



Copper Applications Technology Roadmap

Preferred Directions for Innovation

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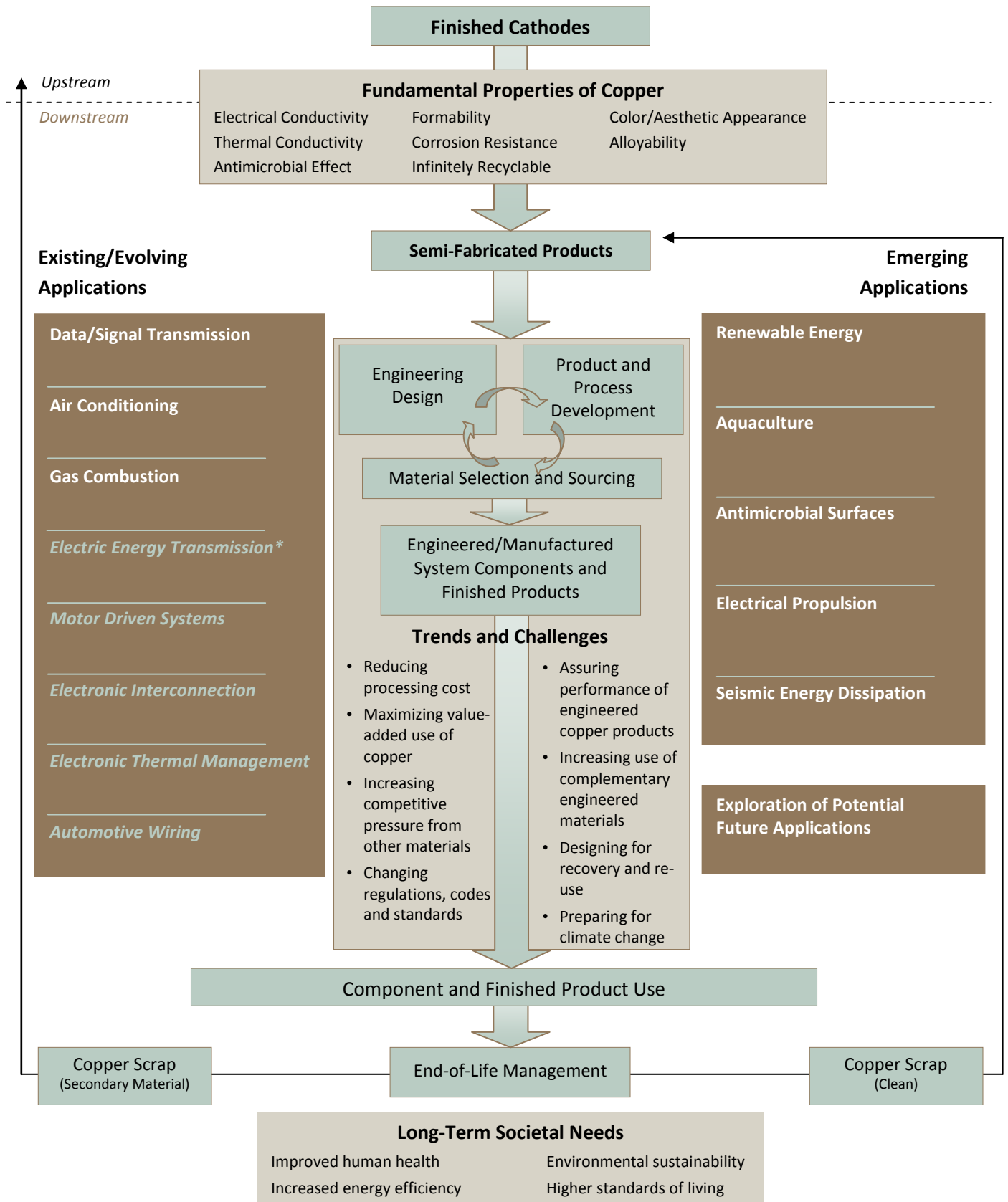
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R&D Priorities



* Green/Italic items were in first edition of the Roadmap and are not current R&D priorities.

Executive Summary

Global Outlook

Copper has a remarkable uninterrupted record as an integral part of human life and civilization¹. It possesses a unique combination of properties that through scientific insight and creativity have been applied in some of history's greatest innovations: precision navigation instruments, electrical systems, distribution of safe drinking water, air conditioning and data communications. This *Copper Application Technology Roadmap* points the reader toward promising new copper developments with the potential for global application.

Since the International Copper Association (ICA) introduced the Roadmap in 2007, it has served as a collection of knowledge and a guide for collaborative, pre-competitive research efforts among copper producers and fabricators, copper-using industries, universities, government programs, entrepreneurs, and independent technologists.

New Directions

The diagram shown on page 3 depicts the copper industry's complete downstream Roadmap. The green/italic areas represent applications where significant improvements have been made over the last three years. While these areas are no longer seen as priorities, work still continues to promote the advancement of copper technology in these applications.

The first section of the Roadmap looks more closely at the outer edges of the diagram, specifically existing/evolving applications and emerging applications. Appendix A provides an illustration of how an advance in copper technology moves through research, process development and engineering design and into commercial use. Appendices B, C and D address the center area of the diagram, describing the fundamental properties of copper, discussing the trends and changes influencing copper use, and examining how these attributes can assist in society's future progress.

Today's top existing/evolving applications include:

- **Data/Signal Transmission**—Copper-based cables with higher bandwidth and reduced power consumption that offer easier installation and connection will strengthen the industry's competitive position. Copper also delivers power and data over the same cable, thus simplifying the connection of digital entertainment, communications, computing, and security equipment into high-speed networks and providing a cost-effective solution.
- **Air Conditioning Systems**—A relative lower price for competing materials systems threatens the continued use of copper in air conditioning heat exchangers. Since the first version of this Roadmap, a team of industry and academic researchers organized by the ICA has reduced the copper content in some high-production-volume air conditioning heat exchangers by 40 percent. This effort continues. Copper offers advantages in sustainable energy efficiency, ease of manufacturing, antimicrobial effect and indoor air quality. The trend toward more compact, energy-efficient systems and the growing use of environmentally friendly refrigerants presents both design implications and opportunities for copper that can be addressed by collaborative R&D.
- **Gas Combustion Equipment**—Copper heat exchangers are used in high-performance, compact tankless water heaters. Engineered acid-resistant coatings protect copper materials, enabling the use of copper's outstanding heat transfer properties. Opportunities exist to improve heat exchanger design and manufacturing technologies, advance protective coatings, and expand the use of copper materials in a wider range of high-efficiency, gas-combustion equipment.

Emerging applications open entirely new markets for copper, broadening and increasing its use. Each area requires the development of new and improved copper-based technologies. The top emerging opportunities include:

- **Renewable Energy**—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. The combination of copper and PCMs (phase change materials) is being validated as a conductivity enhancer in solar thermal systems.
- **Aquaculture**—Copper alloy marine aquaculture cages are emerging as an effective solution to significant problems facing the fish-farming industry. Typical cages constructed from synthetic materials with anti-fouling coatings become encrusted with marine organisms after several months of use. 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. The mechanical strength and resilience of a copper alloy structure also prevent predator attack or the escape of fish.
- **Antimicrobial Surfaces**—Copper touch surfaces inhibit the growth of harmful pathogens and reduce the chance of disease transmission. Copper surfaces on frequently handled medical equipment in health-care facilities and public buildings made from copper fight bacteria that cause hospital-acquired infections, including dangerous multi-drug resistant organisms. In addition, copper prevents the growth of odor causing mildew and mold in heating, ventilating and air-conditioning systems that affect the air quality inside buildings and hinders system efficiency.
- **Electrical Propulsion**—Automotive electrical propulsion systems are undergoing substantial development toward more highly engineered, compact and efficient approaches. Electrical propulsion systems incorporate copper in batteries, electrical control, recharging plugs and leads, motors and thermal management. Powering electrical vehicles requires changes to the electrical infrastructure that will benefit from copper.
- **Seismic Energy Dissipation**—Earthquake damage to buildings, their contents and to occupants can be controlled through the use of copper-based devices that isolate structures from ground motions or absorb energy to limit building motions. This new application area applies superelastic copper alloys and the plastic deformation property of refined copper.

Future Application Concepts

The copper industry, acting through the ICA, funds pre-competitive research and development that may create or enable significant future market applications for copper or enlarge an existing one. Readers are invited to propose creative concepts derived from scientific advances, technology transfer or business/societal needs. Such proposals must identify the breakthrough required and describe a credible approach. There is a preference for a relatively rapid demonstration and/or development timescale. Nonetheless, proposals regarding longer-term scientific investigation are always welcome.

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, it focuses on the perceived highest-priority pre-competitive needs of the copper industry and its customers. Identifying and defining new research activities continues to be a challenge. To that end, the third section of this document outlines plans for an industry-managed process to create, launch and manage copper applications projects beyond those described in this Roadmap.

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.

Driving Innovation: Copper's Fundamental Properties

The *Copper Applications Technology Roadmap* looks downstream from mines, mills, smelters, and refineries to fabricators, processors and manufacturers, and also to specific disciplines, industries and applications (see R&D Priorities diagram). Material substitution is growing in traditional copper markets, and it is imperative that the copper industry actively identify and evaluate new technology opportunities. The Roadmap seeks 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.

Copper has a remarkable uninterrupted record as an integral part of human life and civilization¹. Copper's fundamental properties have met society's needs throughout history. In order to drive innovation, the copper industry must continue to explore copper's fundamental properties, such as:

- Electrical conductivity
- Thermal conductivity
- Antimicrobial effect
- Formability
- Corrosion resistance
- Infinitely recyclability
- Color/aesthetic appearance
- Ease of joining
- Alloyability

As the industry moves forward, it must collaborate with its partners to examine the ways copper's intrinsic advantage can help society apply the benefits of copper for a better, sustainable world.

- Success will come through the development of new materials—alloys, composites and compositions—providing 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.
- Success will result from optimizing the way copper is used or fabricated. The International Copper Association (ICA)-sponsored development of cost-effective copper die casting is an example of collaborative process R&D in the copper industry (see Appendix A).
- Success will come through innovation that takes appropriate advantage of copper's attributes and counteracts potential substitution by alternative materials.
- Success will come from imaginative thinking that connects copper with new applications and overcomes technical challenges.



Copper Mine



High-tech Copper Alloy

Copper's Intrinsic Advantages

No other metal, alone or in alloy form, so effectively offers the amount and breadth of useful properties as copper. Over the coming decades technological progress will largely depend on advanced materials such as metals, alloys, composites and other structures, many of which can potentially contain copper. In addition to having high-technical performance, these materials must positively influence issues such 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 discusses the trends and challenges influencing copper use. Appendix D offers insight into copper's role in meeting societal needs. *Note:* Appendices B, C and D follow the flow of center section of Roadmap diagram.

From Cathodes to Finished 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 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 to achieve the desired functionality and performance in the final application.

The copper industry, using its own representatives and those of 28 copper centers throughout the world, offers users a high level of support to assist in the selection of the most effective copper material solution. Additional details on the key issues, opportunities and recommended pursuits for copper that will support future technical collaboration with product and process engineers follow.

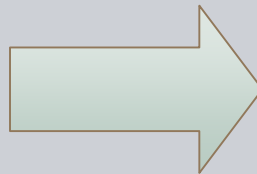


Copper Cathode

A Visual Transformation of Copper



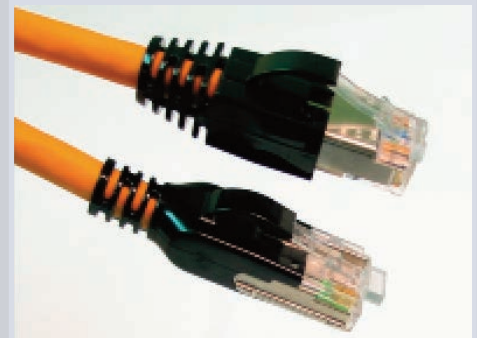
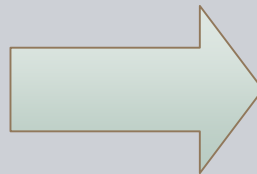
Recycled Copper



Fish Cage



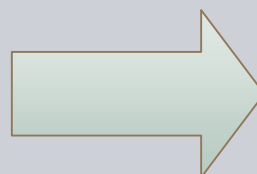
Precision Rolled Copper Alloy



Connectors



Extruded Copper



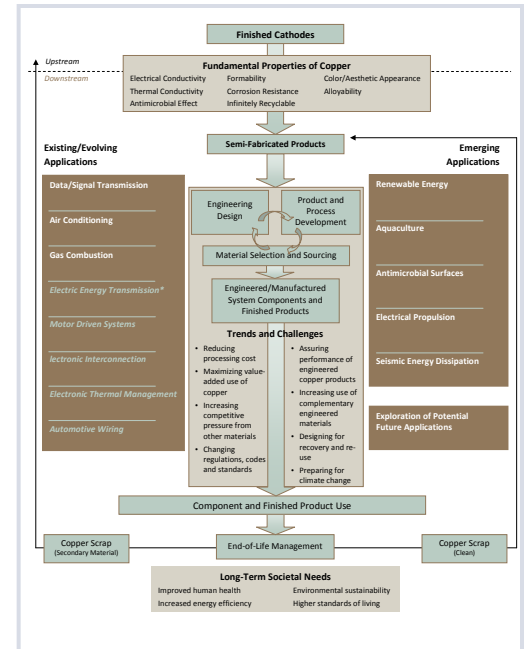
Air Conditioning Tubes

Roadmap Priorities

This Roadmap guides collaborative, pre-competitive R&D programs that benefit the copper industry and society. Industry favors this collaborative and pre-competitive approach because costs are distributed among the parties that expect to gain benefits, and a range of expertise is available to project teams. The ICA seeks high-quality R&D proposals for all priority opportunity areas.

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 address technical issues that, if resolved, should result in a significant positive impact on copper utilization, and the results of R&D efforts should show innovation or substantial improvement in the respective technology or market sector.
- Priority activities should have a high probability of commercial implementation due to the involvement of a range of industry participants, research organizations and co-funding organizations.
- Priority activities should enhance the positive environmental and societal image of copper. Copper is essential to health, its use promotes energy efficiency, and its recyclability is nearly unsurpassed among all engineering materials.



Classification of Prioritized Opportunities

Prioritized opportunities described in this Roadmap are grouped into two broad classifications: Existing/Evolving Applications and Emerging Applications.

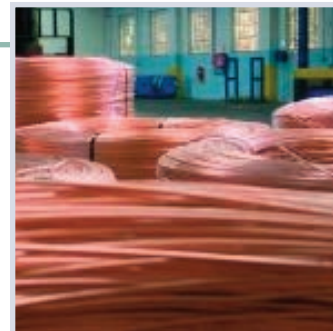
Existing/Evolving Applications maintain or increase current large-scale uses of copper. Typically cost pressure, inter-material competition and design constraints (e.g., miniaturization) influence copper use in these applications. The objective is to apply copper's technical properties more effectively to maintain copper's position as the material of choice.

Emerging Applications open entirely new markets for copper, thereby broadening and increasing its use. The focus is on the creative application of copper properties to solve new technology problems. The exploitation of copper's antimicrobial efficacy for touch surfaces and the commercialization of copper-based energy dissipation devices is an example of this category.

Existing/Evolving Opportunities

Data/Signal Transmission

More than 80 percent of signal-carrying equipment interconnections in data centers use copper cables and connectors. However, industrial, commercial and consumer computing installations continually demand higher bandwidth capacity. In most data communication cases, typically densely spaced short-reach links, copper competes successfully against optical fiber. For runs less than 100 m long (over 99 percent of connections in data centers and local-area-networks [LANs] horizontal links are less than 100 m), 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 are under development and have been demonstrated.



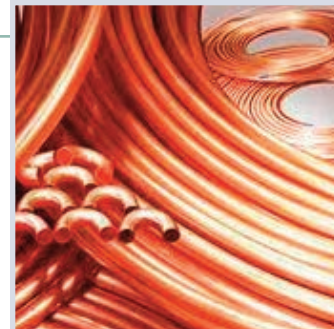
Replacing copper with fiber requires additional optical/electrical coupling devices, reducing both cost and complexity. However, the cost of fiber-based installations continues to decrease, and this market reality demands ongoing development of higher speed, copper-based cabling systems in order for the metal to remain competitive. In addition to providing adequate bandwidth, new copper-based cables should reduce power consumption and be simpler and more robust than existing systems with regard to user-friendly installation and connectivity.

Key features of copper include the ability to deliver power and data simultaneously and the ability to provide a reliable source of power that enables network devices such as Internet-protocol phones, wireless access points, security cameras, portable device network ports, and even low-power computers to operate where conventional power sources such as cords or AC outlets are not practical.

Trends, Issues and Drivers	<ul style="list-style-type: none">• Continued increases in connections speeds: 10 Gbps (10 billion bits per second) is now replacing 1 Gbps in data centers—100 Gbps will dominate after 2020; 1 Tbps is already being discussed• Optical fiber suppliers also continue to promote high-speed data connection solutions but with decreasing cost reductions• Copper cables will continue to be competitive as they continue to match fiber in speed albeit over short (<=100m) distances• Data center power consumption is becoming a limit on growth
Opportunities and Recommended Pursuits	
High-Speed Copper Interfaces	<ul style="list-style-type: none">• Develop technology to maximize data speed over the industry-standard 100 m distance with copper data cables and low-noise connectors• Support development of industry standards for copper interfaces and promote development of networking gear that includes copper interfaces
Power to Remote Network Devices	<ul style="list-style-type: none">• Support the development of industry standards incorporating ability to deliver 30W or more over standard copper data cables• Expand availability of networked products that take advantage of available power over data cables
Reduced Power Consumption	<ul style="list-style-type: none">• Develop low-power signaling techniques that take advantage of improved copper cables to reduce data center/network power consumption

Air Conditioning Systems

Smaller diameter copper tube (≤ 5 mm diameter) and flat tube technologies offer significant advantages, including reduced size, reduced refrigerant charge, lower cost, and higher energy efficiencies. 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.

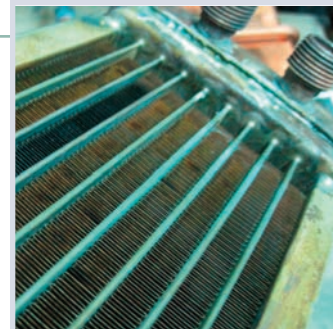


Currently, R410A and other hydro-fluorocarbons are the refrigerants of choice in appliance heat exchange applications. Systems using R410A refrigerant run at a pressure approximately 60 percent higher than similar systems using R22. This presents both design implications and opportunities. In the intermediate term, new hydrofluoroolefin (HFO) refrigerants are prime candidates to replace R410a and R134, and in the long term, carbon dioxide and water may become preferred alternatives. Growing interest in hydrocarbon refrigerants, such as butane and propane for selected applications, means copper must continue using environmentally friendly refrigerants. In addition, other technologies, such as magnetocaloric refrigeration, may influence the copper intensity in these systems in the future.

Trends, Issues and Drivers	<ul style="list-style-type: none"> • Increasing demand for more efficient, compact air conditioning systems • Intensifying inter-material competition • Reducing manufacturing cost • Reducing ozone depletion and global warming potential by making changes to refrigerants
Opportunities and Recommended Pursuits	
Next Generation Environment-Friendly Working Fluids	<ul style="list-style-type: none"> • Optimize small diameter MicroGroove™ copper heat exchanger designs for next generation of low global warming potential working fluids and possible future refrigerants • Develop tube configurations with integral gas to liquid heat transfer (e.g., for CO₂ working fluid/water refrigerant) split systems
Manufacturing processes	<ul style="list-style-type: none"> • Scale-up manufacturing processes for fabricating flat and round multi-channel tubes and heat exchangers (evaporators and condensers) for use in cooling only and heat pump units • Develop low-temperature brazing process using inexpensive braze materials for assembly of all-copper heat exchangers in high-volume production
Energy Efficiency	<ul style="list-style-type: none"> • Develop super-thin evaporators and fan coil unity to reduce room space package and parasitic fan losses for domestic heating, ventilation, and air conditioning systems (HVAC) and refrigeration applications • Develop higher-performance copper heat-transfer fins in thin material gauges • Explore the use of solar thermal, engine and waste industrial heat for air conditioning systems • Develop and optimize new concepts for copper-intensive air-conditioning systems (Ref: ARPA-E BEETIT http://arpa-e.energy.gov/ProgramsProjects/BEETIT.aspx): 1) cooling systems that use refrigerants with low global- warming potential; 2) energy-efficient air conditioning (AC) systems with an increased coefficient of performance (COP) for warm and humid climates; and 3) vapor-compression AC systems for recirculating air loads with an increased COP in hot climates

Gas Combustion Equipment

A large, global market exists for heat exchangers that transfer heat from the combustion products of gaseous fuels to water in the range of about 3 to 300 kilowatts thermal (kWth). Such units have widespread residential and commercial use in a variety of water heating and heating boiler appliance applications. Total annual production of these appliances is estimated to be about 20+ million units, with millions of these units produced in China alone.



Prior work sponsored by the ICA has shown that copper can be protected in the corrosive, condensing acid and water environment found in the high-efficiency, gas-fired heat exchangers used in water heaters and heating boilers. Coating technologies for copper have been demonstrated in China for one particular application, and at least two manufacturers serve a growing Chinese market. Durable coatings or other surface treatments preserve the intrinsic advantages of copper in the design and manufacture of compact heat exchangers across the high-efficiency water heater and boiler industry.

The evolving opportunity is:

- To supplant the use of heat exchangers made from other materials with those formed with corrosion protected copper, and
- To develop an integrated burner and copper heat exchanger product with a fully modulated burner technology suitable for wide market application.

Over time, high-efficiency fired water heaters and heating boilers will dominate the market and require corrosion-resistant materials. Fuel economics and governmental energy efficiency mandates will drive this change.

Trends, Issues and Drivers	<ul style="list-style-type: none">• Increasing demand and regulations for more efficient, compact heat transfer systems and environmentally friendly coatings• Increasing inter-material competition• Resistance to extremely corrosive acids• Reducing manufacturing cost• Rising availability of natural gas production techniques• Increasing use of natural gas due to low global-warming impact
Opportunities and Recommended Pursuits	
More Efficient Heat Exchange and Combustion Systems	<ul style="list-style-type: none">• Develop advanced protective coatings to permit copper use in condensing applications where combustion products can create condensate containing a dilute mixture of carbonic, sulfuric and nitric acids, together with variable proportions of hydrochloric and hydrofluoric acids• Explore and develop a variety of design concepts that:<ul style="list-style-type: none">- Lowers heat exchanger cost- Achieves high reliability during prolonged operation- Allows for a reliable and consistent coating- Reduces scale and deposits build-up inside tubes- Are not prone to boiling- Have low water and airside pressure drop• Develop integrated high and low-temperature heat exchanger for boilers• Develop integrated package of a fully modulated burner and heat exchange module for application by OEMs

Emerging Opportunities

Renewable Energy

Copper plays important roles in clean energy systems, particularly in generators, transformers, power electronics, switchgear, cabling, grounding, controls, and protective devices utilized in wind, tidal, biofuel, wave, geothermal, and solar thermal plants. Solar photovoltaic systems need copper for component interconnections, current transport, grounding, and a variety of system components. Ocean-based electrical-energy-generating systems can benefit from copper alloys' resistance to biofouling and corrosion and require sub-sea electrical cables to bring the energy to shore. Copper in solar thermal energy systems can be applied for electricity generation and in heat exchangers for water desalination



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

Trends, Issues and Drivers	<ul style="list-style-type: none">• Growing national interests in improving energy security/reliability• Avoiding the market volatility and supply challenges related to fossil fuels• Clean energy for environmental protection and climate change mitigation• Energy access for the world's poor through decentralized energy generation
Opportunities and Recommended Pursuits	<ul style="list-style-type: none">• Explore copper use in advanced large-scale or distributed systems for:<ul style="list-style-type: none">- Concentrated solar power- Wind power generation- Ocean wave and current power- Solar photovoltaic power- Waste heat recovery- Water desalination- Geothermal or ground-coupled systems• Develop compact copper-enhanced phase-change thermal energy storage devices• Explore use of copper to enhance heat flux in geothermal grouting and concrete thermal storage systems• Develop method to print copper current collectors on silicon photovoltaic cells• Apply copper alloy materials to ocean energy systems for corrosion and biofouling resistance and develop copper alloy mesh to protect marine life from moving systems• Develop desalination systems powered by renewable energy• Research low-cost, copper-based solar photovoltaic approaches• Develop and promote renewable energy systems for off-grid rural electrification in developing economies• Explore copper-based solutions for cooking in developing countries• Inform government and industry research organizations about advances in copper materials and processing techniques applicable to renewable energy systems

Aquaculture

Fish farming is a multi-billion dollar global industry. Depletion of wild fish stocks and the growing demand for farmed fish has increased nearshore aquaculture and expansion into the offshore environment. Concerns exist over fouling of fish nets by marine organisms, the spread of infectious disease, predator attack and possible threats to human health from the antibiotics fed to farmed fish. The combination of copper alloys' antifouling and antibacterial properties, as well as its 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 maintaining a healthy environment. In addition, copper may mitigate the spread of infectious diseases by preventing formation of a fouling environment (i.e., algal films, various brachiopods) that facilitates the spread of parasites and pathogens, thus reducing or eliminating the need for antibiotics. The mechanical strength and resilience of a copper alloy structure will also prevent 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.



In the 1960s - 1980s the copper industry developed various copper-based cages for aquaculture. These cages were rigid and not easily scalable to large volume production. Recent development activities in copper alloys and cage design include woven and welded wire nets and sheet-based expanded metal meshes with service lives extending beyond four years. Copper-alloy nets have enabled a 10 – 15 percent faster fish growth rate, a 50 percent reduction in fish mortality due to improved fish health, more efficient use of feed and an increased profit for farm owners.

Trends, Issues and Drivers	<ul style="list-style-type: none"> • Global expansion of aquaculture • Need for a reduction in fish loss due to parasites, predators, infection and handling • Movement away from protected coastal areas to areas exposed to more energetic sea conditions • Consumer demand for a reduction in antibiotic use • Expansion of offshore submersible cages
Opportunities and Recommended Pursuits	
Fish Pen Development	<ul style="list-style-type: none"> • Design cages and floatation systems for nearshore and offshore exposed conditions • Investigate submerged systems and floating structures that submerge as needed • Reduce cage weight while significantly extending useful life • Develop low cost cages to improve small scale aquaculture • Investigate the use of flexible connections between semi-rigid panels • Develop nursery nets using copper materials
Alloy and Mesh Development	<ul style="list-style-type: none"> • Develop alloys with improved resistance to mechanical wear • Investigate mesh forms and alloys appropriate for predator exclusion • Develop/investigate alloys that can avoid attachment of marine organisms with optimum copper ion release • Establish a supply chain for copper alloy mesh materials
Fish Health	<ul style="list-style-type: none"> • Perform research activities related to understanding the effects of copper-alloy mesh on fish stress, parasites, pathogens, mortality rate, growth rate and food conversion rate, as well as safe levels of copper release to the nearby marine environment

Antimicrobial Surfaces

More than 50 percent of the world's populations live in cities; therefore, the spread of infection-causing bacteria in hospitals and public buildings continues to be a public health concern. Antimicrobial Copper is the only touch surface material registered by the U.S. Environmental Protection Agency (EPA) to continuously kill more than 99.9 percent of the bacteria that cause healthcare-associated infections within two hours of contact.



Lab tests sponsored by the ICA in support of the EPA registration prove that copper is the most effective touch surface. Clinical trials are underway to determine the effect on the bioburden in an actual use environment and to demonstrate that copper surfaces break the chain of infectious disease transmission. Three primary characteristics make copper (in combination with regular cleaning) effective:

Continuously kills bacteria

- Proven to be far more effective than stainless steel or silver-containing coatings
- Proven to continuously kill the bacteria that cause infections
- Never wears out

Continuous and ongoing antimicrobial action

- Lack of degradation even after repeated wet and dry abrasion and re-contamination
- Natural tarnishing does not impair efficacy
- Safe to use

Not harmful to people or the environment

- Inherently antimicrobial, no chemicals added
- Completely recyclable

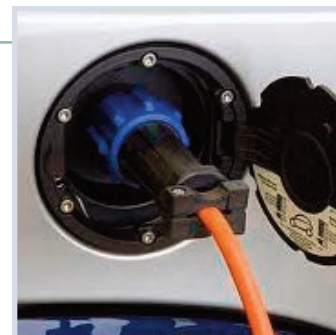
The installation of copper alloy “touch surfaces” in hospitals, schools, public-transportation systems and public buildings should reduce disease transmission while at the same time generating a significant new market for copper and its alloys.

In a related application, copper inhibits the growth of fungi in air-handling systems, thereby improving air quality and promoting system efficiency. Laboratory testing shows the odor-causing mold and mildew will not grow on copper materials. After 24 hours of exposure to copper surfaces, total die off was observed in several common mold species. Clinical testing is underway to support these findings.

Trends, Issues and Drivers	<ul style="list-style-type: none">• 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	<ul style="list-style-type: none">• Scientific studies to explore the reduction in disease transmission enabled by antimicrobial copper in various high-risk settings• Technical research to expand range of micro-organisms on which antimicrobial copper is known to be effective• Develop antimicrobial copper products for high-touch surfaces in various high-risk settings• Ultimately, develop “stainless” copper and copper-alloy products with permanent antimicrobial properties• Provide technology transfer to potential manufacturers of copper-based antimicrobial materials• Present findings at scientific meetings and publish findings in peer-reviewed journals• 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

Electrical Propulsion

Electrical propulsion systems incorporate copper in batteries, electrical control, recharging plugs and leads, motors and thermal management. The rail, marine, heavy construction, and automotive sectors comprise important markets employing electrical propulsion technology. The priority area for R&D is automotive electrical propulsion where 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 batteries, as well as the infrastructure to support recharging of electrical vehicles.



Vehicle designers seek smaller, less costly, more efficient motors. The typical fill rate (i.e., volume density) of copper windings in the stators of electrical machines is around 50 – 60 percent. A fill rate in excess of 80 percent speeds the transition of automotive power transmission systems toward new copper-intensive components and reduces 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.

One U.S. manufacturer 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, potentially expanding the use of CMR technology and producing an important gain in copper use. This approach avoids using rare earth materials that are in short supply. (See Appendix A.)

Trends, Issues and Drivers	<ul style="list-style-type: none">• Push for environmental protection and climate change mitigation• Growing consumer acceptance of electrical vehicles, growing interest in plug-in electric vehicles and hybrid electric vehicles• Steady improvements in battery technology• Concern about availability of rare earth elements for permanent magnet electrical machines
Opportunities and Recommended Pursuits	<ul style="list-style-type: none">• Increase fill rate of copper in motor stator lamination slots to exceed 80 percent• Reduce costs to produce die cast copper motor rotors• Optimize high production volume propulsion systems incorporating copper motor rotors• Explore copper's role in advanced battery concepts, including thermal management• Explore needs of climate control systems in electrical vehicles• Explore the need for copper components in charging infrastructure• Expand visibility of copper industry to automotive OEMs and suppliers

Seismic Energy Dissipation

Maintaining the structural soundness of buildings in earthquake zones remains a challenging yet critical task as more than 50 percent of the global population resides in cities. Some buildings utilize seismic dampers constructed from steel and cement; however, these dampers lack elasticity and will not return to their original position following a seismic event. Earthquake damage to buildings, their contents and their occupants can be controlled through the use of copper-based devices that isolate structures from ground motions or absorb energy to limit building motions. Two different copper-based systems present a new range of possibilities for energy dissipation devices (EDDs).



EDDs fabricated from superelastic copper alloys, such as a copper aluminum manganese (80 percent copper), offer 8 – 10 percent elongation. This highly effective alloy also promises a cost savings versus competitive titanium-alloy materials. Annealed copper deforms plastically due to cyclical vibrations yet maintains high ductility; it is being considered as an ideal material for EDD components.

Design tests by structural engineers will facilitate the placement of EDDs into seismic structure models. Potential applications for copper-based EDDs include flexible and critical structures such as large office buildings, hospitals, bridges, port structures and mining facilities.

Trends, Issues and Drivers	<ul style="list-style-type: none">• Protect buildings and occupants in earthquake zones• Prevent building collapse and deformation• Avoid catastrophic collapse of vital infrastructure• Develop cost-effective building materials
Opportunities and Recommended Pursuits	<ul style="list-style-type: none">• Develop mass production process for superelastic Cu-Al-Mn-based alloy slab and rod including heat treatment process to achieve large grain size• Increase rod diameter beyond 15 mm• Develop a more detailed understanding of the superelastic Cu-Al-Mn-based alloy under typical seismic loads• Develop a more detailed understanding of the behavior of annealed copper under typical seismic loads• Design and test new EDD designs, characterize their behavior and provide structural engineers with engineering parameters so they can incorporate them into their seismic models• Pursue placement of copper-based EDDs in as large office buildings, hospitals, bridges, port structures, and mining facilities• Explore potential applications of copper in seismic isolation in addition to energy dissipation• Explore use of superelastic copper in dynamic counteracting devices, e.g., returning bridge spans to center of support columns to avoid catastrophic collapse

Potential Future Applications

In addition to the priority opportunity areas presented in this document, the copper industry seeks research ideas that promise new copper applications. 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 with proposals that identify the breakthroughs required and describe a credible technical approach to successful realization.



A successful copper technology proposal will:

- **Require R&D effort to achieve a technical breakthrough** enabling potential global application.
- **Create a new market application** or defend an existing copper application from alternative materials or technologies.
- **Provide a clear path to commercialization.** For example, the ICA has funded the development of a copper sorbent material with the University of Michigan that is moving toward commercialization with an international leader in the oil and gas industry.
- **Apply copper's superior attributes.** Copper is essential to health, its use promotes energy efficiency, and its recyclability is nearly unsurpassed among all engineering materials.
- **Lead to use of at least 10,000 metric tons of copper annually** within five years of initiation. Proposals with smaller tonnage impact but large societal benefit are also preferred. Technology with a longer timeline to market requires stronger market impact and a clearer path to commercialization.
- **Provide material data on existing alloys for new emerging applications.**

Trends, Issues and Drivers	<ul style="list-style-type: none"> • 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 • Surface chemistry-oriented applications for use in the energy industry
Possible Areas for Exploration	<ul style="list-style-type: none"> • Printed electronics using copper “inks” that are compatible with silicon and polymer surfaces • Improving the electrical conductivity of copper by >130 percent while maintaining the ability to process into wires to create room temperature “ultraconducting” wire • Copper materials as a catalyst or as a substrate for other catalysts for: <ul style="list-style-type: none"> – Hydrogen production – Oxygen transport – Carbon dioxide capture – Capture of acid gases – Copper composite materials containing various forms of fiber or particles to achieve unusual or enhanced properties • Nano-engineered copper-containing structures • LED lighting • Fundamentally new forms for heat-exchange surfaces and structures
Recommended Pursuits	<ul style="list-style-type: none"> • Research and develop advanced materials based on copper through government/industry/academic scientific research initiatives in a number of countries

Implementation

The *Copper Applications Technology Roadmap* continues to evolve as the 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 customers. 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 and refine this Roadmap, the industry has taken steps toward important business technology transformations.

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 continued idea development regarding copper application opportunities and required R&D.
- **Roadmap Implementation Forums** will provide focused venues for brainstorming about specific opportunity areas and will disseminate findings among the networks created.
- **Roadmap Oversight and Project Coordination** involves managing interactions among the diverse organizations participating in the use of the Roadmap. The ICA has historically taken a coordinating role in the development and implementation of major copper applications R&D, and the ICA will continue in this role. The ICA will also spearhead efforts to secure co-funding from third parties, including governments, nongovernment organizations and appropriate industry organizations.

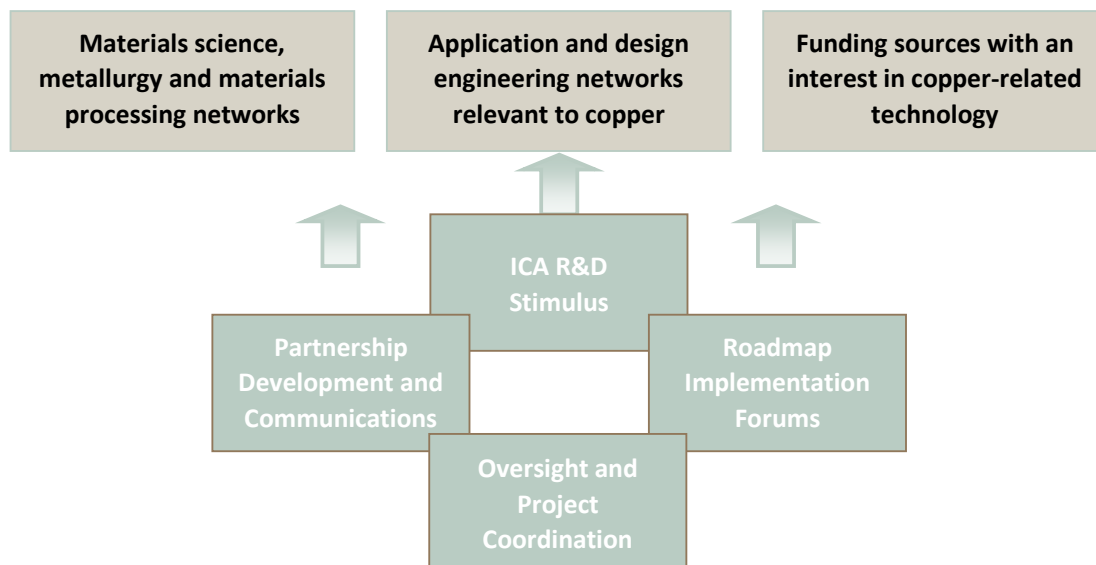
Figure 1 outlines the main implementation steps. These steps are designed to catalyze dialog about copper, and subsequently launch and manage scientific research on copper application-development projects. Strong leadership and persistence ensures that important opportunities do not fall through the cracks. In addition, achieving early success helps maintain the momentum generated by the Roadmap and convince companies that the technology collaboration model can work.

Partnership Development and Communications

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 copper-related markets ensures that their needs are met and anticipated. Information and cost-sharing minimizes the duplication of technology development efforts and maximizes resources to efficiently achieve effective solutions. The roles of companies and organizations in implementing this Roadmap have not been determined. These roles will take shape as specific activities are designed and implemented.

Ongoing communications is important to keep industry groups across the globe informed and up-to-date regarding effective strategies and technologies to enhance the value of products. 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 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 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 organize activities that bring together the range of expertise necessary to think creatively about potential responses. This effort 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 opportunities. This affords companies and organizations the flexibility to pursue projects that correspond with their unique interests. However, the lack of a unified structure makes it challenging to adequately identify, organize, fund and track the diverse activities and their corresponding benefits. In accordance with its mission, the ICA will fulfill this role by providing the required oversight and coordination 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.

Moving Forward

The revised Roadmap provides the copper industry with an updated set of copper application-development paths. 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 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 a life-connecting, environmentally friendly, advanced technical material.

Appendix A—The Evolution of the Die Cast Copper Motor Rotor

The copper industry has been investing in the potential of die cast copper motor rotors for 15 years. As in many research and development activities, the technical focus shifted over time and application opportunities changed. Solving the initial technical challenge was only the beginning; launching this new technology has required persistent effort and the right market conditions.

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. Industrial motors consume about 40 percent of global electricity production, so any improvement in efficiency is significant. Industry responded to this legislation with more efficient motors using an increased amount of copper in the stator windings, thereby reducing resistive, or I^2R , losses.

As this project was initiated in the mid-1990s following decades of incremental improvements in induction motor efficiency, few technical opportunities remained to reach significantly higher efficiencies at a reasonable cost. The die cast copper rotor appeared to be the best approach. Copper in the rotor reduced resistive losses in the motor on the order of 40 percent and had the potential to reduce overall losses by 10 - 20 percent, compared with conventional aluminum rotor motors. It was subsequently shown that motors with copper rotors can be made smaller and lighter and can operate at lower temperatures to decrease maintenance requirements. 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 fabricated in commercially available pressure die casting equipment.

Pursuing the Opportunity

In 1996, recognizing that a copper rotor was a sound design platform for increasing the efficiency of industrial induction motors, 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 challenges of reducing processing cost and assuring adequate copper rotor performance. During the high-pressure die casting process, conventional die steels are susceptible to surface cracking (heat checking) due to thermal stress and strain in the die as temperatures cycle from a few hundred degrees to the melting point of copper (about 1085°C, 1984°F). Die casting life decreases drastically when casting copper compared to aluminum, which melts at 660°C and, therefore, induces significantly lower thermal stress and strain in the die. It was also recognized that the design of the rotor and motor should be changed to apply copper more effectively



SEW Eurodrive with Traditional Aluminum Rotor (Left); with a Copper Rotor (Right)

Solutions

The CDA-led team of industry and academic researchers determined that die cracking could be reduced and die life extended with two changes: replacing critical portions of the steel die with a ductile, heat-resistant, nickel-base super alloy and pre-heating the die to approximately 600°C (1,100°F). These actions rendered the copper die casting process economically viable. Motor design was also investigated. Starting torque is reduced in a high-conductivity rotor conductor, so the shape of the rotor bars, or rotor slots, was modified to further improve the motor's operating characteristics. This was done to incorporate a starting bar to take advantage of copper's high conductivity, allowing the rotor designer to use the "skin effect"—the tendency of alternating current flow to crowd toward the external conductor surfaces. At a given efficiency, a copper rotor uses less lamination steel in the rotor and stator stacks to save material costs, possibly reducing the overall size of the motor.

The Opportunity in Standard Industrial Motors

By spring 2006 one major international motor manufacturer, Siemens, had embraced the new die cast copper rotor technology and brought to market a line of super-efficient industrial motors. Within a year, the motors found widespread commercial acceptance in the U.S. The motors were up to two percentage points more efficient than those meeting NEMA Premium™ standards and offered substantially lower life-cycle costs. While the initial cost of purchasing a copper motor rotor may be higher than an alternative solution, the life-cycle cost for a less efficient motor far exceeds the cost of a copper motor rotor. The initial cost represents only 2 percent of the total cost of ownership. Energy costs, maintenance and other variables make up the other 98 percent of the cost over the lifetime of the motor.

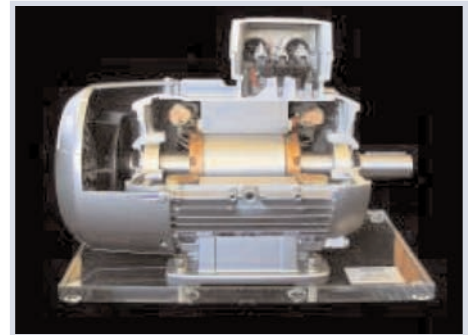
The Opportunity in Integral Motors

Several manufacturers of electromechanical system components recognized the value of using a copper motor rotor. They believed the overall size of the motor could be reduced to exactly match the requirements of their equipment. Rather than continue to exclusively use aluminum rotor motors, a leading manufacturer of motor-driven gear-drive systems, SEW Eurodrive, decided to reduce the product variations in their product line and use integral motors with die cast copper rotors in about a third of their product line. This allowed retrofitting existing drives with high-efficiency motors that would fit in the same package. This large scale commercial application signaled that the challenge facing die casting copper rotors had been overcome. Other manufacturers followed. Applications for integral motors include compact, lightweight electro hydraulic systems for aircraft, refrigeration compressors and traction motors.

The Opportunity in Automotive Propulsion

As global interest in electric vehicles increased, automotive engineers recognized that they required special motor designs to meet complex technical, cost and volume production requirements. Interest in using motors with die cast copper rotors increased due to concerns about the availability of rare earth materials such as neodymium and magnet performance at elevated temperatures. Technical studies showed that induction motors could have similar compact, high-power density and higher system efficiency in a parallel hybrid-drive system, generating interest in using die cast copper rotors. With funding from the U.S. government, Baldor Reliance demonstrated a hybrid military vehicle using four fluid-cooled, very high-energy density traction motors with die cast copper rotors.

In the parallel hybrid traction application, the copper motor rotor offered substantial advantages:



Siemens Super-premium Motor with Die Cast Copper Rotor



Hybrid Military Vehicle



Horizontal CMR Press

- The ability to redistribute losses to the stator for more effective cooling due to reduced size and weight
- The ability to be de-excited when not producing torque, thereby eliminating no-load rotational and magnetic losses
- The meeting of efficiency requirements across a broader range of loads and speeds
- Better mechanical properties and ruggedness than aluminum-rotor or fabricated copper rotor motors
- Use of readily available copper and steel

Around the same time, Tesla Motors launched their plug-in electric vehicle with a power train that included a motor with a 32.5 cm diameter copper rotor with a maximum operational speed of 13,500 RPM, a power inverter and lithium ion battery packs. (The large amount of copper in the inverter, cables, batteries and motor reduces electrical losses and avoids heating under high-amperage conditions). More automakers are investigating power trains using induction motors for a variety of vehicles with die cast copper rotors. Millions of cars with copper motor rotors at their core will signal success for copper and a substantial contribution to sustainable transportation.

Continuing Research, Development and Commercialization

The ICA has helped to develop and transfer copper motor rotor die casting technology to manufacturing companies across the world. The capacity to produce die cast rotors for automotive propulsion exists in Germany, France, Japan, Korea, India, Taiwan, China and the U.S.

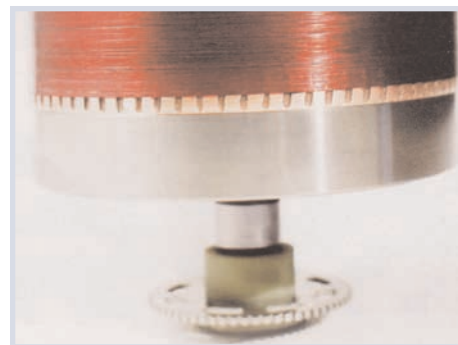
Research into the vertical die casting process continues at the Non-Ferrous Technology Development Centre (NFTDC) in Hyderabad, India. This work is supported by ICA with co-funding from the U.N. Common Fund for Commodities and the Global Environment Fund (GEF). The technical team at NFTDC has developed sophisticated, cost-effective methods for die casting copper rotors and is now licensing this technology to industry for application in industrial motors and vehicle powertrains.

Beginning in 2006, with the support of the ICA, Yunnan Copper Group and Nanyang Explosion Protection Group established a joint venture company, Yunnan Copper Die Casting Co. Ltd (YCD), to commercialize copper rotor motors in China. In the last five years, based on hundreds experiments and tests, a sophisticated and mature technology base on horizontal press was developed and is already licensed to industry. YCD has produced more than 100 different types of rotors for 18 OEMs.

The ICA has supported the Chinese government in developing two national standards for super-efficiency motors including copper rotors. These are the world's first national standards for industrial motors with copper rotors.

Collaborative Technological Projects

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



Copper Motor Rotor in Tesla Motor's Powertrain



Technology Development at NFTDC



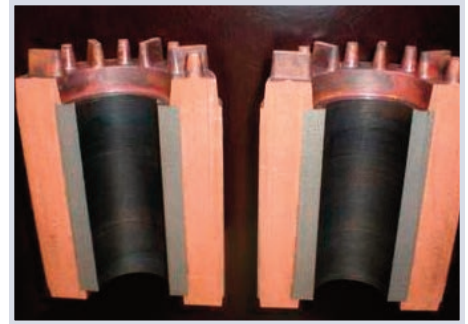
Rotors Die Cast at NFTDC with Vertical Press

Facts

- Direct ICA funding 1996 - 2010: \$2.1 million
- Co-funding from industry and governments: >\$10 million
- Die cast copper motor rotors produced: >500,000

Key Business/Technology Learning

- Die casting of copper motor rotors is entirely feasible and commercially viable on horizontal and vertical die casting machines.
- Motor designs and rotor design must be optimized to use die cast copper rotors effectively. Substituting a copper rotor for an aluminum rotor does not achieve maximum benefits.
- The initial focus on high-efficiency, standard industrial motors, which was reasonable in 1996, is still attractive and economically viable. Further improvements in required energy efficiencies and Minimum Energy Performance Standards will assist in further penetration of die cast copper rotors due to the fact that other material/design improvements have already been incorporated. The U.S. Department of Energy and regulators in other countries are now studying raising the minimum efficiency standard for industrial motors to a “super super premium” range. An announcement of this U.S. standard is expected in 2012 for adoption in 2015.
- Custom motor designs can benefit from the reduced material use, compact size and lighter weight enabled by a die cast copper motor rotor. The die cast copper motor rotor appears to be well suited to the needs of automotive propulsion systems, which was not a focus of the initial technology development effort.
- Motor-driven systems using die cast copper motor rotors in industrial induction motors is no longer a research priority in the *Copper Applications Technology Roadmap*. This is because attention has shifted from research to application engineering and large-scale commercialization. The challenge of applying die cast rotor motor technology to automotive propulsion systems remains a focus area.



Cross-section through Rotor Bars and End Ring of Die Cast Copper Motor Rotor



Cross-section through Rotor Bars of Die Cast Copper Motor Rotor



YCD Die Cast Copper Motor Rotors

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 percent 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. Gas- or electric-derived water heating is one of the largest energy expenditures for any building or home. Copper may significantly reduce energy costs.
- **Antimicrobial Effect**—Concerns over hospital-acquired infections and those originating in the food-processing industry continue to grow. The bactericidal, fungicidal and, to some extent, virus-cidal properties of copper, copper compounds, and copper alloys have been known for centuries. Copper, in the form of copper or copper-alloy surfaces, is a significant deterrent to the transmission of fungal and bacterial disease in healthcare and air-handling systems.
- **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 lead frames. Hot- and cold-forged copper products are demanded by companies requiring reliability and ease of machinability. A number of cast copper alloys provide corrosion resistance as well as good thermal or electrical conductivity.
- **Corrosion Resistance**—Copper metals can resist attack under a wide range of corrosive environments, which makes them 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 attractive patina that retains its functionality for centuries.
- **Repeated recyclability**—Copper has the longest recycling history of any material. It is estimated that 80 percent of all copper ever mined during the past 10,000 years is still in use somewhere today. Recycling copper does not result in any reduction in quality or loss of properties and can be repeated as often as required. Recycling saves natural resources, reduces energy consumption and avoids the loss of valuable materials.
- **Color/Aesthetic Appearance**—Copper is increasingly utilized for its aesthetically pleasing appearance and the broad palette 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**—Copper's industrial importance has grown due to the ease with which it alloys with other metals. The result is an extensive family of more than 400 alloys in use today. This endeavor is far from being exhausted.
- **Abundant and Available**—Copper is an integral part of human life and civilization. Copper's fundamental properties have met society's needs throughout history. Copper is routinely processed by common manufacturing methods and is available in many forms and alloys that enable efficient production.

Appendix C—Trends and Challenges Influencing Copper Use

Market trends, regulations and innovations continue to influence copper use. While it is impossible to predict the future, insight into possible development pathways and priorities can be gained by considering the common economic, social and technological forces that influence the global copper industries. For information on the end-use markets of copper, see Appendix E.

- **Reducing processing cost**—To remain competitive, fabricators must continue to reduce their cost of manufacturing while maintaining high quality. Copper is routinely processed by common manufacturing methods and is available in many forms and alloys that enable efficient production. Copper adapts to net-shape processing techniques, and some copper products can be semi-fabricated using the “upstream” electrowinning step in copper cathode production.

Copper’s ability to be manufactured as formed 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 utilized 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 percent in product cost.

- **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 that combine mechanical strength and conductivity. The same concept applies to aquaculture applications where high mechanical strength is needed in combination with resistance to corrosion and biofouling.

Copper’s ability to perform well even when used in reduced thicknesses and weight is a characteristic that presents added value. For example, in copper tubes used for drinking 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 the amount of copper needed and, therefore, reduces product cost. In automotive applications, copper’s formability and high conductivity helps reduce the size of circuits, connectors and wiring harnesses.

- **Increasing competitive pressure from other materials**—Many of copper’s traditional markets have been challenged by metals, composites, polymers, multi-layer systems, and other alternative materials. Copper offers potential systemic improvements and/or economies unachievable with other materials. The designer’s challenge is to make the most efficient use of all materials, including copper. While copper costs may initially appear prohibitive, it is often the best suited material for a specific application and the most cost-effective material in the long term. Copper, with its unique features, must offer system improvements unachievable with other materials, thus diminishing the effect of cost sensitivity in the purchasing decision. However, end users of any input material, including copper, face constant competitive pressure to improve performance, reduce cost and demonstrate responsible stewardship. This leads end users to intensify materials competition, minimize material usage and focus on high-value applications, driving the need for innovation in copper applications.
- **Changing regulations, codes, and standards**—Energy efficiency and sustainability issues remain at the forefront of business and government policy agendas. Copper is increasingly perceived as energy-efficient and infinitely recyclable.

Higher motor efficiency standards have been instituted, and the market for high, premium and super-premium efficiency motors has increased. Motors utilize more than 20 percent more copper in stator windings and conductor bars, compared with older, “standard-efficiency” motors. Efficiency increases are also important in air conditioning, electrical grids and lighting.

Other regulations impacting the copper industry involve soils, waters, wastes and sediments. These regulations are prompting governments to support scientific investigations to understand any environmental effects of copper use.

- **Assuring performance of engineered copper products**—Computer simulation is increasingly applied to predicting and validating 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, the 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 high certainty. Improving the control of thermal, electrical, physical and mechanical properties will also enhance copper's performance in advanced applications.

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**—Materials that can change copper's performance can be added to the surface or embedded within copper. Copper is frequently combined with other engineering materials, and the properties of the resulting materials system are tailored to a specific application's needs. Complimentary materials applied to the copper surfaces can provide thinner layers of electrical insulation, protection against rough handling, protection against corrosion, 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.
- **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 because it is 100 percent recyclable without any loss in performance. Recycling meets 34 percent of the global copper demand. When total life-cycle costs are analyzed, superior energy efficiency and end-of-life recyclability make copper an attractive alternative in energy-related applications. 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, some copper becomes waste, and this excess material needs to be recovered and recycled. Uncontaminated material facilitates reuse.

Appendix D—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 utilized in electrical and data transmission, copper helped usher in the telecommunications era. The telephone serves as an excellent example of how copper accelerated development and commercialization. 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 signal loss. Telecommunications favored copper due to its strong, uniform, high-conductivity wire.

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 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. The unique combination of strength and formability make copper and its alloys ideal for use in applications where repetitive actions stress the components, such as fasteners, electrical connectors, springs and electrical switches.

Long-Term Societal Needs

A large portion of the world's population does not 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. At the same time, actions must be taken to foster greater integration between technological innovation and broader social, economic and environmental concerns.

- **Improved Human Health**—Copper is required for the normal functioning of plants, animals, humans, and microorganisms. It is incorporated into a variety of proteins that perform specific metabolic functions. Because it is an essential metal, daily dietary requirements have been recommended by a number of agencies around the world. Copper can control the growth of organisms, making it an effective anti-pathogen, anti-plaque agent in mouthwashes and toothpastes. In addition, touch surfaces made from copper aid in disease prevention by controlling the growth of infectious bacteria.
- **Increased Energy Efficiency**—Wasted energy raises costs for consumers and can have negative environmental impacts. Improvements in electrical energy efficiency help secure 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, reduces costs and mitigates emissions.
- **Environmental Sustainability**—Recycling has long been used to minimize waste and conserve valuable resources. Copper is 100 percent 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. It is estimated that 80 percent 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 percent less energy than the amount needed to convert copper ores to metal.
- **Higher Standards of Living**—The proportion of the world's population living in cities with more than 10 million inhabitants continues 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. In

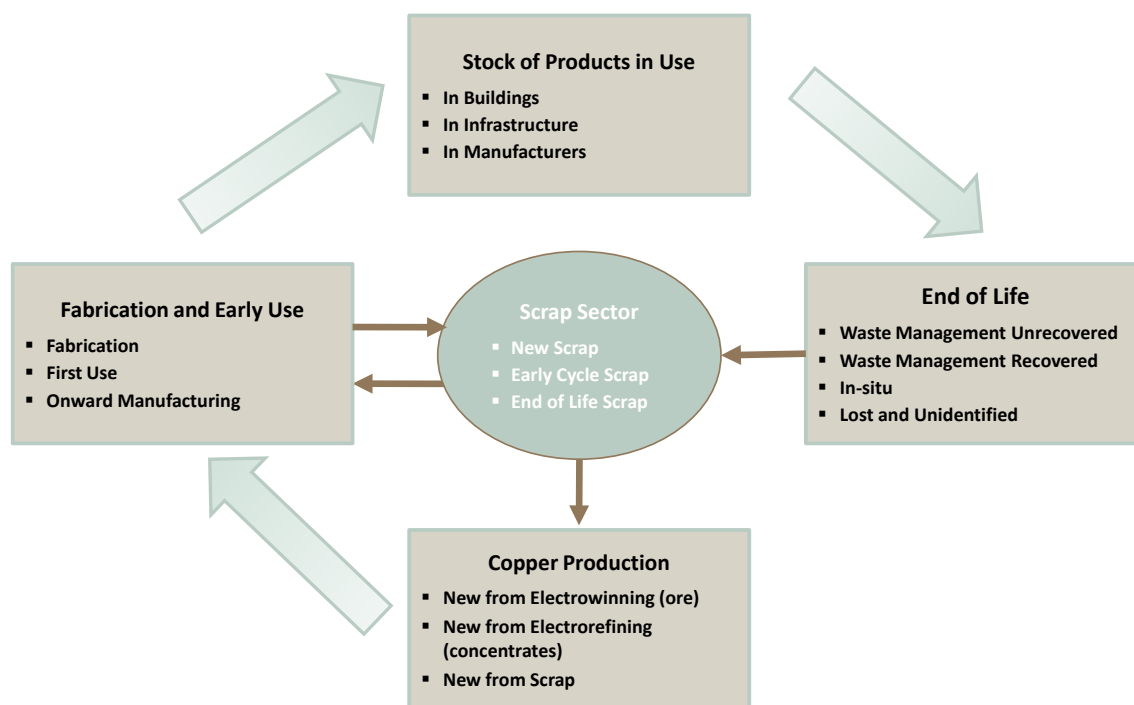
addition, the growing senior population increases the demand for technologies that help correct vision, hearing, motor, and other impairments, allowing seniors to continue to live comfortably as active members of society. Achieving higher living standards amid a population boom requires materials and products that aid in sustainable development and an improved quality of life for everyone. Copper use spurs economic development and increases living standards.

Appendix E—Copper Lifecycle

Sustainable mining practices and 100 percent recyclability add to the value and importance of copper. The broad range of properties of copper and copper alloys used in end-product applications is achieved through a variety of processing steps and can be obtained using newly mined or recycled copper. Copper materials can be recycled repeatedly without any loss in properties or performance. It has also been estimated that at least 80 percent of all copper ever mined is still in existence, due to copper's infinite recyclability.

- **Refined copper originates through two quite distinct process chains.** The smaller, and simpler, is the electrowon route, where refined copper is nearly always formed at the mine site through a leaching process. The more complex route incorporates electrolytic refining, where mined copper is formed into concentrates at the mine, processed to make blister or anode at the smelter, and then processed into refined copper cathode at the refinery. At both smelter and refinery stages scrap may be introduced.
- **Refined copper and high grade scrap are combined for processing** into fabricated products, primarily electrical wire and cable and mill products. Material may be used directly (as in plumbing tube), it may go through simple one-stage manufacturing (as in plumbers' fittings), or through one or more intermediate manufacturing stages (as in winding wire used in motors used in automotive). Once copper has gone through all of its process stages it starts its useful life as a functional (stock) product. These products are classified by end-use market such as building construction, infrastructure and equipment manufacture.
- **At the end of a product's life, three things are possible:** it can be earmarked for materials recovery through the waste-management system, it can be disposed of nonproductively or it can remain in situ, no longer being used. Scrap may usefully be divided between new scrap, early-cycle scrap and end-of-life scrap. The former two categories apply before copper enters its useful product life. The distinction between the two categories is useful as new scrap, generated during fabrication and some first stage processing, is generally clean, while in the latter stages it is more likely to be contaminated by other materials.

Figure 2: Copper Flow Model: Production, Fabrication, Stock and End of Life

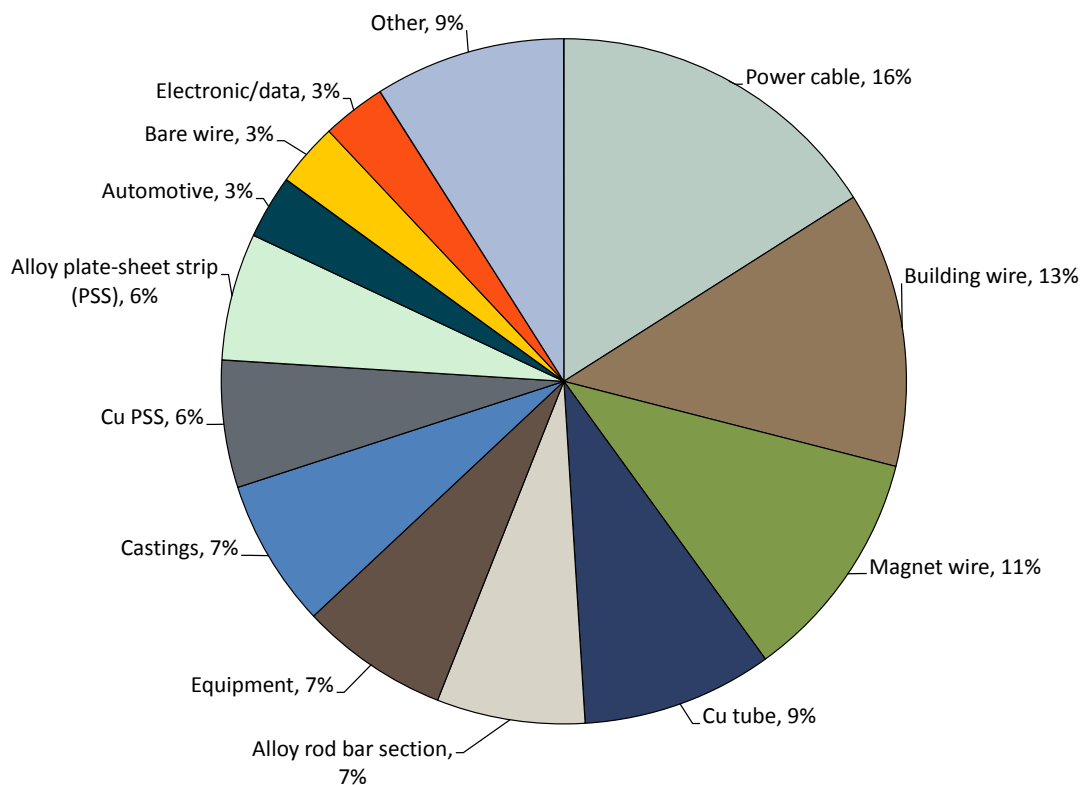


Appendix F—Copper Today

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 3). Copper contributes 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 support expanding economies.

Copper demand derives principally from electrical energy transmission. Wire and cable made from newly refined copper meets stringent performance and safety specifications. Figure 3 illustrates global total end uses of copper, by product share, in 2009.⁴ Base: 22.1 million tonnes copper content

Figure 3: 2009 End-Use Markets for Copper



Note: Figures are rounded

Source: ICA Global End Use Data Set

Copper is primarily used for wire and cable; however, it is also used for the plumbing tube and fittings industry (e.g., water distribution). The global copper electrical market, which is partly denoted by the three largest sections of the pie chart, is greater in size than the global brass mill market. Brass mills produce wrought copper-alloy products. The semi-fabricated products are used by industries to make finished goods and are segmented according to physical shape. Of the global copper market, brass mill is the second largest constituent. In 2009 the global copper market was 57 percent electrical, 36 percent brass mill, and 7 percent foundry and powder.

Brass mill consists of eight segments: alloy mechanical wire, alloy plate, sheet and strip, alloy rod, bar and section, alloy tube, copper foil, copper plate, sheet and strip, copper rod, bar and section and copper tube.

A review of copper's global market share in 2009 shows Equipment Manufacture at 52 percent, Building Construction at 33 percent and Infrastructure at 15 percent.

Appendix G—Contributors

The International Copper Association gratefully acknowledges the important contributions of the following individuals and the associated sponsors in preparing the 2010 *Copper Applications Technology Roadmap*.

Contributors:

Advanced Technology Institute

Mike Stebbins

Amira International Ltd.

Joe Cucuzza

Arubis

Jo Rogiers

BHP Billiton

Cleve Lightfoot

Codelco-Chile

Jürgen Leibbrandt

Consultant, Editor

Konrad Kundig

Consultants

Steve Bone

Dale Peters

Derek Tyler

Jean-Marie Welter

Copper Development Association

Andy Kireta Jr.

Harold Michels

Bob Weed

Copper Development Centre,**Australia**

John Fennell

Deutsches Kupferinstitut

Anton Klassert

European Copper Institute

Colin Bennett

Nigel Cotton

Hans De Keulenaer

John Schonenberger

Freeport-McMoRan Copper & Gold Inc

Stephen Higgins

Golden Dragon Precise Copper Tube Group Inc

Deng Bin

International Copper Association, Ltd.

John Mollet

Tony Lea

International Wrought Copper Council

Mark Lovett

Kinghorn, Hilbert & Associates

Ted Kinghorn

KME Group

Christoph Geyer

Heinz Klenen

Armando Sbrana

LS-Nikko Copper

Jeong-Ha Lee

Luvata

Warren Bartel

Ed Rottmann

Mitsubishi Materials Corporation Metals Company

Kazumasa Hori

Nexans

Eric Lawrence

Michel Rousseau

Revere Copper Products, Inc.

Thomas O'Shaughnessy

Wieland-Werke, AG

Uwe Hofmann

Gerhard Schuez

Yazaki Corporation

Akibumi Sato

Yunnan Copper Industry (Group) Co., Ltd.

Wang Qin

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KGHM Polska Miedź
KME Group
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Southern Copper Corporation
Sumitomo Metal Mining Co.
Teck Resources
Tenke Fungurume
Wieland-Werke AG
Xstrata Copper
Yunnan Copper Industry (Group) Co., Ltd.

Coordinators:

International Copper Association, Ltd.
Hal Stillman
Kevin Krizman
Nicole Witoslawski

Facilitators (2007 Roadmap):

Energetics Incorporated
Katie Jereza
Ross Brindle

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