A Logbook Across the Ocean of Electrons
A Story of Material Technology in Furukawa Electric: Now and Then

*Toru Fukushima**

ABSTRACT We commercialized copper wire cables through the refining of pure copper at the dawn of the Meiji era. We have been deeply involved in the modernization of Japan, helping to develop power cable networks, to popularize motors and generators, and to expand telephone and telegraph networks.

These origins of our founder's business generated the driving force for the industry development and became one of the sources for social contributions, which the company should make, while lighting up the city with safe electric lights, and encouraging interactions among people beyond time and space. Since then, we have been proposing the world a variety of material, which was derived from our founder's business, and have started the beginning of a new information society, for example, by adding optical fibers and semiconductor lasers to material technologies.

On the other hand, the climate warming and its resulting large-scale natural disasters are becoming a new threat to our planet. In the search for effective and permanent means, attempts to realize a fusion power generation as soon as possible are increasing. The material that supports this is superconducting wires, which we have cultivated over many years. We will continue to pursue material technologies to make a new contribution to the society.

In this article, I would like to describe about our "Now and Then", starting with our exploration of copper materials, and aiming to commercialize new materials such as superconductors.

1. INTRODUCTION -Furukawa Electric's Hydroelectric Power Generation-

The development of the Ashio Copper Mine undertaken by Furukawa Head Office (later, after being Furukawa Mining Co,. Ltd., it became Furukawa Co., Ltd.) dates back to 1877 when the dry mountain was sold to the private sector and purchased by our founder, Ichibei Furukawa.

On the other hand, in order to transform the crude copper produced into an extremely low-resistance pure copper, i.e. an electric wire, it undergoes a purification process called an electrolytic refining. In other words, the loop of using a lot of electricity to produce transmission lines must be closed. Incorporating the function of the "power generation" as a part of our business would have been a natural progression. From 1906, Furukawa General Partnership sequentially installed hydroelectric power plants at four locations (Hosoo, Uwanoshiro, Umamichi, and Setoyama) near Nikko Copper Electrolyzing Refinery (now our Nikko Works) and began their operation. The electric energy produced there was transmitted to the Ashio Copper Mine, and transmission lines of those days are still in operation today. Today, our Nikko Works also operates on electricity generated by these hydroelectric power plants.

The idea of utilizing natural energy called the "hydropower" was an ideal choice, in terms of the natural environment in which our Nikko Works is located and the need for local community contributions. The desire of people at the time of our founding to take advantage of the water volume in Lake Chuzenji and to pass it on to the next generation, combining both the beautiful forest river and the business, is still being carried on today.

We will contribute to the society based on our material technologies toward the realization of the next-generation social infrastructure and new mobility, and will inherit the spirit of our founder as described above. The environ-

* General Manager,
Sustainable Energy Succession Project Team and Deputy General Manager, Research & Development Division

ment of the earth is changing rapidly these days, and we would like to add another "contribution to the earth" scenario on top of the material technologies and product businesses that we have cultivated so far. This is, so to speak, the theme of this report.

2. THE DAWN BROUGHT BY PURE COPPER WIRES

When impurities are thoroughly removed by the electrolytic refining, the purified copper mass becomes the "ocean of electrons" with a core of uniformly aligned copper atoms surrounded by an abundance of free electrons. The secret why the copper functions as a "good conductor" is that this "ocean of electrons" transmits energy, from huge currents to minute voltage amplitudes, like a tsunami or a ripple wave, over great distances without losing its momentum of wave crest. The pure copper functions as a good conductor of heat as well as an electrical energy. In addition, as it is purified more, it increases the ductility and becomes easier to process into thin and long wire rods.

The reason why the copper material broke away from ancient uses of "copper" such as ornaments, precious metals, or coins and became a basic material that played a role in industrial development in the early 19th century must be the overlapping of discovery of the "ocean of electrons", the realization of "wire rod" product, and the need for electrical applications at the perfect timing.

Although the copper is often seen as a mature field now, but if we look back at its history, we can trace the magnitude of impact that the pure copper wire has had on the world. The world's first transatlantic telegraph cable in 1858 is its best example. The world's first transatlantic Morse code was transmitted by a central conductor of 7 pure copper wires stranded together, with a total length of 3,200 km. It was a poignant story that the "ocean of electrons" could be transformed into a communication channel that spanned the oceans of the earth, but this project was difficult to complete and took more than two years to complete[1].

Queen Victoria of the British Empire and President Buchanan of the United States of America exchanged 98 words telegraphs via an undersea cable that had been opened. At a time when there was no other means of communication than sending letters by ship, the feat of simultaneous communication created a sensation comparable to that of the Apollo moon landing. However, the first transatlantic telegraph cable stopped functioning within a few weeks after the feat. The cause of the malfunction was attributed to the deterioration of the insulation coating material (natural rubber), which allowed the central conductor to conduct with seawater. The first challenge to the "great ocean of nature" by the "ocean of electrons" in the hands of mankind ended in a defeat.

Time moved on to 1884. The Honjyo Copper Smeltery was established and began businesses, ranging from the pure copper to the electric wire manufacturing. With this as a starting point, Furukawa Electric was born in 1920. It has been a long time since it lagged behind Europe and America, and a quarter of a century had already passed since the successful completion of the transatlantic telegraph cable. Now, we look back the earnest desire of our predecessors to bring the dawn of electricity and communications to our country as soon as possible. The guts of our predecessors, who hurriedly overcame difficulties of the wire drawing process and the coating material research in quick succession, based on the refining of pure copper[2], are immeasurable. They must have poured their heart and soul into the development of improved structures and coating insulation technologies, referring also to the precedent of submarine cables in the US and European teams.

3. ELECTRIC RESISTANCE AND HORIZON OF THE OCEAN OF ELECTRONS

Now, copper wire carries the electric power, transmits the information, and contributes to the industrial development, but needless to say again, its electrical resistance is not zero. This is also true for other metals such as aluminum, which is a good conductor like copper, but the higher the temperature, the higher the resistance (Table 1).

Table 1　The dependency on the operating temperatures for the resistivities in Copper and Aluminum.

Metal	Volume resistivity [μΩcm]					
	–195℃	0℃	100℃	700℃	1083℃	1200℃
Aluminum	0.21	2.5	3.55	24.7	-	32.1
Copper	0.2	1.55	2.23	6.7	21.3	-

This is the limit of the "ocean of electrons," and the horizon that will never be reached. The higher the temperature at which it is operating, the more intense the thermal oscillation of the metal atoms becomes. By way of an example, the surface of the ocean of electrons boils violently, disrupting the wave crests that transmit energy, and impeding their voyage. At extremely high temperatures, it reaches its melting point and melts down. It can no longer function as an electrical wire to transmit the energy.

Now, on the contrary, if we thoroughly cool wires made of copper or aluminum, what will happen? The -195°C temperature shown in the above table refers to the state in which wires are cooled by immersing them thoroughly in the liquid nitrogen. Compared to the room temperature operation, the resistance value is reduced to about one-tenth. The thermal energy generated when the same current is applied decreases by a factor of 10 in proportion to the resistance value. Now, a simple question comes to mind what will happen if cooled down further to an extremely low temperature, where the ocean of electrons becomes completely silent. This is exactly the state of absolute zero, or –273°C. Since metal atoms stop the thermal vibration and electrons around them are free to move around, the resistance must be extremely close to zero. If a much larger current is desired, achieving zero resistance is the ultimate ideal since the calorific energy generated increases drastically as the square of the current.

However, unfortunately, even when cooled to absolute zero, the electrical resistance of copper wire is never zero. The insatiable pursuit of “Why is that?” and “Is there somewhere a dreamlike material that has zero electrical resistance?” will lead to the realization of superconducting wires.

4. ACROSS THE SUPERCONDUCTIVITY AND THE OCEAN OF ELECTRONS

When a pure metal is cooled to absolute zero, the intrinsic quantum-mechanical character of free electrons appears. In other words, electrons are clearly separated into 2 types (positive and negative spin polarity) that are spinning clockwise and counterclockwise. And when two electrons with the same spin polarity meet, they will hinder each other’s progress on the contrary. This is the limit of the ocean of electrons i.e. the cause of tiny electrical resistance that remains at the end. The search for a way to break through this limit continued.

On the other hand, the phenomenon that mercury becomes zero resistance and superconductivity if it is cooed at an extremely low temperature was discovered by the Dutch scientist Kamerlingh Onnes in 1911, much earlier than theoretical elucidation. Later, alloys of niobium and titanium, for example, were found to reach a state of “zero resistance” at a liquid helium temperature (–269°C). The underlying physics of this phenomenon attracts the keen inquisitiveness of researchers.

What would happen if electrons having two different spin polarities, positive and negative respectively, could pair up and behave like a single particle without spin? And then, wouldn’t one pair be able to move freely without any interference from the other pair, with absolutely zero resistance? Three scientists (John Bardeen, Leon Neil Cooper, and John Robert Schrieffer) approached these hypotheses and succeeded in explaining the phenomenon of superconductivity quantum mechanically in 1957. And, they showed the possibility that instead of individual electrons, a new pair of electrons, the Cooper pair, could achieve a superconducting state with zero electrical resistance. This discovery was named the “BCS theory” after the initials of the three men, and for their work on the BCS theory, Bardeen et al. were awarded the Nobel Prize in Physics in 1972.

Around the time when the BSC theory of superconductivity was being explained in the world of theoretical physics, a series of discoveries of superconductors that were not only high in superconducting critical temperature but also resistant to magnetic fields and electric currents were made also in the world of experimental physics. The possibility of practical application of superconducting materials, which had been thought to be difficult up to that time, was shown. In 1963, basic researches on superconducting metal materials began at our Nikko Works, and we succeeded in commercializing niobium alloy superconducting wires with no loss of time. Since then, we have been continuing to supply low-temperature superconducting wires to customers around the world.

However, low-temperature superconducting filaments such as niobium-titanium cannot maintain a perfect superconducting state unless they are covered with an oxygen-free copper (ultra-high purity and ultra-low resistance). There is a secret story of struggles and ingenuities in the development of this high-purity and oxygen-free copper. This can be said as a good example that the commercialization of new materials can be achieved by aiming for the ultimate in existing materials. It was in 2003 when we established the ideal oxygen-free copper technology. Efforts to thoroughly eliminate the pathways for impurities to enter the process, which prevented the high purification, and to fundamentally improve the process and facilities have borne fruit. The Residual Resistivity Ratio (RRR) value, an indicator of ultra-low resistance, was 500. The improvement was more than three times greater than that of conventional products, and laid the foundation for the quality and brand of our low-temperature superconducting wires. We have been also continuing our improvement research and have earned a good reputation for top-level performance and quality[3].

On the other hand, these alloy-based superconducting wires will not reach a superconducting state unless they are cooled to an extremely low temperature (4 K/–269°C) with liquid helium, which is expensive and difficult to handle. According to the aforementioned BCS theory, there is a limit to the temperature range in which a superconducting state can be achieved, and the search for a more convenient refrigerant, which becomes zero resistance, for example, using liquid nitrogen (77 K/–196°C), was considered extremely difficult.

However, in the spring of 1986, two IBM researchers (Johannes Georg Bednortz, and Karl Alexander Muller) found that an oxide combining barium, lanthanum, and copper could be used to create a superconducting state with zero electrical resistance at about 35 K/–238°C. It can be said that its discovery was as close to accidental as Columbus’ arrival in the Americas.

Taking this opportunity, in the short period from 1986 to 1987, research institutes in Europe, the U.S., and Japan published their results one after another, and a variety of high-temperature superconducting materials were born. In addition to the oxide that combines three metals, rare earths such as yttrium, barium, and copper, so called Rare Earth, Barium, Copper Oxide (REBCO), it has been revealed that the bismuth-based copper oxide, Bismuth, Strontium, Calcium, Copper Oxide (BSCCO), etc. have been found to show a superconducting state at a liquid nitrogen temperature with a good reproducibility. What these materials have in common is that the path of superconducting carriers is formed on the crystal plane where copper and oxygen are bound, and they are collectively called the "copper oxide-based superconducting materials".

Incidentally, the perfect theory that can explain the high-temperature superconducting state found in the above oxide materials is still a matter of debate among many researchers, and several hypotheses have been formulated. At the end of this debate, another material may be discovered by chance, and a new horizon may suddenly appear beyond the ocean of electrons.

5. MASS PRODUCTION AND PRACTICAL APPLICATIONS OF REBCO HIGH-TEMPERATURE SUPERCONDUCTING WIRES

We began basic researches in 1986 and worked on the prototype production and the evaluation of copper oxide-based superconducting materials. The REBCO crystals are brittle ceramics themselves, and it took many more years to realize a thin, long, and flexible shape to function as a superconducting wire.

Current REBCO superconducting wires consist of a metallic tape as the base material, dielectric multilayers deposited on top of it, and a REBCO crystal thin film (1 to 2 μm thick) that carries the superconducting current. Even if bending and tensile stresses are applied to the entire structure, as long as the magnitude of stresses is below the elastic limit of the metallic tape substrate, each layer of thin film is not damaged and functions normally.

And, in 2012, we acquired SuperPower Inc., which had achieved remarkable results in the deposition process of Yttrium, Barium, Copper Oxide (YBCO) thin films by introducing Metal Organic Chemical Vapor Deposition (MOCVD), and took a major step toward the mass production of REBCO superconducting wires[4)].

When zirconia (Zr) is added during deposition using the MOCVD method, an effect of pinning a magnetic flux appears. This improves the critical current density in high magnetic fields. By combining this technological feature and our manufacturing know-how, they have been improving quality, characteristics, and process capability[5)].

In February 2020, a new one floor building was constructed in consideration of a line layout suitable for mass production, and the relocation of existing process lines was completed. As of 2023, they are continuing to increase its manufacturing capacity by adding new process facilities to meet the demand for REBCO high-temperature superconducting wires[6)].

Now, an important thing as well as the technological efforts toward the mass production is finding appropriate applications. As mentioned at the beginning of this paper, the lineage of pure copper wires has expanded the use of electrical energy and laid the foundation for a consumer-oriented economy and industry since the 20th century, but more than 20 years have passed since the turn of the century, and social needs have already reached a turning point. So, what kind of contribution can the advantage of REBCO wires bring to the global environment both now and in the future? There are high expectations for this new material, which has spanned the ocean of electrons and exceeded the limits of Cooper pairs, and finally materialized after more than 30 years of work. Contributions with something new uses and new ways of using things are required.

So, let's take a look back at the advantages of superconductivity again. First of all, the first advantage that there is no transmission loss because the heat generated by electrical resistance is reduced to zero, and that 100% of the input power reaches the other end, is a consumption economic benefit. However, from a different perspective, we should focus on the second advantage that no heat is generated even when extremely large currents are passed through them. In other words, it is possible to wrap a small coil that cannot be achieved using the copper wire, and it is possible to confine an "ultra" strong magnetic field within it. This is a "thing" that users of this wire really appreciate. Utilizing the ultra-high magnetic field generated by superconducting coils, we are contributing to the advancement of technological fields listed in Table 2.

In addition, all of the application fields listed in Table 2 have already been pioneered using a niobium-based superconducting wire (We manufacture it at our Nikko Works). For example, in the International Thermonuclear Experimental Reactor (ITER), the basic concept of condensing and confining deuterium and tritium fuel plasma using the magnetic field generated by an electromagnet using niobium tin superconducting wire is becoming a

Table 2 Examples of applications for superconductors.

NMR (Nuclear Magnetic Resonance)	The stronger the magnetic field generated, the more complex proteins and macromolecules can be identified. This analyzer is indispensable in fields such as advanced medical research, new drug development, and food hygiene.
Particle accelerator	Contribution to the advancement of particle physics research (e.g., European Organization for Nuclear Research (CERN) and medical equipment (heavy particle irradiation equipment for cancer treatment).
Fusion power generation	Research is underway at International Thermonuclear Experimental Reactor (ITER) for practical use. Several private projects are being launched because the use of REBCO wire allows for more compact equipment. The dream of an artificial sun is one step closer to reality.
Magnetic levitation, rotation, and movement	Superconducting coils will be used to levitate heavy objects, enabling them to rotate and move in a straight line with zero frictional resistance. Expected applications in the mobility field, such as flywheel energy storage, next-generation transportation, and high-performance motors, etc.

reality. However, this is a gigantic project in which multiple countries are participating in the development by sharing and constructing a large electromagnet and a reactor body. It will take a long time furthermore to complete the project.

On the other hand, when the high-temperature superconducting wire is used, it is possible to create electromagnets that generate an even stronger magnetic field. This allows the plasma to be condensed more compactly and densely, making it possible to reduce the size of fusion reactors to less than a fraction of its size. It is expected that the cost and period required for the fusion reactor construction will be reduced, and realization is expected to be faster. In the application fields listed in Table 2, systems and equipment are currently becoming more efficient and more compact due to the switch to new high-temperature superconducting wires such as REBCO, or their combination (hybrid configuration). The achievement of Tokamak Energy Ltd. which showed the possibility of a compact fusion reactor, producing a prototype superconducting magnet using our REBCO wires and generating a magnetic field of 20 T, is an example of such efforts (Figure 1).

Figure 1 The HTS magnet for compact fusion reactor developed by Tokamak Energy Ltd.

The application of superconducting wires can bring what was once considered the science fiction world into a reality world. For example, if we could create an artificial sun on Earth using a fusion reactor, we would no longer need to burn fossil fuels. Or, if the high magnetic field is used to create new compounds, they could rapidly fix growing amounts of carbon dioxide. If new medicines and new ingredients are created using highly sophisticated NMR, diseases and hunger may disappear. If a transportation network that floats and moves at high speed is created, people and goods will be transported more safely and quickly. It will spin empathy and co-creation, and eliminate the seeds of conflict around the world.

We will continue to improve our mass production technology for high-quality superconducting wires and meet the expectations of customers who are developing these application fields.

6. CONCLUSION

A somewhat circuitous voyage from the “ocean of electrons” that begins with pure copper wires, to the “horizon line” drawn by superconductivity was described. Material technologies form the basis of various fields in which it is applied, but it takes a tremendous amount of effort and time to reach that point. The cycle of reincarnation in which materials give birth to new technologies, and new technologies give birth to the next materials, must continue to be spun in the future. The path from the basic research to the business is not an easy one, but the source of the strength to keep going through it is nothing but a sense of mission to contribute to the health and security for the next generation, and the preservation of the global environment.

The flow and density of information have been greatly improved by the optical fiber communication technology, which was one of the first to break out of the ocean of electrons. World events spread far more quickly and widely than they did during the time of the first transatlantic telegraph cable, and thanks to this, people’s minds and the ways of thinking have started to change at a more rapid pace than ever before. But something is still missing. How long will this earth remain calm? Can people really live their lives with peace of mind?

It may still be a dream story for now, but we would like to connect the Mother Earth and people’s future with new materials and new technologies. Furukawa Electric Review carries the thoughts of so many engineers and will continue to tick away without stopping its second hand.

REFERENCES

1) Allison Marsh, Tiffany’s transatlantic telegraphy doodad, IEEE Spectrum, Vol. 56 Issue 11 (2019), 60. https://ieeexplore.ieee.org/ document/8889974
2) Tsuneo Hanawa: “The Electrolytic Copper Refining at Nikko Copper Works of the Furukawa Electric Co., Ltd.”, Journal of the Mining and Metallurgical Institute of Japan, 84-963(1968), 729-731.
3) Masahiro Sugimoto, et al.: “Development of Cu-Nb Reinforced Nb_3Sn Wires”, Furukawa Electric Review, 55(2024), nn-nn.
4) Drew Hazelton, Toru Fukushima, et al.: “Introduction of SuperPower Inc. and High Temperature Superconducting Wire”, Furukawa Electric Review, 48(2017), 8-10.
5) Furukawa Electric: “High Performance REBCO-HM Wire”, Furukawa Electric Review, 55(2024), nn-nn.
6) Gene Carota, Tetsu Tateishi, et al.: “Introduction of SuperPower Inc.”, Furukawa Electric Review, 55(2024), nn-nn.