packing density (>80%) in stator windings

2.6 Existing/Evolving Opportunity: Electronic Interconnection

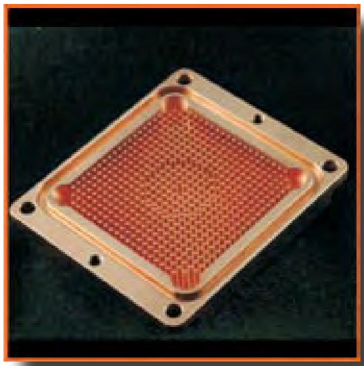
Leadframes, plugs, terminal blocks, and other forms of connectors are widely used in electronic equipment. Annual growth rates for these devices currently range between 15 and 20%, due to the global increase in production of electronic products.

Leadframes, which are common to all solid-state electronic equipment, distribute electrical signals and power between integrated circuit (IC) chips and external circuits; transfer heat from chips to heat sinks, and support chips inside encapsulating material. Connections are made by wire-bonding tabs on the IC chip to the leadframe.

Leadframes comprise more than 60% of today's semiconductor packaging market for copper alloys, and the leadframe industry continually addresses rising performance requirements to support high-frequency input/output (I/O) products for the memory market, high I/O counts for the high-performance computing market, and lightweight, robust packaging in the hand-held and automotive markets. Miniaturization requires denser integration of dissimilar materials for mechanical reinforcement and higher performance. The connector and leadframe industries, being reliant on innovation, should be viable partners for collaborative development programs.

Trends, Issues, Drivers	• Further miniaturization • Reducing process cost • Increasing inter-material competition • Increasing regulatory restrictions of certain alloying elements, such as cadmium, lead, etc.
Opportunities and Recommended Pursuits	
Miniaturization	• Develop miniature high-bandwidth connectors for >10 Gbps with low radiated emission and crosstalk • Improve integration of micro/nano-scale cooling circuits within leadframes • Develop ultra-compact cooling and thermal management technologies • Determine electrical behavior of the surface and sub-surface regions of copper and relevant copper alloys
Thermal Environment	• Improve molding compound adhesion and thermal conductivity to optimize thermal performance and reliability • Develop production technologies for copper-based heat spreaders and heat transmission products using techniques and materials to inhibit or enhance heat flux in desired directions
Heat Treating	• Develop thermally-preferential solidification process (e.g., material doping, seed introduction, cooling-assisted directional growth zones)
Joining	• Evaluate and develop particle brazing and fusing technologies (e.g., CuproBraze®) • Expand knowledge of mechanical behavior when reducing the amount of copper or copper alloys for small systems • Study copper-to-dissimilar-material interfaces to predict durability of composite structure
Recycling	• Improve methods for recovering valuable materials from components and boards at end-of-life • Improve understanding of contamination issues when recycling integrated copper materials

2.7 Existing/Evolving Opportunity: Electronic Thermal Management

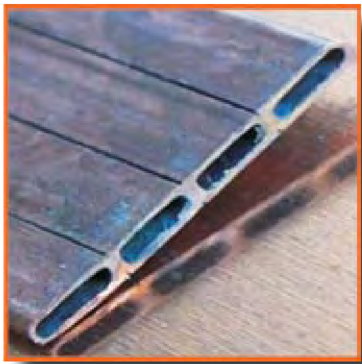


Thermal management deals with problems arising from heat dissipation, and thermally induced stress in the packaging of microelectronic and optoelectronic devices. Thermal management is a key to improved performance, especially in compact electronic systems, power semiconductors in variable speed drives, aerospace equipment, high-power laser systems, and automotive electronics. Cooling technologies need to manage devices with heat fluxes up to 1000 W/cm^2 and perhaps higher.

Copper heat sinks and heat pipes are widely used in electronics to efficiently transfer heat away from components efficiently. Flexible thermal circuits made from copper composites conduct electricity while providing excellent thermal management for applications such as circuit interfaces and cable harnesses.

Copper can improve thermal management of electronic systems at all levels, including the chip (dielectric breakdown, hot carrier aging, electromigration), package (die cracking, popcorning) and board (solder joint fatigue, board delamination). Also, heat sinks constructed of copper composites with phase change materials can assist in managing heat in cyclically operating systems and by absorbing and spreading heat from point sources. While copper is the heat-transfer material of choice in applications such as forced convection air-driven computer cooling systems and liquid cooling systems, the industry must remain vigilant to maintain copper's competitive edge.

Trends, Issues, Drivers	• Increasing power and frequency increases heat flux • Increasing use of optoelectronic devices increases heat flux • Increasing use of dissimilar materials with different thermal behaviors
Opportunities and Recommended Pursuits	
Thermal Management	**Power Semiconductors in Variable Speed Drives, Aerospace Applications, High-Power Laser Systems, and Automotive Electronics** • Develop strong, high-conductivity, copper-base composites • Develop passive copper composite thermal management systems based on phase change materials • Develop improved production method for copper cold plates • Develop production technologies for copper-based heat spreaders and heat transmission products using techniques and materials to inhibit or enhance heat flux in desired directions **Compact Electronic Systems** • Create isothermal surfaces with faster and more efficient heat removal, spreading, and translocation • Develop high thermal conductivity thermal spreader materials and composites
Copper Bonding	• Develop high thermal conductivity bonding of copper heat sinks to ceramic substrates and packaged devices • Develop method of producing bond without heating devices to destruction
Next-Generation Heat Transfer Devices	• Develop micro-scale machining, forming, and assembly processes to leverage use of copper-based materials in fluid heat exchange systems • Design next-generation microscale heat transfer devices using single-phase fluids (e.g., coolers, heaters) or two phase fluids (e.g., evaporators, condensers, heat-pipes, thermo-siphons) • Develop integrated on-chip cooling technologies • Explore moment wave and thermal wave technologies to increase thermal performance of microscale fin arrays over 500 W/m^2K



2.8 Existing/Evolving Opportunity: Appliance Heat Exchange

Current residential air conditioning heat exchangers are fabricated with round copper tubes ranging from 5-16 mm in diameter. In the face of high material costs and the desire to move to higher efficiency, manufacturers are replacing round copper tubes with smaller diameter tubes, tubes of different geometries, and/or tubes of different materials. Similar technical and market forces apply to refrigeration, vending, and commercial food merchandising systems.

Smaller-diameter copper tube (≤ 5 mm diameter) and flat tube technologies offer significant advantages, including size reduction, reduced refrigerant charge, and lower cost. Technical challenges include making flat, multi-port brass or copper tubes capable of sustaining a 38.6-bar (560 psi) working pressure and a burst pressure of three times the working pressure. Achieving cost-effective solutions involves R&D in materials joining, metal fabrication, design engineering, applied heat transfer, and alloy development/optimization.

R410A and other hydrofluorocarbons are the current refrigerants of choice in appliance heat exchange applications. Systems using R410A refrigerant run at a pressure that is approximately 60% higher than similar systems using R22, which presents both design implications and opportunities for copper. In the long term, carbon dioxide may become a preferred alternative. However, worldwide interest in hydrocarbon refrigerants, such as butane and propane, means copper must continue to consider the use of the evolving environmentally friendly refrigerants. There is also interest in other technologies, such as magnetocaloric refrigeration, which may influence the copper intensity in these types of systems in the future.

Trends, Issues, Drivers	• Increasing demand for more efficient, compact air conditioning systems • Intensifying inter-material competition • Reducing manufacturing cost • Changes in refrigerant to reduce ozone depletion
Opportunities and Recommended Pursuits	
Next Generation Environment-Friendly Working Fluids	• Optimize copper heat exchanger designs for next generation, environment-friendly working fluids, and possible future refrigerants, including nano-particles
Smaller, More Efficient Heat Exchangers	• Develop super-thin evaporators to reduce room space package and parasitic fan losses for domestic heating, ventilation, and air conditioning systems (HVAC) and refrigeration applications • Develop design tools and production technology for air conditioning heat exchangers with round tube diameters of 5 mm or less • Develop methods of fabricating flat and round multi-channel tubes and heat exchangers (evaporators and condensers) • Develop methods for achieving brazed assembly of all-copper heat exchangers in high volume production • Improve thermal conductivity of tube-to-fin interface when mechanically expanding 5 mm and under copper tubes into aluminum fins
Energy Efficiency	• Explore use of copper nanoparticles in refrigerants to improve heat transfer • Enhance condensation and evaporation of refrigerant inside round and multiport tube • Develop high-performance copper heat-transfer fins in thin material gauges • Develop systems that distribute heat or cooling without applying energy to circulate a fluid

2.9 Emerging Opportunity: Electrical Propulsion

The rail, marine, heavy construction, and automotive sectors comprise important markets employing electrical propulsion technology, of which copper is an integral component. Automotive electrical propulsion systems are undergoing substantial development and moving away from relatively simple electric motor-based systems and towards more highly engineered, compact, and efficient approaches. Additional opportunities include copper components for high current capacity and thermal management in power electronics, as well as the infrastructure to support recharging of electrical vehicles. Promising developments are taking place in superconducting propulsion systems, including the construction of very large, copper-intensive marine propulsion motors.

Vehicle designers seek smaller, less costly, more efficient motors. The typical fill rate of copper windings in the stators of electrical machines is around 50-60%. To speed the transition of automotive power transmission systems towards new copper-intensive components, a fill rate in excess of 80% is useful to reduce component size and weight.

Charging a 35 kWh battery in 10 minutes requires 250 kW. An electric charging station for four cars would need 1 MW. Quick charging eliminates the need for large-scale energy storage and is much more attractive to consumers who would prefer to charge cars at home or while parked. Copper's excellent thermal conductivity may offer heat-transfer solutions that improve the cooling capacity of rapid-charging stations.

Fuel cell vehicles require far more heat-transfer area than traditional fossil-fuel vehicles. For example, some prototype fuel cell vehicles require three heat exchangers compared to one heat exchanger for traditional vehicles. To meet space constraints, heat-transfer devices should preferably be ultra-compact.

One U.S. manufacturer recently introduced AC-induction copper motor rotor (CMR) traction motors in military and commercial trucks. Some auto manufacturers are reported to favor AC-induction drive motors for passenger vehicles as well, and for these applications, introduction of CMR technology would produce an important gain in copper use.

Trends, Issues, Drivers	• Growing consumer acceptance of electrical vehicles, growing interest in plug-in electric vehicles • Increasing interest in large, superconducting marine propulsion motors • Steady improvements in battery technology

Opportunities and Recommended Pursuits

- Develop new motor topologies with higher power density
- Develop high production-volume electromagnetic transmission to eliminate gearbox
- Develop higher voltage, smaller, high-speed induction motor technology
- Explore copper's role in advanced battery concepts
- Increase fill rate of copper in motor stator lamination slots to exceed 80%
- Explore the need for copper components in charging infrastructure
- Further develop electrical propulsion of bicycles and other personal mobility devices
- Develop electrical aircraft propulsion

2.10 Emerging Opportunity: Renewable Energy

Copper plays important roles in clean energy systems, particularly in generators, power electronics, cabling, controls, and protective devices used in wind, tidal, biofuel, wave, geothermal, and solar thermal plants. Solar photovoltaic systems need copper for current transport, grounding, and a variety of system components. Ocean-based systems can benefit from copper alloys' resistance to biofouling and corrosion. Newer systems will need to be even more efficient with less environmental impact.

Development of copper use in this area may require close technical cooperation between the copper industry renewable energy systems technologists to ensure that the most appropriate copper materials, material forms, and processing techniques are selected for specific applications.

Copper is an important "energy metal" with remarkable thermal and electrical properties that are vital in renewable energy systems.

Trends, Issues, Drivers	• National interests in improving energy security/reliability • Avoiding the market volatility and supply challenges related to fossil fuels

Opportunities and Recommended Pursuits

- Advanced large-scale or distributed systems for
  - Solar thermal power
  - Wind power generation
  - Ocean wave and current power
  - Solar photovoltaic power
- Develop compact copper-enhanced phase change thermal energy storage devices
- Develop new generator topologies capable of high power density and efficiency at low rotational operating speed

2.11 Emerging Opportunity: Aquaculture

Fish farming is a multi-billion dollar global industry. There are concerns over fouling of fish nets by marine organisms, spread of infectious disease, predator attack, pollution from fish waste and possible threats to human health from the antibiotics fed to farmed fish. The combination of copper alloys' antifouling, antibacterial properties, and mechanical strength addresses these issues. The copper metals' antifouling property permits clean, oxygenated water to flow through fish nets or cages, flushing out debris and thus maintaining a healthy environment. In addition, copper may mitigate the spread of infectious diseases by eliminating the fouling environment (i.e., algal films, various brachiopods) in and around which pathogens can thrive, thus reducing or eliminating the need for antibiotics. The mechanical strength and resilience of a copper alloy structure would also prevent predator attack or the escape of fish. Additionally, unlike nets made from synthetic materials, copper alloy structures are completely recyclable at the end of their useful life.

In the 1960s through the 1980s, the copper industry developed various copper-based cages for aquaculture. These cages were rigid and not easily scalable to large volume production; however, they proved the concept in semi-commercial size fish pens installed in commercial salmon farms in Scotland and the United States. Recent improvements in copper alloys and cage design take the form of woven wire nets with service lives extending beyond four years. The nets also allow 50% more fish per cage, a 10-15% faster fish growth rate, and increased profit for farm owners.

Trends, Issues, Drivers	• Global expansion of aquaculture • Reducing fish loss due to parasites, predators, infection, and handling • Movement away from protected coastal areas to areas exposed to more energetic sea conditions • Reducing antibiotic use
Opportunities and Recommended Pursuits	
Cage Design	• Optimize wire diameter and mesh design for various fish species • Design cages and floatation systems for near-shore and offshore applications • Investigate submerged systems and floating structures that submerge as needed • Reduce cage weight while significantly extending useful life • Revisit low-cost, expanded metal cages
Alloy Development	• Develop alloys with improved fretting corrosion resistance to prevent material loss • Develop/investigate alloys that can meet anti-fouling performance needs with optimum copper ion release

2.12 Emerging Opportunity: Hygienic Surfaces

According to a large number of studies, surfaces of (non-copper-base) doorknobs, push-plates, bed rails, and writing instruments in hospitals are infested with high concentrations of micro-organisms, including dangerous pathogens. ICA-supported research, including thousands of tests of copper metal samples under tightly controlled laboratory conditions, confirmed that surfaces with greater than or equal to 65% copper:

- Destroy 99 percent of resident bacteria within two hours;
- Prevent re-infestation for 24 hours (or more); and
- Continuously reduce bacterial counts thereafter.

Thus, the installation of copper-alloy "touch surfaces" in hospitals, schools, public transportation systems, and public buildings should reduce disease transmission while at the same time generating a significant new market for copper and its alloys.

Promotion of copper use in the healthcare and food handling industries will require cooperation between the copper industry potential users to ensure the appropriate selection of alloys and product forms.

In a related application, it is known that copper-rich surfaces can prevent the growth of fungi in air conditioning systems, thereby improving air quality and keeping heat exchange and condensate drainage surfaces functioning at optimal efficiency.

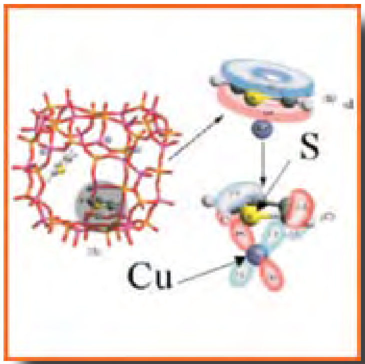
Tests of copper-based hygienic surfaces have been underway for several years, and approval by the U.S. Government for the promotion of copper as a biostatic material is expected. International standards require that medical devices comply with relevant regulations and pass application-related tests. Copper alloys, including some tarnish-resistant compositions, have successfully passed tests in Germany, and trials of copper-alloy door hardware and bed rails are being planned.

Trends, Issues, Drivers	• Growing multi-drug resistance by bacteria • Increased travel leading to increased rate and extent of disease transmission • Increasing infection rates in hospitals and communities • Aging population, implying lower disease resistance • The need to transfer successful laboratory data to the clinical environment

Opportunities and Recommended Pursuits

- Develop and promote hygienic copper and copper-alloy products
- Develop or determine optimum cleaning materials/methods for copper alloy surfaces
- Improve tarnish resistance for cosmetic appeal without mitigatging antimicrobial properties
- Ultimately, develop "stainless" copper and copper-alloy products with permanent antimicrobial properties
- Provide technology transfer to potential manufactures of copper-based hygienic materials
- Promote the use of copper-base fins and drip pans in heating, ventilation, and air conditioning (HVAC) systems in buildings, automotive vehicles, and public-transportation

2.13 Emerging Opportunity: Potential Future Applications



In addition to the Opportunity Areas presented in this document, the copper industry seeks further application-directed projects that promise new copper applications, identify the breakthroughs required, and describe a credible technical approach to successful realization. As noted earlier, the industry, acting through the International Copper Association, Ltd. and its network of national/regional copper promotion organizations, funds pre-competitive research leading to the creation of significant new applications for copper. Researchers in academia or industry working in either basic or applied research related to copper, and whose work addresses the interests of the copper industry, are encouraged to contact the ICA.

Proposals may address technical issues encountered in a specific product development or simply entail exploratory research. Interdisciplinary research proposals involving collaborators in industry or among various fields are welcome. ICA is always willing to review proposals for funding.

Trends, Issues, Drivers	• Increasingly rapid cross-fertilization of ideas and global collaborative creativity • Pervasive digitization, communication, and computing • Simulation and modeling of metallurgical phenomena • Deeper scientific understanding of living systems • Greater concern about environmental consequences • Global spread of venture capital investment model
Opportunities and Recommended Pursuits	
Examples of Existing Application Research	• Develop technology to control grain size and grain boundaries for development of copper and copper alloys simultaneously possessing high yield strength and high ductility • Copper-based zeolites have the potential to be an economical solution to the desulphurization of transport fuels. Existing desulphurization technologies are prohibitively expensive when used to remove trace quantities of sulphur from transportation fuels. It is known that copper salts such as cuprous chloride exhibit a strong affinity for removing (absorbing) sulphur-containing compounds. • Copper foam combined with a phase change material has the potential to significantly improve the energy efficiency of buildings. A compact building product that stores/releases thermal energy could provide a uniform indoor temperature with reduced energy input

3. Implementation

The *Copper Applications Technology Roadmap* will continue to evolve as industry reacts to societal trends, competitive pressures, related technical developments, and unanticipated opportunities. While it does not cover all technological pathways to the future, this roadmap does focus on what its contributors believe are the highest priority pre-competitive needs of the copper industry and its users. As such, it is intended to guide the planning and implementation of collaborative R&D programs that will involve copper producers and fabricators, copper-using industries, universities, government laboratories, entrepreneurs, and independent technologists.

Many of the organizations that participated in the creation of this roadmap invest significant resources each year in developing innovative products, new copper alloys, and advanced process technologies. Their history of technology investments are, and will continue to be, a major source of their own future market success. By working together to develop this roadmap, the industry has taken its first step in business technology transformation. However, implementing change is the most difficult and complex step in achieving desired outcomes. Without a clear idea of how to implement the roadmap, it will become another report for the bookshelf.

The ICA will play three roles in implementation of the *Copper Applications Technology Roadmap*:

- **Outreach and Partnership Development** activities will engage relevant individuals and organizations to inspire additional fresh thought regarding future needs and required R&D concerning copper.
- **Roadmap Implementation Forums** will provide focused venues for brainstorming about specific opportunity areas and will disseminate findings among the networks thus created.
- **Roadmap Oversight and Project Coordination** of the diverse organizations taking part. ICA has historically taken a coordinating role in the development and implementation of major copper applications R&D, and ICA will continue in this role. ICA will also spearhead efforts to secure co-funding from third parties, including governments, non-government organizations, and appropriate industry organizations.

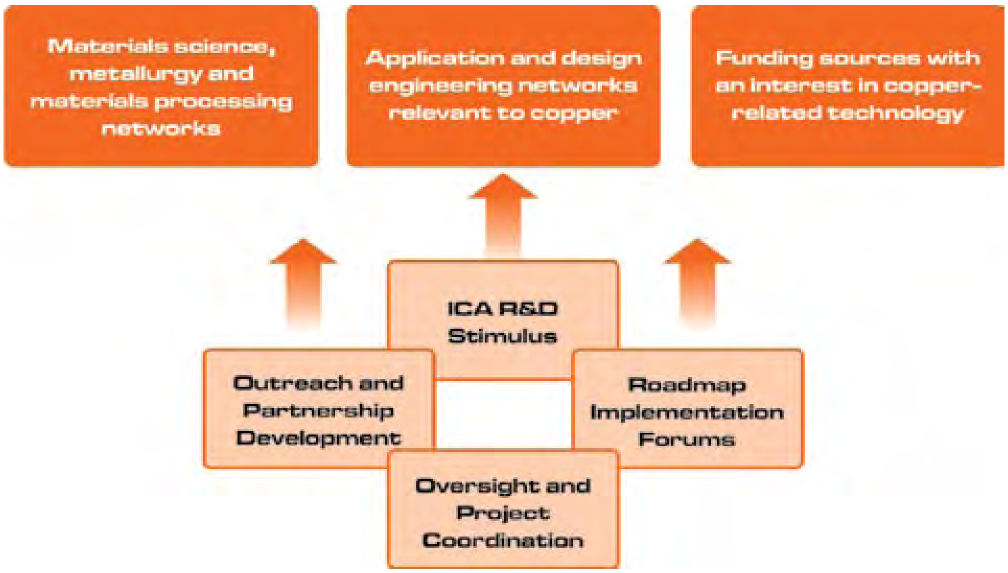
Figure 3.1 outlines the main implementation steps. These steps are designed to catalyze dialog about copper, and subsequently launch and manage copper applications projects. Strong leadership and persistence will be needed to ensure that important opportunities do not fall through the cracks. In addition, achieving early successes is important to maintaining momentum generated by the roadmap and convincing companies that the technology collaboration model can work.

Outreach and Partnership Development

Collaborative partnerships will leverage resources and capabilities among copper semi-fabricators, component producers, system manufacturers, original equipment manufacturers (OEMs), government organizations, universities, producers, and other stakeholders. Combining the expertise and perspectives of all facets of the copper-related markets ensures that their needs are being met and anticipated from every angle. Additionally, information and cost-sharing minimizes the duplication of technology development efforts and maximizes resources to efficiently achieve effective solutions. While the precise roles of companies and organizations in implementing this roadmap have not yet been determined, these roles will take shape as the roadmap is disseminated and reviewed by those engaged.

Outreach activities are equally important, as they keep industry groups across the globe informed and up-to-date regarding effective strategies and technologies to enhance the value of products using the intrinsic advantages of copper. Online web-forums, journal articles, published reports, conference briefings, and regular news updates can increase global awareness of the latest developments in copper innovation.

Figure 3.1 Catalyzing Conversations About Copper—Connect Individuals and Networks Within Key Domains and Stimulate Thinking About Copper-Related Technology



Roadmap Implementation Forums

A roadmap implementation forum can provide the means to solicit new ideas to accelerate progress for the most time-sensitive projects. If it is determined that a particular roadmap opportunity is not being addressed through ongoing efforts, copper industry leaders, including the ICA, will need to be step forward to organize activities that will bring together the range of expertise necessary to think creatively about potential responses. This investment may be directed toward applied research, commercialization of technology, product integration, field testing, training/outreach, or any other means or method that advances a particular opportunity.

Prior to launching new projects, the copper industry must clearly define the desired outcomes, resources, and capabilities required, and how the results will contribute to achieving a particular accomplishment. Each of these factors will be integrated into requests for proposals to solicit innovative solutions and projects from universities, private companies, government laboratories, researchers, or the technical community.

Roadmap Oversight and Project Coordination

This roadmap encourages organizations and individuals to participate in ways that will best capitalize on their distinct skills, capabilities, and resources for developing the opportunities described herein. This affords companies and organizations the flexibility to pursue projects that correspond with their unique interests. However, without a unified structure it will be difficult to adequately identify, organize, fund, and track the diverse activities and their corresponding benefits. In accordance with its mission, the ICA can fulfill this role by providing the required oversight and collaboration to initiate and resource projects and activities.

ICA's Mission:

Advance copper as the material of choice for current markets and new applications given its superior attributes in terms of technical performance, aesthetic value, sustainability, essentiality for life, and its contributions to a higher standard of living.

Conclusion

In this roadmap, the copper industry provides a baseline for copper application development efforts. Subsequent efforts can produce a more in-depth set of directions and an effective path toward success in specific markets. Collaborative partnerships among materials science, metallurgy and materials processing researchers, application and design engineers, manufacturers, and government can generate the requisite power and momentum to drive copper and its industries along these paths.

As the industry looks to the future, the success of this roadmap will be measured by the number and scope of collaborative R&D projects that it inspires and the benefits those projects accrue. Complementary but equally important benefits will — and rightfully should — include the enhancement of the perception of copper as a life-connecting, environmentally friendly, advanced technical material.

Appendix A — Innovation in the Copper Industry

Case Study on the Copper Motor Rotor

Figure A.1 Comparison of a Traditional Rotor (left) with a Copper Rotor (right)

The mid-1990s saw great interest in the development of more efficient, lighter, and smaller AC induction motors for use in industry and government sectors. Passage of the U.S. Energy Policy Act of 1992 and similar legislation in Europe reflected a growing awareness of the importance of motor efficiency in the larger arena of energy conservation. Industry responded with more efficient motors using an increased amount of copper in the stator windings, which reduces resistive, or I^2R, losses.

After decades of incremental improvements in motor efficiency, few technical avenues remained to reach significantly higher efficiencies at a reasonable cost. The die-cast copper rotor appeared to be the best approach with a potential to reduce overall losses by 10% to 20%, compared with conventional rotors. Copper rotors could have less metal volume, making them lighter, and operate more efficiently at a lower temperature, increasing motor life. Despite these advantages, existing copper die-casting methods were not economical for high-volume production. In addition, motor manufacturers demanded that the copper rotor be producible in commercially available pressure die-casting equipment.

Pursuing the Opportunity

Recognizing that a copper rotor was essential to further increasing motor efficiency and thereby gaining energy and cost savings in motor-driven applications, the International Copper Association Ltd. (ICA) initiated funding for an R&D project to create a practical copper motor rotor suitable for mass production. Led by the U.S. Copper Development Association Inc. (CDA), a consortium of motor manufacturers, die casters, and government representatives initiated (and cooperatively funded) the Die-Cast Copper Motor Rotor program.

Challenges

Researchers addressed the coupled challenges of reducing processing cost and assuring adequate copper rotor performance. During the die-casting process, conventional die steels are susceptible to cracking (heat checking) as temperatures cycle from a few hundred degrees to the melting point of copper (about 2,000º F; 1,100º C). Die life decreases drastically compared to the use of traditional metals, which melt at a lower temperature, and therefore induces significantly lower thermal stress and strain in the die.

Figure A.2 Close-up of One of Many New Potential Rotor Bar Designs

Solutions

The CDA-led team determined that cracking could be reduced and die life extended by doing two things: replacing critical portions of the steel die with a ductile, heat-resistant, nickel-base superalloy; and by pre-heating the die to approximately 600º C (1,100º F). These actions rendered the copper die-casting process economically viable.

The shape of the rotor bars, or rotor slots, was modified to further improve the motor's operating characteristics. Copper's high conductivity allows the rotor designer to use the "skin effect" — the tendency of alternating current flow to crowd towards the external conductor surfaces — which improves the starting torque and running performance of the rotor. Further enhancement of these bars continues, but the team has already transferred their initial findings to industry members for immediate application and further independent development.

Results

By spring 2006, one major international motor manufacturer had embraced the new die-cast copper rotor technology and brought to market a line of super-efficient motors. Within a year, the motors found widespread commercial acceptance in the United States. Currently, the motors are up to two percentage points more efficient than those meeting NEMA Premium™ standards, and thus offer substantially lower life-cycle costs. Ongoing research is directed at, among other parameters, optimization of rotor slot design to take full advantage of the copper motor rotors' properties. Additional work directed at the die-casting process itself continues at the Non-Ferrous Technology Development Centre in Hyderabad, India. This work is supported by ICA with co-funding from the UN Common Fund for Commodities. Technology transfer is being undertaken by various copper organizations and the U.S. government-supported Copper Base Technology Program.

Conclusion

The Die-Cast Copper Motor Rotor program embodies the principles and objectives of the *Copper Applications Technology Roadmap*. Given well-defined technological needs, industry has organized a collaborative consortium to fund and implement projects that produce innovative solutions that benefit society at large.

Appendix B — Fundamental Properties of Copper

Pure or alloyed in literally hundreds of compositions designed to meet specific requirements, copper-based metals provide optimized properties for innumerable products.

- **Electrical Conductivity** — Copper has an exceptional current-carrying capacity, better than any other non-superconducting conductor except silver. The copper in today's building wire has a conductivity rating higher than 100% of the International Annealed Copper Standard (IACS), the accepted maximum a century ago. Copper's excellent electrical conductivity means motors with new copper rotors can be smaller and run cooler than traditional motors.

- **Thermal Conductivity** — Copper conducts heat up to eight times better than other engineering metals. Combined with its inherently high corrosion resistance and ready formability, copper's thermal conductivity makes the metal ideal for heat exchangers of all types, including solar water heating systems. Since gas- or electric-derived water heating is one of the largest energy expenditures for any building or home, copper holds the promise of reducing energy costs directly and significantly.

- **Formability** — Copper's formability can cut installation time and reduce labor cost, particularly in the plumbing trades. Tubes and fittings are easily joined by soldering or brazing, and press fittings further reduce installation times. Copper and its alloys are ubiquitous in electrical and electronic components, including switches, current-carrying springs, connectors, and leadframes. Hot- and cold-forged copper products are demanded where reliability and good machinability meet. The menu of cast copper alloys is also abundant, particularly where a need for corrosion resistance is combined with good thermal or electrical conductivity.

- **Corrosion Resistance** — Copper metals can resist attack under a wide range of corrosive environments, which makes it ideal for use in applications in the offshore power, offshore oil and gas, and desalination industries. In the presence of moisture and a variety of natural and manmade atmospheric constituents, copper eventually weathers to a protective and pleasing patina that retains its functionality for centuries.

- **Antimicrobial Effect** — Today there is growing concern over hospital-acquired infections and those that originate in the food-processing industry. The bactericidal, fungicidal, and, to some extent, viruscidal properties of copper, copper compounds, and copper alloys have been known for centuries. Copper, in the form of copper or copper-alloy surfaces have proven to be a significant deterrent to the transmission of fungal and bacterial disease in healthcare and air-handling systems.

- **Color/Aesthetic Appearance** — Copper is increasingly utilized for its aesthetically pleasing appearance and the broad palate offered by its alloys. As copper use extends to hygienic surfaces, the "look" of copper will gain added consumer acceptance as a "healthy" metal.

- **Ease of Alloying** — The industrial importance of copper has been extended by the ease with which it alloys with other metals. An extensive family of materials more than 400 in use today — is the result. This endeavor is far from being exhausted.

Appendix C — Copper and Society

Copper is essential to living organisms and plays a vital role in modern technology. From the irrigation systems of ancient Egyptian kings to revolutionary inventions like the cellular phone, copper has continually contributed to societal development.

As the virtually exclusive element used for electrical and data transmission, copper helped usher in the telecommunications era. Perhaps never in human history — even considering the accelerated pace of contemporary progress — has a new development been commercialized as quickly as was the telephone. First introduced in the 1930s, copper telephone wire was used in place of iron to send weak, high-frequency voice signals more than 50 miles without losing the signal along the line. Strong, uniform, high-conductivity wire was the first and undoubtedly the most important attribute favoring copper's use in telecommunications.

Combined with its strength, corrosion resistance, and durability, the natural beauty of copper has inspired countless architects and designers to feature the metal on both exterior and interior building surfaces for millennia. Copper has covered and protected some of the most important buildings of antiquity, as well as centuries-old universities, financial institutions, government buildings, and houses of worship.

Copper can be cold-rolled into thin sheets, which despite their relatively high strength (in rolled tempers or heat-treated form in appropriate alloys), can be readily shaped into connector components by simply bending them. The unique combination of strength and formability make copper and its alloys ideal for use in applications where repetitive actions stressed the components, such as fasteners, electrical connectors, springs, and electrical switches.

Long-Term Societal Needs

While copper still enjoys most of its historic uses, there remains a large portion of the world's population that does not even have access to electricity or safe drinking water. Additionally, societal concerns over improved public health, increased energy efficiency, environmental sustainability, and higher standards of living have spawned the development of cleaner energy systems, marine aquaculture, portable electronics, and nearly limitless global communications. Recognizing the profound effect that technology has on nearly every aspect of life, the copper industry plans to continue to participate in the advancement of technology and explore further uses for the red metal. At the same time, actions must be taken to foster more integration between technological innovation and broader considerations for social, economic, and environmental concerns.

- **Improved Human Health** — Copper is required for the normal functioning of plants, animals, humans, and even microorganisms. It is incorporated into a variety of proteins which perform specific metabolic functions. Because it is an essential metal, daily dietary requirements have been recommended by a number of agencies around the world. Some of the uses of copper come from its ability to control the growth of organisms. For example, copper has been demonstrated to be an effective anti-pathogen, anti-plaque agent in mouthwashes and toothpastes. Touch surfaces made from copper can aid in disease prevention by controlling the growth of dangerous pathogens.

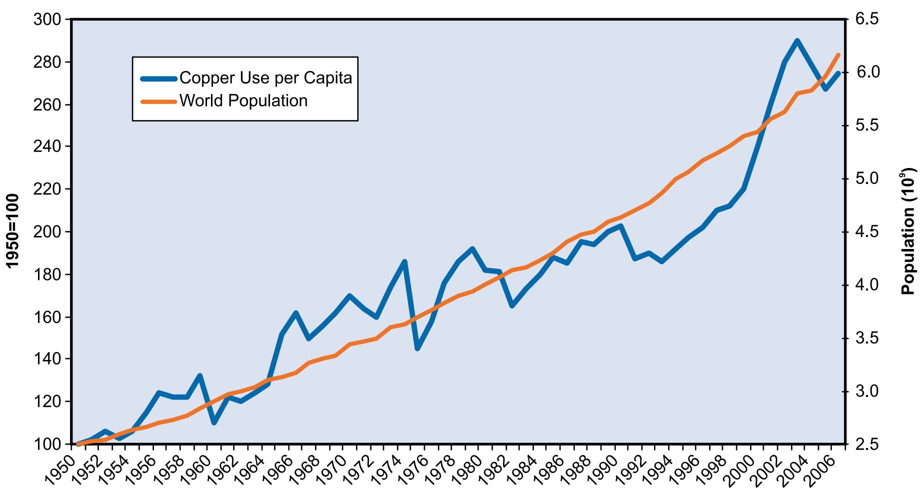
- **Increased Energy Efficiency** — Wasted energy raises costs for consumers and can have negative environmental impacts. Improvements in electrical energy efficiency are helpful in securing improved standards of living. Converting to energy-efficient equipment, especially premium and super-premium efficiency copper motor rotor (CMR) motors, as well as high-efficiency copper-wound transformers, helps reduce costs and mitigate emissions.
- **Environmental Sustainability** — Recycling has long been used to minimize waste and conserve valuable resources. Copper is 100% recyclable without loss of performance. It is not "consumed" in the sense of being "used up." Rather, it is used, recycled, and reused time and again (see Figure C.1). Copper has the longest recycling history of any material known to civilization. It is estimated that 80% of all copper ever mined during the past 10,000 years is still in use somewhere today. Copper reclaimed through recycling also requires 75-92% less energy than the amount needed to convert copper ores to metal.
- **Higher Living Standards** — The proportion of the world's population living in cities with more than 10 million inhabitants is continuing to rise. Population growth, particularly when concentrated in clusters requiring massive electrical infrastructures, greatly increases the need for materials and energy; a need that should ideally be filled in a cost-effective, environmentally friendly manner. Additionally, the currently large and growing aging population increases the demand for technologies that help correct vision, hearing, motor, and other impairments, allowing seniors to continue to live comfortably as active members of society. Achieving higher living standards amid a population boom requires materials and products that can aid in sustainable development and an improved quality of life for everyone.

Figure C.1 Copper Recycling: Refining, Fabrication, Recovery, and Reuse

Appendix D — Copper Today

Over the past 50 years, the per capita usage of copper has roughly doubled, reflecting copper's role in the advancement of technology, expansion of economic activity, and increased standards of living (See Figure D.1).[3] Copper is an important contributor to many technical systems in developed regions such as construction, energy, communications, and transportation. In less developed regions, copper supports important building blocks needed to raise standards of living, bringing electricity, clean water, and efficient transportation to fuel expanding economies.

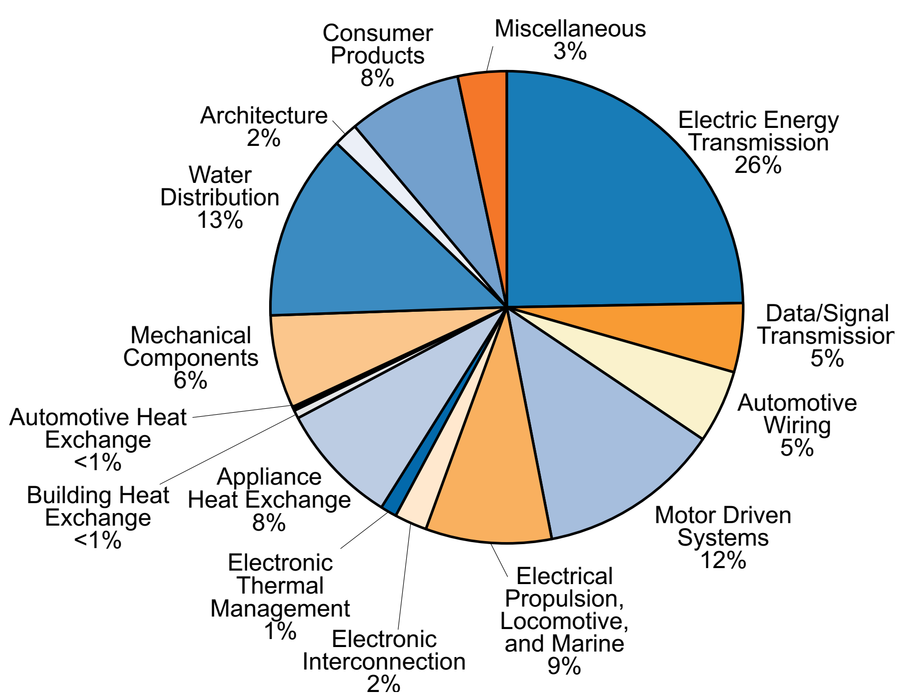
Figure D.1. Copper and World Population Trends



In 2006, global demand for refined and recycled copper was 22 million tons, with approximately one-third produced from recycled copper scrap.

Copper demand derives principally from the electrical energy transmission, data/signal transmission, and motor-driven system industries. Wire made from newly refined copper is used here due to stringent performance and safety specifications. The plumbing tube and fittings industry (e.g., water distribution) is the main use of copper other than wire. Figure D.2 illustrates the end-use markets for copper and their relative percent of total copper use.[4]

Figure D.2 2006 End-Use Markets for Copper



Appendix E — Trends and Challenges Influencing Copper Use

As the copper industry plans for the next five years, it must consider how copper use will change in response to trends, economic conditions and various market drivers, and the obstacles these factors may erect. While it is obviously impossible to predict the future, insight into likely developmental pathways and priorities is gained by considering the common economic, social, and technological forces that influence the global copper industries.

- **Reducing processing cost** — The automotive and primary metals industries have, over the past two decades, been forced to reduce their cost of manufacturing without reducing quality. The semiconductor industry now pays increasing attention to lowering parts costs, and a dramatic increase in demand for goods in China and India has driven up costs for many commodities, including copper. In applications where copper is uniquely suited to a specific application or substitution risk is too high, manufacturers will initially respond to high copper costs by seeking more efficient fabrication and assembly processes to reduce costs. Prolonged periods of high costs will eventually lead to reducing the amount of copper and, ultimately, substituting alternative materials.

  Copper's ability to be manufactured as wrought or powder/metal (P/M)-derived products enabled significant cost reduction in a variety of electronic applications. For example, components for 150-A and 200-A fuse blowouts used in coal mining equipment were converted from machined copper bar stock to a near-net-shape powder/metal P/M copper part, saving approximately 25% in product cost.

- **Maximizing value-added use of copper** — End-product designers tend to seek the greatest economy (i.e., minimum amount) of material for adequate functionality, while avoiding over-engineering and maintaining acceptable product life. The copper processor's desire to add value (and profit) may be met by meeting end-user requirements through increasing the engineering content of a product, e.g., gauge reduction, the use of specialty alloys and profiles, etc. Engineered copper products are high value-added materials that typically perform better than pure copper or products made by conventional fabrication methods. Such products, for example, are lighter, have broader services temperature ranges, are multifunctional, or have lower life-cycle costs.

  Copper's ability to function well even when used in reduced thicknesses and weight is a characteristic that produces added value. For example, in copper tubes used for potable water, wall thickness can be reduced from 1.0 mm to 0.3 mm without destroying functionality. In solar thermal collectors, reducing copper sheet thickness from 0.2 mm to 0.12 mm decreases copper use and therefore product cost, but thereby enables copper to maintain 60% of product share in a market that is growing by 30% per year in Europe. In automotive applications, copper's formability and high conductivity gains the metal a favored position in reducing the size of circuits, connectors and wiring harnesses.

- **Increasing competitive pressure from other materials** — The changing nature of competitive pressure now requires companies to compete on several aspects of performance simultaneously. Some 15 years ago, steel was considered such an old-fashioned and heavy material of questionable uniformity that automakers threatened to convert major body parts to plastic. Now, after 15 years of consistent effort at improving quality, steel continues to outperform competing materials. Aluminum and other materials have similar success stories to report. Copper, with its unique features, must offer system improvements unachievable with other materials, thus diminishing the effect of cost sensitivity in the purchasing decision.

- **Changing regulations, codes, and standards** — Owing principally to higher energy costs and political concerns over future supply security, energy efficiency has rapidly climbed the European Union's (EU) policy agenda. Industries are becoming increasingly attentive to the value of energy efficiency and its effect on life-cycle economics. The institution of higher motor efficiency standards provides a good example, and the market for high, premium and super-premium efficiency motors has increased and is currently accelerating. High efficiency, premium efficiency, and especially super-premium efficiency CMR motors utilize more than 20% more copper in stator windings and, in CMR motors, conductor bars, as well, compared with older, "standard-efficiency" motors.

  Other regulations that will impact the copper industry involve soils, waters, wastes, and sediments. In Asia, increasing industrialization, infrastructure development, and residential and commercial construction are prompting governments to support scientific advances in the understanding of metal behavior and toxicity in soils, waters, and sediments. Similar regulations will also be reviewed in the coming years in Chile and North America. Concern over the loading of copper in water and soils via sources such as architectural copper, automobile brake pads, fertilizers, paints, irrigation, etc. are also growing in North America but have, in several important instances (e.g., Connecticut and the San Francisco Bay region) been mitigated by the application of sound environmental science.

- **Assuring performance of engineered copper products** — Computer simulation is increasingly used to predict and validate copper's performance in new applications. Miniaturization and material integration will prompt additional research into the mechanical properties of small systems, the behavior of surface and sub-surface regions of copper and its alloys, phenomena that affect the interfaces of copper with other materials, and the impact of a stronger integration of different materials on recyclability. The development and use of new alloys, combined with more stringent design constraints, requires that the properties of those alloys (and other, conventional materials) be known or predictable with higher certainty. Improving the control of thermal, electrical, physical, and mechanical properties will also enhance copper's performance in advanced applications.

- **Increasing use of complementary engineered materials** — Materials that can change the performance characteristics of copper can be added to the surface or embedded within copper. Copper is most frequently used in combination with other engineering materials, and the properties of the resulting materials system are tailored to the needs of a specific application. Complimentary materials applied to the copper surfaces can provide thinner layers of electrical insulation, protection against rough handling, corrosion protection, or any number of desirable qualities. Demands for materials with higher strength-to-weight ratios have led to increased interest in composite materials, in which a reinforcing material is added within a material in order to increase strength and durability, and in some cases, effect weight reduction. Copper is not intrinsically a material with a high strength-to-weight ratio, and it is not often used where this property is singularly specified. However, formulations such as silicon carbide fiber-reinforced copper-base composite material have thermal conductivity and high strength at elevated temperatures. Other possibilities based on this example should be sought.

- **Designing for recovery and reuse** — Copper and its alloys are 100% recyclable, and secondary copper is an important industrial material. Copper is routinely extracted from automobiles, electronics, and buildings at the end of their useful lives. It is important for engineers to consider how products will be disassembled and the copper recovered. In addition, during manufacturing processes, not all copper is converted into useful products and this excess material needs to be recovered and recycled. It is beneficial if this scrap material remains uncontaminated to facilitate reuse.

Appendix F — Contributors

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