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Superconductivity Web21

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Change of ISTEC President

Katsumi Tajima, Managing Director
ISTEC

At the 48th ordinary Board of Directors' meeting and the 38th Board of Councilors' meeting held at Shiba Park Hotel on June 15, 2011, International Superconductivity Technology Center (ISTEC) unanimously appointed Mr. Shosuke Mori, Chairman of Kansai Electric Power Company, as the new president in place of Mr. Tsunehisa Katsumata.

President Katsumata had assumed the post in June 2010 as the successor to the then-president Mr. Araki and served as the president for a year, while greatly contributing to the progress of superconducting technology development and the growth of ISTEC.

New president Mr. Mori delivering his speech

After the Board of Directors' meeting, the new and old presidents delivered speeches. Mr. Katsumata said, "I had thought the superconducting technology was dream technology before, but now I feel confident in the technology, finding the practical applications of superconducting technology to electric power equipment are foreseeable. Even so, I would like to ask you to continuously strive for the technology development under the new president Mr. Mori, as we are still halfway to the goal." The new president Mr. Mori said, "I feel very encouraged because I have realized superconducting technology projects are progressing well. I will do my best toward practical applications realization of superconducting devices at an earlier date, and I would like to ask all the concerned people for continued support and cooperation."

In addition, draft proposals, including "Activity Report and Settlement of accounts for FY 2010", were passed at the Board of Directors' meeting and the Board of Councilors' meeting.

When the proceedings were completed, Mr. Fukushima, Director, Research and Development Division, Ministry of Economy, Trade and Industry, delivered a lecture titled "The Present Status of R&D in Japan."

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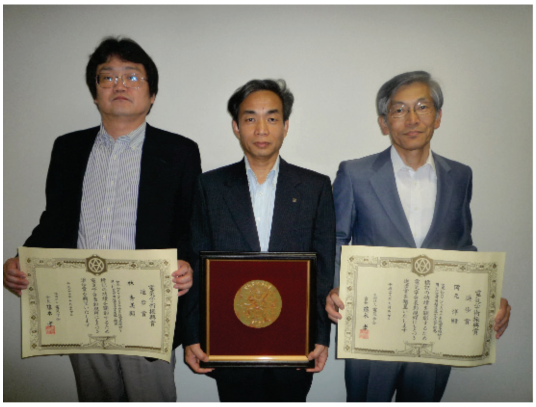
IEEJ Academic Promotion Awards for Technical Development presented for the Development of the "World's First Yttrium-based Superconducting Power Transformer"

Hidemi Hayashi, Group Leader
Power Storage Engineering Group, Research Laboratory
Kyushu Electric Power Co., Inc.

At the 99th Ordinary General Meeting of the Institute of Electrical Engineers of Japan (IEEJ), held on 27th May, the world's first "Superconducting Transformer utilizing yttrium-based Superconducting Wires for Electric Power Equipment," developed in collaboration with Kyushu Electric Power Co., Inc. and Kyushu University, was presented the "IEEJ Academic Promotion Award for Technical Development." Together with this award, "A letter of appreciation for the successful nurturing of researchers" was presented to Mr. Shimoda, General Manager of Research Laboratory of Kyushu Electric Power Co., Ltd. This award was unique as it was only presented to the academic that accomplished a significant advancement in both new theoretical understanding and the demonstration of technologies for electricity-related systems.

The award was for the development and demonstration of a 400kVA yttrium-based superconducting transformer aimed towards the establishment of a technology for practical use. The technology resulted in the establishment of areas such as, durable short-circuit and uniform current distribution technologies in wires. Furthermore, the ability of the transformer to withstand short-circuits during accidental power outages as well as the performance during strong electromagnetic forces that accompany large short-circuits were verified. This has remarkably advanced the practical realization of a Y-based superconducting transformer. It was these outcomes that the award highly appraised. The future plans for this technology involve the improvements in the design and the development of a more compact and efficient 2MVA-class superconducting transformer, including a cooling system are planned.

This technology has been developed in collaboration with the International Superconductor Technology Center (ISTEC), Fujikura Ltd., SWCC Showa Cable Systems Co. and Japan Fine Ceramics Center (JFCC), under the "Technological Development of Y-based Superconducting Transformer," one of the "Technological Development of Y-based Superconducting Electric Power Equipment" projects commissioned by the New Energy and Industrial Technology Development Organization (NEDO). (Please refer to Winter issue of 2011 of Superconductor Web21.)



Persons awarded, starting from the left, Associate Professor Iwakuma, Group Leader Hayashi, Senior Researcher Okamoto

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Feature Article: Refrigeration and Cryogenic Technologies - The Progress in Refrigeration and Cryogenic Technologies for Superconducting Electric Power Equipments

Norihisa Nara
Cryogenic Development Group
Taiyo Nippon Sanso Corporation

While the research and development efforts for high temperature superconducting (HTS) power equipments have led to research in practical applications, activities in the development of refrigeration systems have accelerated. The requirements of refrigeration systems for HTS power equipments include, 1) the operating temperature and the cooling capacities required to maintain superconductivity, 2) the reliability in the long-term continuous operation, 3) the cooling efficiency (low running costs), 4) the compactness of the system (minimization the installation space), and 5) reduced maintenance costs. Currently the operating temperatures for refrigeration systems to cool HTS power equipments ranges from 40 to 80 K, with refrigeration capacities ranging from 2 to 10 kW at 80 K. Cryocoolers available in the market offer 1 kW or less cooling capacity at 80 K, and additionally are equipped with sliding parts that require regular maintenance, usually once per year. On the other hand, expansion turbine has been adopted in large-scale cryogenic systems such as cryogenic air separation units and helium liquefiers. However, these expansion turbine cryogenic systems have too large cooling capacity for HTS power equipments. In 2007, a prototype expansion turbine refrigerator utilizing neon as the working fluid was fabricated, as a refrigerator having the suitable cooling capacity.

This prototype refrigerator yielded a 2 kW refrigeration capacity at 70 K. In 2009, the operating process pressure was changed from 2.0 MPa/1.0 MPa to 1.0 MPa/0.5 MPa. In order to improve compactness of the refrigerator, a small turbo-compressor was developed. The turbo-compressor is based upon a centrifugal compressor design, equipped with two-stage compressors, with the inlet pressure at 0.5 MPa, with a pressure ratio of 2.0, and a neon gas flow rate of 1200 Nm^3/hr. Furthermore, the adoption of magnetic bearings in the compressor and in the expansion turbine eliminates any sliding parts and results in a maintenance-free refrigerator. The unit test of a small turbo-compressor with a pressure ratio of 2.0 has achieved an adiabatic efficiency ranging from 67 to 70 %. Figure 1 shows a reciprocating compressor and a turbo-compressor. And those

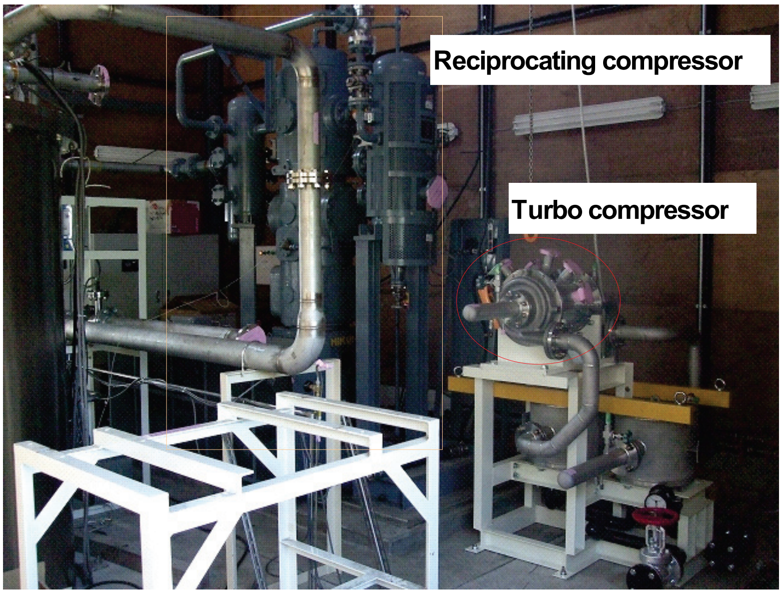

Fig. 1

compressors have the same specifications. Considering the installation space, a refrigerator consisting of a small turbo-compressor is more compact than an equivalent refrigerator comprising of reciprocating or screw-type compressors, and thus can meet the requirements of compactness to cool HTS power equipments.

After completing unit tests of the small turbo-compressor, further tests were undertaken to verify the operational performance of the neon refrigerator, when combined with a small expansion turbine and a heat exchanger. One of performance evaluations is aimed at compactness and thus the heat exchanger was reduced down to 4/5 its size. The refrigerator revealed a 2.0 kW cooling capacity at 65 K and a Coefficient of Performance (COP) of 0.059 at 80 K. The future research and developments will be aimed to improve the stability, reliability and the adiabatic efficiency of the small turbo-compressor. Summarizing the results achieved thus far, some more efforts can achieve the performances which are cooling capacity of more than 2 kW at 65 K and a COP of 0.06 at 80 K. It is desired in the next stage of development that further enhancements of adiabatic efficiency in the small expansion turbine be achieved, as well as improvements in the compression ratio and the adiabatic efficiency of the small turbo-compressor.

Additionally, it is very important for the future to research and develop the entire cryogenic system and a heat transfer from HTS power equipments to the refrigerator. Thus, studies have begun for the heat exchanger (sub-cool heat exchanger) to cool liquid nitrogen by utilizing neon gas coolant to maintain and sub-cool the liquid nitrogen. The current sub-cool heat exchanger system is to immerse the neon gas-cooled coil into liquid nitrogen, thus allowing the sub-cool heat exchanger to be installed separately from the refrigerator cold box. In order to successfully install the sub-cool heat exchanger within the neon refrigerator cold box, a plate-fin type heat exchanger was selected as the sub-cool heat exchanger. The analysis of the heat exchanger was undertaken by simulating the flow channel geometry and the numbers of flow channels in the heat exchanger. The results from these investigations showed that the optimization of the sub-cool heat exchanger and the neon refrigerator can realize a more efficient cooling system. To do so, further detailed analysis and experimentation is needed.

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Feature Article: Refrigeration and Cryogenic Technologies -The Cryogenic Cooling System for High Temperature Superconducting Cable

Masamitsu Ikeuchi
Research and Development Center
Mayekawa Manufacturing Co., Ltd.

1. High temperature superconducting verification project

Research and development efforts of the next generation High Temperature Superconducting Cables (HTS cables) with the benefits including high capacity and compactness have commenced worldwide. In Japan, a "HTS Cable Verification Project" started back in 2007. The project is being planned at the Asahi substation of Tokyo Electric Power Co., Inc. located in Yokohama city. By integrating the HTS cable system into the actual power grid the project aims are to carry out long-term testing studies to verify the reliability and stability of the complete system, including the operation and maintenance. This report summarizes the liquid nitrogen cooling system (cooling system), which forms an important component for the operation of the HTS cable, with verification test results, needing to be undertaken prior to the installation at Asahi substation.

2. The cooling system setup

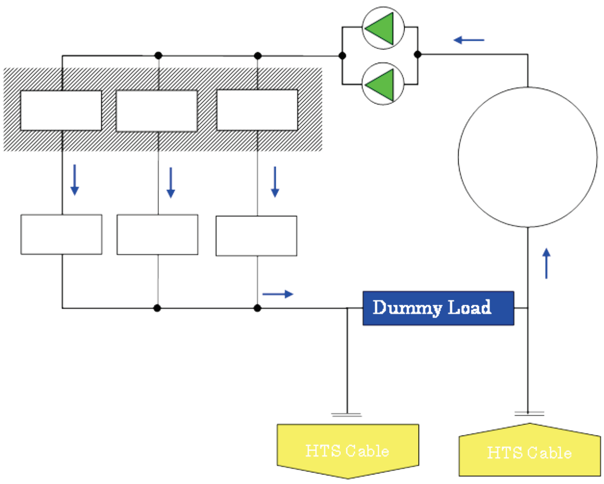

Fig. 1 Cooling system flow

The cooling system needs to be highly reliable with the ability to handle variable HTS cable heat loads due to changes in transmission power. A stable supply of liquid nitrogen is required as well and thus certain levels of pressure, operating temperature and flow rate of liquid nitrogen need to be maintained. The system evaluated comprises of cryocoolers, a liquid nitrogen circulation pump and a reservoir tank, as shown in figure 1. The numbers of cryocoolers required was determined by considering the expected heat load and the reliability. This led to the installation of six units, each being a 1 kW-class, Stirling cryocoolers and included a spare unit. The units were arranged in two rows of three, and installed to minimize the pressure loss of coolant as well as being easier to maintain. Similar considerations were taken into account for the installation of the liquid nitrogen circulation pump, with the installation in parallel of two centrifugal pumps including a spare. The reservoir tank held a 1000 litre capacity, enough to absorb the expansion and contraction caused by temperature fluctuations of liquid nitrogen. For these verification tests there was no HTS cable used and a dummy-load heater was installed to simulate the heat load of a cable. Due to space restrictions at the factory facilities, three of the six cryocoolers were used (excluding the hatched area of the figure) for the tests. The other three cryocoolers were kept for latter-half testing, where cryocoolers were replaced during operation, thereby allowing maintenance evaluation tests to be undertaken.

3. Verification testing

Testing commenced to study the safety, the control, the operation of the system during the stop and run, the reliability and the maintenance. The following reports are accounts of the results obtained from the verification tests.

a. Pressure control tests
In order to maintain a healthy electrical insulating property of the HTS cable, it is important to maintain the required constant pressure of liquid nitrogen to prevent the generation of bubbles within the HTS cable. The performance of the cooling system was evaluated by simulating three types of increasing pressure environments; heater pressure method in the reservoir, gas pressure method that utilizes an external nitrogen gas cylinder and a natural pressure method without the need of external power, here, the pressure forms by partially evaporating the liquid nitrogen using the heat exchanger. Results confirmed a stable pressure environment under the proper combination of testing methods undertaken.

b. Operating temperature control tests
Here the evaluation tests were aimed at maintaining the operating temperature of the HTS cable to within a certain temperature range by controlling the number of cryocoolers operating at a given time. The test results from this evaluation are shown in figure 2, and clearly show that by controlling the stop and run of the cryocoolers in accordance with varying dummy loads, the operating temperature remained safe within the targeted operating temperature range of ± 1 K.

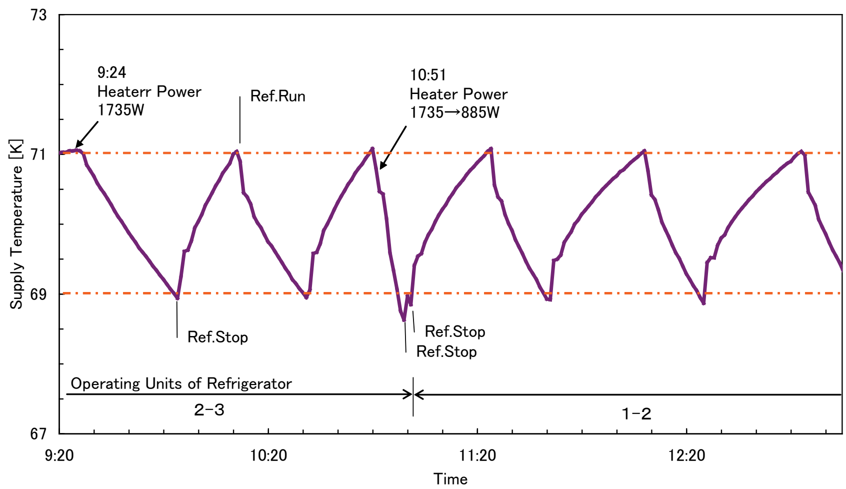

Figure 2 The results of operating temperature control tests

This research was carried out under the “High Temperature Superconducting Cable Verification Project” commissioned by New Energy and Industrial Technology Development Organization (NEDO).

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Feature Article: Refrigeration and Cryogenic Technologies
- The Development of Helium Circulation Cryocooling Technology

Tsutomu Tamada, Research Engineer
Superconductivity Group, Electric Power R&D Center130
Chubu Electric Power Co., Inc.

High temperature superconducting wires have superior characteristics such as high energy densities, thus allowing the fabrication of large-scale, high power-output superconducting equipment applications. A high voltage is desired to achieve a large power output from a superconducting coil, and is realized by improving the insulating properties of the coil with the introduction of solid insulation. However, since high temperature superconducting wires have high critical temperatures and thermal tolerance compared to metal based superconducting wires, the benefits offered allow the insulated superconducting coil to be d irectly cryocooled.

Conventional conduction cooling methods directly remove heat from cryocoolers by heat conduction of solids. However, in large-scale applications, such as a superconducting coil, the longer distance required for heat transfer results in a t emperature gradient. This raises concerns regarding the ability of the coil to maintain its superconducting properties in the large heat generated under this temperature gradient. Therefore, by installing the refrigerator as close as possible to the coil usually surmounts any temperature gradients. However, for this method, it is required to place the refrigerator close to the coil, resulting in some issues such as limits space (several refrigerators required per one large-scale coil) and the extra labour time required during maintenance. Thus, the focus of this research group has been in the development of a helium circulation cryocooling technology, allowing cooling over longer distances and completely cooling the heat generated along the length of the coils.

The helium circulation cryocooling system is explained here. For the system, the aluminium-fabricated transmission heat shields are coated around the surface of the coils to cryocool equally, and embedded into the transmission heat shields with the conducting pipe allowing helium gas to circulate. This method circulates cryocooled helium gas through this conducting pipe, distributing cooling equally along the length of the coils. Additionally, as the cooling gas can be transported from some distance away, immediate benefits arise from being able to install the refrigerators away from the coils, further simplifying equipment maintenance. The figure shows the helium circulation cryocooling demonstration system.

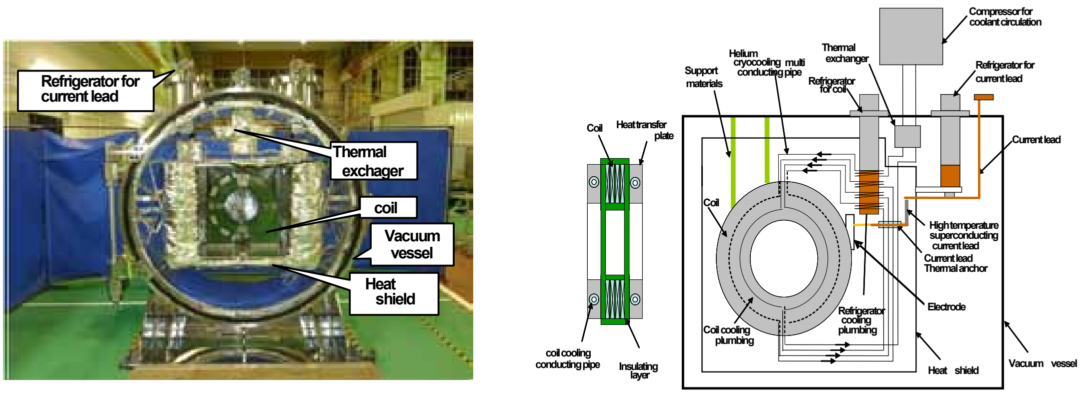

Figure Helium circulation cryocooling demonstration system

This demonstration system has verified the following characteristics.
1) The ability to realize a cooling of more than 3 W/m^2 of coil surface heat flux at an operating temperature of 20 K.
2) 6 kV-rated electrical insulation characteristics under vacuum and at 20 K.
This cooling technology is compatible for large-scale designed superconducting equipment and enables the realization of a wide range of applications such as industrial and electric power fields.

This research and development was carried out under the "Y-based Superconducting Power Equipment Technology Development" commissioned by NEDO.

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Feature Article: Refrigeration and Cryogenic Technologies - The Research and Development of a Cryogenic Cooling System for Direct Current Superconducting Cable

Sataro Yamaguchi, Professor
Center of Applied Superconductivity and Sustainable Energy Research
Chubu University

It was back in 2005 when Chubu University commenced full-scale research and development activities aimed at direct-current superconducting power transmission. For such a system the heat load at the cooling system determines the cable loss. Thus, it is the performance of the cryogenic cooling system that determines the feasibility of the superconducting DC-power transmission system. Hence, the majority of research and development efforts undertaken at Chubu University have focussed on reducing the heat leakage to the cooling system. The following briefly summarizes the research for the low-temperature system, mainly on the 200m-long cable experimental device.

1. Use of a small-diameter cable

As the diameter of the superconducting cable is reduced, the concentric double-pipe diameter can too be reduced, thus minimizing heat leakage to the cooling system. It is therefore important to fabricate a small diameter cable capable of carrying high current densities. The superconducting coaxial cable used for the experiments consists of two conductors that share a common axis with ±10kV, 2kA@78K, with a diameter of 35ϕ.

2. A thermally insulating concentric double-pipe utilizing a straight pipe

Utilizing a straight pipe with a reduced surface area can minimize heat leakage by radiation, and at the same time reduce the coolant circulation pressure loss.

Furthermore, only the cable is wound around a transmission drum to minimize the parts taken up by the cable connection. This design reduces cable construction costs and improves safety further. Figure 1 shows a model of the HTS cable and concentric double-pipe. The inner and outer pipes are 50A and 200A, respectively, with the inner pipe being a small diameter design in comparison to conventional thermally insulated concentric pipe designs. This design improves exhaust conductance and makes the installation of a vacuum pump easier, allowing a high vacuum to be achieved without the need to bake the thermally insulated concentric pipes. For the 200 m-long cable experimental device, a high vacuum of 10^{-4} Pa has been achieved without baking. Additionally, the pressure loss along the cable with a circulation volume of 10 L/min was 2-3 kPa. These cable characteristics were close to the targeted values, however further elaborate designs are required in the future.

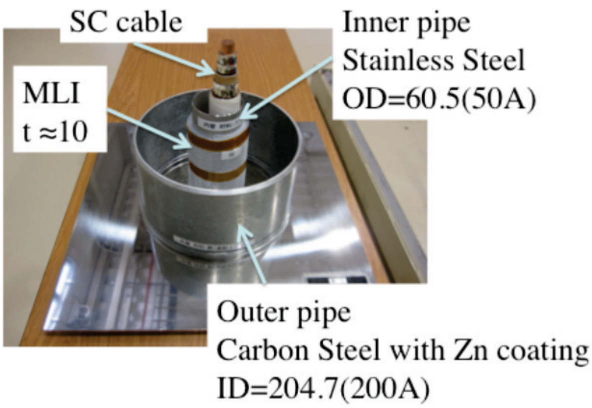

Fig. 1 A cross-section model of the thermally insulated concentric double-pipe

3. Thermal Contraction of cable and cryogenic pipe

When cryogenically cooled, the cable and the thermally insulated concentric double-pipes experience a thermal contraction of approximately 0.3 %. A similar, 60 cm, thermal contraction occurs for the 200 m-long cable. On the other hand, the critical current along the tape reduces with increasing thermal stress. The cable ends were thus not fixed towards or along the directions of thermal contraction to moderate the effects of thermal stress. Cryostat terminals are loaded on a rail and are movable. Bellows pipes are connected allowing heat contraction in accordance with the thermal conditions. Figure 2 shows a schematic of the system tested. An automated TV camera system was developed to monitor both ends of the cable terminals and allowing observation and image processing. On the other hand, in the future when cable lengths increase, the thermal contraction volume is estimated to be 30 m for a 10 km-long cable. Therefore, methods to absorb thermal contraction utilizing only bellow needs to be considered and improved further.

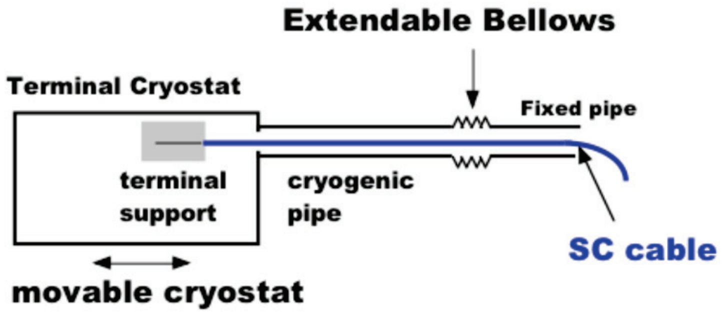

Fig. 2 A schematic diagram of the system, showing the terminal support for the cable and the movable cryostat

4. Low heat leakage cable terminals

At the cable terminal, the superconducting strands are connected directly by a copper lead to the copper terminals, which are at room temperature, leading to a large heat leakage volume. The heat leakage volume is estimated to be approximately 50 W/kA for the conventional terminal, and approximately 200 W/kA in total for all four terminals of the cable. By successfully reducing this heat leakage, will allow the cable to be used for short-distances and low-voltages, with possible applications for power supplies and distribution systems. Chubu University has been advancing the development of Peltier current leads (PCL). For a 200 m-long cable experimental device with a PCL, the targeted values of heat leakage volume are estimated to be around 25 W/kA. However, in principle, the heat leakage of current lead volumes below 10 W/kA are possible thoretically, and therefore further research and development in this area is planned.

5. Use of an external pipe made from iron for the thermally insulated concentric double pipes

For this 200 m-long cable experimental device, the use of iron for the external pipe to insulate the concentric double pipes was employed for the first time in the world, (see fig. 1). The iron was galvanised to reduce heat radiation, and it also formed the vacuum vessel. Additionally, the costs were reduced with iron (1/5 the price compared to stainless steel) and therefore not resource constrained. For DC transmissions, power transformers require large-scale inductors. However, as the external iron pipe has strong magnetic characteristics, the inductance becomes greater for a single-core cable and there is the possibility that an external inductance is no longer required. Further data and testing is currently underway.

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The 200 m-long cable experimental device was almost completed in March 2010, with several tests including three-cyclic thermal tests undertaken. A further two more tests are planned for 2011. Presently, the overall findings from these tests reveal that the loss in the cable is less than 1/5 the loss compared to copper and aluminium transmission wires. Also, with costs reducing all the time, the 200 m-long cable could soon reach the possible diffusion into mainstream market. For the next step of the research, the investigation for construction of a 2 km-class cable experimental device has begun. Since the East-Japan earthquake of March 11th, investigations for wide-area transmissions grids are in planning in order to improve security in Japan. Under these circumstances, it is desired that the research and development of DC superconducting transmission systems be further advanced so that applications will be realized in the near future.

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Feature Article: Refrigeration and Cryogenic Technologies - The 20 K Refrigeration System Development and Hydrogen Engines Automobiles

Kimitaka Yamane, Associate Professor
Hydrogen Energy Research Center and Department of Chemistry and Energy Engineering, Faculty of Engineering
Tokyo City University

Refrigeration and cryogenic technologies are indispensable for applications such as medical, which have superconducting magnets for MRI (Magnetic Resonance Imaging), for space applications, where the re-liquefaction of helium gas is required to cryocool the telescopic cylinder of infrared telescopes, and for ground applications such as power transmission, linear maglev Shinkansen and the liquefaction of gas.

There are concerns associated with the depletion of fossil fuels and the consequent release of toxic exhaust gas such as carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxide (NO_x) when an internal combustion engine burns this fuel, (hitherto known as engine). In order to solve these issues, Tokyo City University (former Musashi Institute of Technology), has investigated hydrogen fuel as an alternative fuel source to fossil fuels. In 1970, under the guidance of the late Professor Shoichi Furuhama (former President of Musashi Institute of Technology), Mr. Masaharu Yuasa, my colleague, and I began research into hydrogen engines, or more specifically, how hydrogen fuel characteristics affect engine.

The primary energy source of hydrogen is natural energy, namely solar energy such as sunlight, Sun's heat, wind, hydropower and wave power including geothermal power and wave power. as well as the abundant water on the earth. The burning of hydrogen and air does not produce the emission of greenhouse gases such as carbon dioxide (CO_2). Strictly speaking, engines require hydrocarbon-based lubricants in similar way when the fossil fuels are used. The lubricants burn with hydrogen fuel producing up to 15 ppm of CO_2, CO and HC. And, as hydrogen is burnt with air, the emission of NO_x in the exhaust gas is dependent upon the operating conditions. However, the volume of greenhouse gases emitted from the exhaust gas is so small that it is not a source of pollution. The initial car engine test carried out at the institute showed that hydrogen fuel could be used as an alternative one to fossil fuels. To demonstrate this, a total of 12 hydrogen engine automobiles were developed. Recently, the technical standard of high pressure light-weight hydrogen gas cylinders fabricated by filament winding for the hydrogen fuelled vehicles has been established. That allows the automobiles to run the public roads with white number-plates on. An automobile equipped with a lightweight composite cylinder including hydrogen supply system for 35 MPa high-pressure hydrogen gas has made demonstration tests on the public roads. However, technical standards for the liquid-hydrogen fuel supply system have not yet been taken into consideration but will be discussed later in this report. It is hoped that these technical standards will be prepared in the not too distant future.

Essential requirements for automobile engines are lightweight, compact, high power output and low cost. To satisfy these conditions using hydrogen fuel, the fuel needs to have a high energy density. This technology is very difficult to achieve in principle, however an analogous hydrogen supply system has already been tested in our laboratory. This system utilizes a liquid hydrogen pump producing pressurized liquid hydrogen on board. The liquid hydrogen is gasified by using the heat of ambient air and engine cooling water. The

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gas at high pressure is directly injected into the combustion chamber of the engine. This prevents the occurrence of abnormal combustion. Moreover, the system produces power outputs,1.2 times greater than engines operating on fossil fuels. By further optimizing the hydrogen fuel drive engine operation, it is expected that the thermal efficiency will improve when compared to engines operating on fossil fuels. Thus, utilizing liquid hydrogen fuels will create an ideal hydrogen engine automobile [1)].

However, when using a standard fossil-fuel tank for liquid hydrogen storage, the liquid hydrogen would soon evaporate and vanish after it is put into the automobile. If, however, the liquid hydrogen remains in the fuel tank, it becomes pressurized owing to the evaporation and has a potential explosive hazard. Adequate insulation is required, but complete thermal insulation is physically impossible. Linde company developed a liquid hydrogen fuel tank having a hydrogen storage capacity of around 100-130 liters with the smallest evaporation loss of 1 % per day for BMW hydrogen fuel cars. However, despite these superior characteristics, this ultra-adiabatic tank proved unfeasible for automobiles from a cost point of view. The evaporation loss for a practical liquid hydrogen fuel tank is estimated to be around 5 % per day. In the future automobiles will have greater intelligence and require more electric power than now. So that BMW, liquid hydrogen fuelled engine vehicle company, they have a plan to capture and utilize the boil-off hydrogen gas. And they convert it to electricity by a small size onboard fuel cell. Even this method cannot solve the problem of the loss of liquid hydrogen in the tank. It is definitely true that the drivers do not want to have the liquid hydrogen in the tank lost while their cars are not used such when the cars are at parking lots and garages. The pressure in the tank of automobiles fuelled by liquid hydrogen hardly increases during driving. Because the hydrogen gas evaporated in the tank is utilized as the fuel while the engines are running. Research has been on-going in the development of a system to store the evaporated hydrogen gas using hydrogen-absorbing alloys, which could then be used, for example, to fuel automobile when the car is driven[2)]. However hydrogen-absorbing alloys have their storage limitations and the issues still remain unsolved while cars are not driven for long periods of time.

Apart from the original initiative of utilizing naturally evaporated liquid hydrogen as an automobile fuel, a study was carried out to find out which was cheaper, refuelling the same amount of liquid hydrogen as that of the liquid hydrogen naturally evaporated out to the atmosphere, or utilizing electricity to drive a cryo-cooler to reliquefy the evaporated hydrogen gas. Figure 1 shows the cost comparison between the cost of electric power for liquefaction and the liquid hydrogen cost for refuelling. The horizontal axis shows the evaporation loss volume (% per day) of a 100 liter fuelling capacity tank, and the associated costs are on the vertical axis. Calculations of liquid hydrogen fuelling costs are based on a selling price per litre. For the costs of the refrigeration system, the efficiency data were obtained from a commercialized small-type GM cycle refrigeration systems and then the calculation for the cost was made. The cheapest price of liquid hydrogen fuelling cost, as planned at the

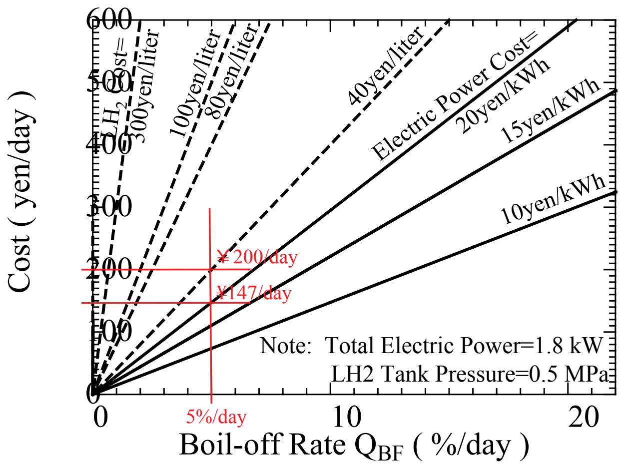

Fig. 1 Cost comparison between the cost of electric power for liquefaction and the liquid hydrogen cost for refuelling

Euro-Quebec Hydro-Hydrogen Project, was 40 yen/liter. Unfortunately, this has yet to be realized. However it is the cheapest price of liquid hydrogen that the author is aware of. The most expensive selling electricity price is that paid by households, priced at 20 yen/kWh. The typical evaporation loss of liquid hydrogen for hydrogen fuelled automobile use is around 5 % per day. Then the evaporation loss makes it 200 yen per day to refill the amount of the evaporated liquid hydrogen into the tank. Even when using the expensive electricity, the cost is only 147 yen per day when utilizing the cooling system with the efficiency data mentioned above. The cost of the electricity power is still cheaper compared to the cost of refuelling the amount of the evaporated liquid hydrogen. In 2002, our research was selected for the innovation task under the WE-NET program, commissioned by NEDO. Professor Yoichi Matsubara was the main member as he held the world's authority on pulse-tube refrigeration. And ten researchers who had interests in the field launched the project aiming at reducing the evaporation of the liquid hydrogen fuel loss to zero. An initial feasibility study was undertaken to investigate and select a compact refrigeration system to match the requirements for automobiles. Table 1 shows the results of the study. It was understood that the pulse-tube refrigeration system was deemed most suitable as a refrigerator for use in automobiles.

The successful development of the small cryo-coolers for reduction of liquid hydrogen evaporation loss to zero is a synonym for realization of an ideal automobile engine fuelled by liquid hydrogen and available for practical use. The project started in 2002, however, the majority of the research and development was carried out with liquid helium or liquid nitrogen refrigeration systems, with nothing for liquid hydrogen. It was repeatedly proposed that the pulse-tube refrigeration system was deemed the most suitable candidate for hydrogen-powered automobile engines, however, there were difficulties in accepting these proposals. Eventually, in 2008, experiments towards the realization of zero evaporation loss in liquid hydrogen got underway under an "exploratory research" provided by a grant-in-aid, sponsored by the Ministry of Education, Culture, Sport, Science and Technology and as "precedence priority research" at our university.

Table 1 Comparison of the Characteristics of Compact Cryo-coolers

Type	Characteristics	Adaptability to Cars			
		Compact & Light weight	Long Life	Simple Structure	Easy Operation
Micro-Joule Thompson Cryo-cooler	◆A few tens of MPa pressure gas required ◆Easy use because of light weight ◆Low vibration, low noise because of no moving parts	○	○	○	× (High Pressure Required)
Regenerative Cryo-coolers ◉Stirling cycle ◉ Vuilleumier cycle ◉GM cycle ◉Solvay cycle	◆Large Compressor required ◆Occurrence of vibration ◆Long start-up time (about 10 minutes) ◆Heavy, Large ◆Switching valves required	×	△	×	× (Large Compressor Required)
Pulse-tube Cryo-cooler	◆Simple structure ◆No moving parts ◆No vibration ◆High reliability to long operation	○	○	○	○

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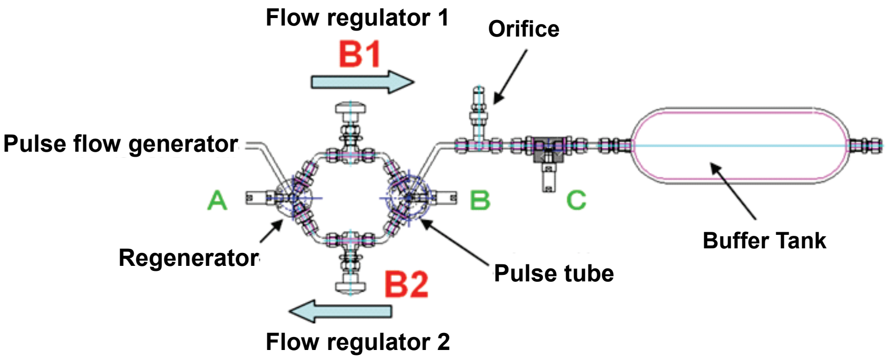

A : Regenerator pressure gauge
B : Pulse tube pressure gauge
C : Buffer tank pressure guage

B1 Cv max 0.37
B2 Cv max 0.37
Orifice Cv max 0.03

Pulse tube shape		Regenerator shape		Pulse moderator	
-Length	194 mm	-Length	120 mm	- Capacity	2 ℓ
-External diameter	20 mm	-External diameter	30.5 mm		
-Internal diameter	19 mm	-Internal diameter	30.0 mm		

Fig. 2 Schematic Diagram of the Prototype single-stage pulse-tube cryo-cooler fabricated

The funds allowed researchers to have a dedicated laboratory and begin the fabrication of a prototype system utilizing a pulse-tube refrigeration system. Fortunately, we also received guidance from Professor Yoichi Matsubara, leading to an initial prototype, single-stage pulse-tube refrigeration system, as shown in figure 2. Since then, the experiments for pulse-tube refrigeration system were carried out and research towards the realization of zero evaporation loss of liquid hydrogen has been advancing. Figure 3 shows the complete view of the prototype single-stage pulse-tube refrigeration system. For the time being, the targeted operational performance of the pulse-tube refrigeration system is to obtain 1W cooling energy against an input electric power of 300 W. In the future, the target would be to obtain 1W cooling energy at an electric power input of 100 W. Considering that the system components are almost the same as those used for the home refrigerators, the cost of the pulse tube cryo-cooler would be less than 100,000 yen when under the mass production.

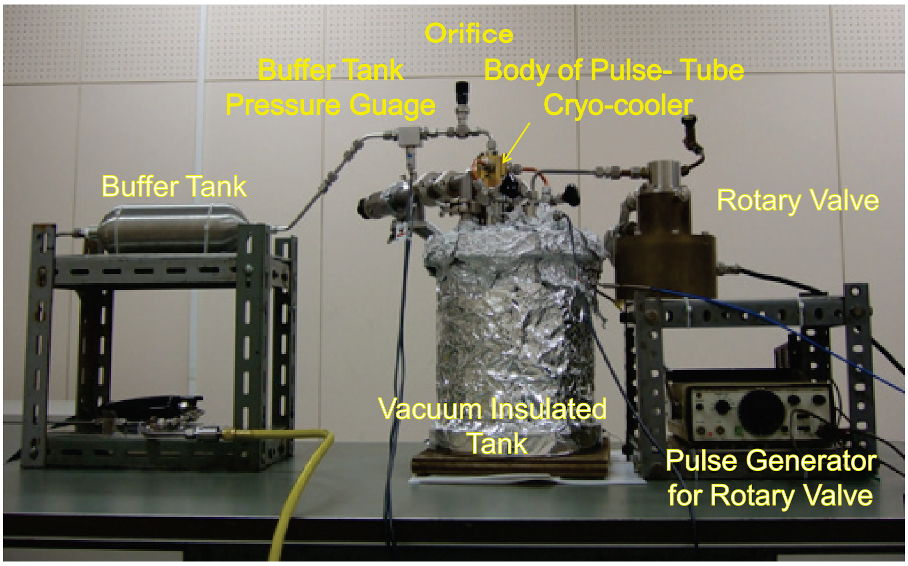

Fig. 3 Photo of the Prototype Pulse-Tube Cryo-cooler Installed on Test Bench

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Feature Article: The Forum on Superconducting Technology Trends - A Report on The 2011 Forum on Superconducting Technology Trends

Satoru Miyazaki, Director
Public Relation Division, ISTEC

International Superconductivity Technology Center (ISTEC) held The 2011 Forum on Superconducting Technology Trends, at Toshi Center Hotel (2-4-1 Hirakawa-cho, Chiyoda-ku, Tokyo), at 9:30~17:00 on 23 May, 2011.

The forum reports on the research outcomes from a vast array of projects, including the technological development on the Yttrium-based superconducting power equipment project entrusted and advanced by ISTEC. Companies, universities and research institutions, all of who have been advancing the research and development related to superconducting technology report their latest topics. The forum is held annually using funds provided by Keirin Race of JKA to facilitate discussions for the future development of industrialization of superconducting technology and the future prospects of research and development.

This year's forum kicked-off with opening remarks from Yutaka Kiyokawa, Executive Director of ISTEC, and was followed with congratulatory addresses by guests including, Hiroshi Fukushima, R&D Manager, Industrial Science and Technology Policy and Environment Bureau of Ministry of Economy, Trade and Industry, and Yoshiteru Sato, Director General, Energy and Environment Policy Department of New Energy and Industrial Technology Development Organization. There were five presentations delivered in the morning session followed by seven sessions in the afternoon. The year 2011 marks the 100th anniversary since the discovery of the superconducting phenomenon, and thus the lectures touched upon the historical aspects and the future technology trends.

Keynote lecture by Director General Shiohara, SRL/ISTEC

A keynote presentation during the morning session delivered by Yuh Shiohara, Director General of Superconductivity Research Laboratory/ISTEC, focused on "Welcoming the 100th Anniversary of Superconductivity – The Emergence of Oxide-based Superconducting Technology". First of all, after he

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conveyed the message of his condolence to all the people affected by East-Japan Earthquake, he reported on the history of superconducting technology, the structure of Y-based wires, the fabrication process trends and the future directions of research and development in Japan.

The afternoon keynote lecture was delivered by Kazumasa Togano, Research Adviser of National Institute for Materials Science, on the theme of “The History and Future of Superconductors”, where he reported about the time when the superconducting phenomenon was first discovered, high-magnetic field applications of metal-based materials, copper-based oxide high temperature superconductor, new superconductors (iron-based and metal-based materials), and the development of future applications.

Professor Jun Akimitsu, Aoyama Gakuin University, reported the “Exploration of New Superconducting Materials (From Hg to MgB_2, The Expectation of the Future)”, summarizing MgB_2 and its applications (MRI, nano-fine processing), the superconducting characteristics of diamond and SiC semiconductors.

Finally, Katsumi Tajima, Managing Director of ISTEC, made his closing remarks and successfully concluded the forum attended by 150 participants. We would like to take this opportunity to express our gratitude.

ISTEC will continue to plan and hold this forum, which contributes to promotion and the realization of practical application utilizing superconducting technology. We would like to ask you for your continuous support in future.

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Feature Article: Forum on Superconductivity Technology Trends - 100th Anniversary of the Superconductor -- Emerging Oxide Superconducting Technology –

Yuh Shiohara, Director General
SRL/ISTEC

Introduction

Firstly I wish to offer my heartfelt condolences to the people affected by the March 11 earthquake that struck northeast Japan, I pray for a quick return to normality as soon as possible.

Amidst the unprecedented countrywide difficulties afflicted by the huge earthquake and tsunami, the resulting nuclear power station accident, the scheduled blackouts due to a lack of electrical power and radioactive air pollution are resulting in social anxiety. Japan is now facing a state of emergency, the likes of which we have never seen before.

With this in mind, the Japanese Government revaluated the 4th Science and Technology Report (Fy2011-FY2015), which was at the midpoint of its framing. On 31st of March this year, the Minister of State for Science and Technology Policy, declared an interim action plan aimed at overcoming present difficulties by taking advantage of the knowledge and outcomes that have been acquired until now, and also clarifying the roles science and technology have to achieve.

With regards to superconducting technology, in March of this year, an "Energy Saving Technology Strategy 2011" plan was drawn up and implemented by the Agency for Natural Resources and Energy, which falls under the Ministry of Economy Trade and Industry, and New Energy Industrial Technology Development Organization (NEDO). This future development and Japan's rapid progress in superior energy saving technologies state that *"a strategic approach is desired to make Japan's world leading superconductor technologies to be a core technology for implementing practical energy saving systems*". Therefore, it is highly expected that Japan's superconducting technology will be at the forefront for energy saving technology initiatives.

This year welcomes the 100th anniversary since the discovery of the superconducting phenomenon discovered in mercury by H. Kamerlingh Onnes in the Netherlands in 1911.
At "The 2011 Forum on Superconductivity Technology Trends," the 100th anniversary was taken as an opportunity to look back at the history of superconductors and ascertain the expectations for future development. Reports were prepared by professors and Research scientists at the forefront in superconducting device applications, ranging from the exploration of new superconducting materials, high temperature superconducting wires and tapes, thin film electronic devices, to energy applications such as superconducting power devices.

1. Progress of Tape/Wire developments since the discovery of the superconducting phenomenon

It is now 100 years since Onnes first observed zero electrical resistance in mercury when it was cooled to 4.2 K. This pioneered future discoveries of various metal-based low temperature superconducting materials

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having a type II structural characteristic. The efforts of Bardeen, Cooper and Shrieffer led to the formulation and successful modelling of the BCS theory of superconductivity, and the basis of these findings allowed the realization of NbTi superconducting wires for commercial use leading to the low temperature superconducting device applications. Since the initial discovery of oxide superconductors in 1986, by Bednorz and Müller, a suite of copper-oxide material systems with high temperature superconducting properties have emerged such as, yttrium-based system (YBCO), a bismuth-based system (BSCCO), a thallium-based system (TBCCO), a mercury-based system (HgBCCO), all with superconducting critical temperatures exceeding the boiling point of liquid nitrogen of 77 K. Around the world efforts to produce superconductors operating at even higher temperatures reached fever pitch. Oxide-based superconducting materials have ceramic characteristics and the fabrication of silver-sheath tapes/wires was initially attempted to circumvent the fragile ceramic characteristics. The critical current density (@77 K, self-field) results from these fabricated silver-sheath wires/tapes were reported worldwide: YBCO - $4.1x10^3 A/cm^2$, BSCCO - $3.5x10^4 A/cm^2$, and TBCCO - $1.0x10^4 A/cm^2$. The disappointing, low critical current densities for the YBCO system made many apprehensive regarding the future potential for applications. In particular, the critical currents and critical temperature characteristics were regarded as important benchmarking characteristics for high temperature superconductor applications, and these initial findings in YBCO temporarily quelled the superconductor fever. Together with the opinions held by renowned physicists from around the world, a world-class science magazine, “Science” published a shocking abstract entitled, “Superconductivity: is the party over?” Just two weeks later, articles were published in the New York Times entitled, “Superconductors showing a flaw that dims hope; maybe inherently incapable of carrying enough current,” followed by an article published by Asahi Newspaper entitled, “High temperature superconductor; is it difficult to realize power transmission applications?” The focus remained on the maximum critical current density capabilities of superconductors at zero electrical resistance, and the applications that would emerge. It was after this that BSCCO long wires were developed, prepared using a single superconducting phase (2223 phase) and high density (oxygen partial pressure and high-pressure heat treatment), and utilizing silver-sheath wires. For the fabrication of YBCO wires/tapes, research and development has progressed allowing the formation of ihigh in-plane grain alignment technology as well as development in processing technologies such as IBAD, RABiTS and ISD. The research outcomes proved that the weak inter-grain linkage could be overcome using high-grain alignment technology. This again ignited the fever pitch worldwide, leading to intensified competition in the full-scale research and development of YBCO superconducting tapes. Recently, it is both the IBAD and RABiTS methods that have been adopted as the processes for grain alignment. In particular the IBAD method developed by Fujikura, has paved the way for ISTEC to develop technology that is quick and leads to high in-plane grain alignment by combining IBAD with PLD. This has led to further developments in the fabrication of longer tapes. A recent research report details PLD film fabrication technology using a Hot Wall RTR heating method, leading to the improvement in the uniformity of superconducting characteristics, achieving an I_C of ±1.35 % in the longitudinal direction.

Using the benchmarking characteristics of critical current (I_C) and length of conductor (L), figure 1 shows the progress of development of BSCCO and YBCO superconducting wires/tapes after the initial discovery of high temperature superconducting materials. The figure shows that after the discovery of high temperature superconducting materials, there was a rapid advance in the development and understanding of BSCCO silver-sheath superconducting wires as mentioned earlier. However, rapid advances in YBCO superconducting wires have overtaken these initial BSCCO materials. A comparison was made between the characteristics of each conductor having approximately a 1.1 mm^2 cross-sectional area (BSCCO wire 4.4 mm wide and 250 μm thick, YBCO wire 10mm wide and 110 μm thick, and both measured at a critical current (@77 K, self-field).

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The international benchmark comparison of conductor characteristics is shown in figure 2, which highlights the developments in YBCO superconducting conductors, with the critical current capabilities, I_C (@77 K, self-field) on the vertical axis, and the piece length of the conductor L(m) shown on the horizontal axis. The figure highlights the differences in development strategies for YBCO superconducting wires adopted by the USA and Japan. In Japan, research was initially aimed towards improvements in critical current characteristics (I_C), with companies then developing long- conductor technology. On the other hand, the USA, from the outset, focussed their entire research efforts towards the fabrication of longer conductors. Fujikura in Japan has recently reported the highest ever value product of critical current (I_C) and length of wire (L), exceeding 400 kAm. Japan is therefore the world leader for coated conductor development, and it is expected that further improvements in conductor characteristics, the production of longer conductors, an improvement in production yields, will reduce costs and allow mass production.

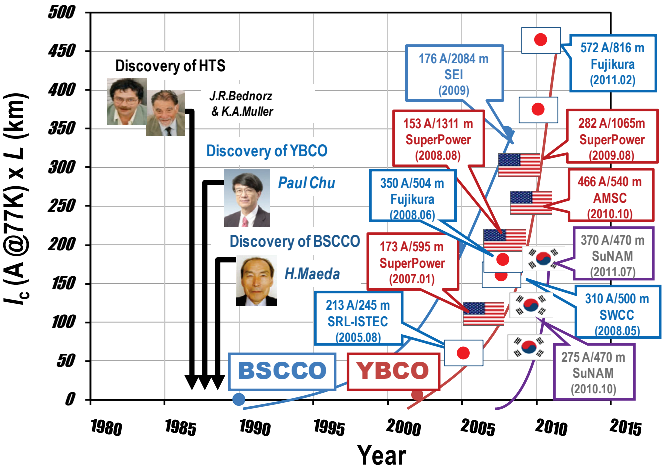

Fig. 1 Development of HTS conductors

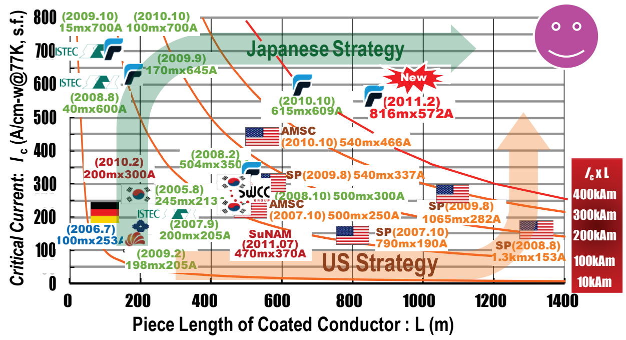

Fig.2 Development of Coated Conductors in the world (2011.2)

2. Development of Y-based superconducting power devices

Figure 3 shows the annual progression of the transmission losses encountered by power equipment in Japan. Over the past 30 years, 5 % of the total annual volume of electricity generated is lost due to transmission losses, which is regarded as being at a saturation point. A rough estimate conducted by the Agency of Natural Resources and Energy, calculate annual transmission losses in 2000 as being approximately 45.807 billion kWh, corresponding to the electricity generated by almost six, 1 million kW-class nuclear power plants, (1 million kW x 24 hours x 365 days x 12/13 (operation rate) x 6 plants – 48.52 billion kWh). Transmission losses can be categorized as, 2.5 % resulting from transmission lines, 1.9 % from power plants and transformer substations and 0.8 % from no-load losses (iron losses) due to pole transformers. It is expected that with the use of innovative superconducting

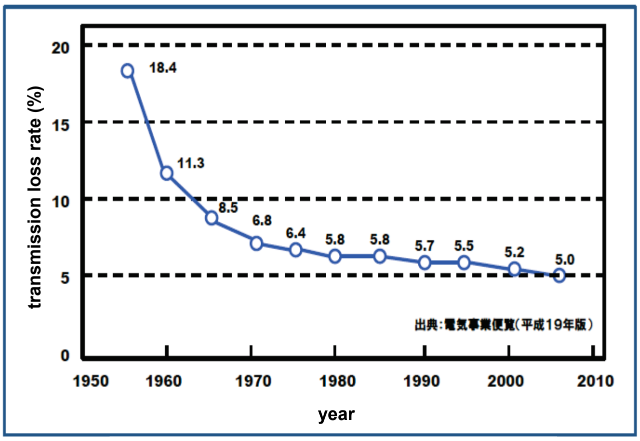

Fig. 3 Progress of transmission loss rate

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technologies saturated transmission losses could be reduced, as superconducting conductors have no Joule-losses caused by electrical resistance. The lower AC loss significantly reduces transmission losses and evades any cryocooling penalties.

2.1 Superconducting cable

Table 1 shows the historical developments of superconducting transmission cables. During the 1970s, the USA began cable developments utilizing metal-based low temperature superconducting wires (Nb_3Sn). After the discovery of high temperature superconducting materials in 1986, the period from 1999 to the early half of the 2000s saw Japan, USA, Europe and China advancing the development of AC transmission cables utilizing Bi-based superconducting wires. Since 2008, the focus of world research efforts has been shifting towards the development of Y-based superconducting cables.

Table 1 R&D Trend in development of superconducting cables

	Year	Superconducting Cable
1900		
	1911	Hg Discovery of Superconductivity
	1967	Design of 100GW DC cable (IBM) (Nb_3Sn, 1000km, 100GW, DC200kV/500kA, LHe@4.2K)
≀	1972	Brookhaven Superconducting AC-Power Transmission System, Start of research and development
	1982	Start of operation of the above (Nb_3Sn, 115m, 138kV-three-phase, 980MVA, @ 9K)
	1986～	Discovery of high temperature superconductor (YBCO: 1987, BSCCO: 1988)
	1999	30m Single-phase Bi cable *(SUMITOMO ELECTRIC, TEPCO)*
2000	2000	Southwire (USA) Single core three-phase Bi cable (12.5kV, 1.25kA, 30m)
	2001	Three core integrated Bi cable *(SUMITOMO ELECTRIC, TEPCO)* (66kV, 1kA, 100m)
		Detroit Edison (USA) Single core three-phase Bi cable (24kV, 2.4kA, 120m)
≀		Copenhagen Single core three-phase Bi cable (36kV, 2kA, 30m)
	2003	Yunnan project (China) Single core three-phase Bi cable (35kV, 2kA, 33.5m)
		Lanzhu project (China) Single core three-phase Bi cable (10.5kV, 1.5kA, 75m)
	2004	Single core Bi cable *(Super-Ace: CRIEPI, FURUKAWA ELECTRIC)* (77kV, 1kA, 500m)
	2006	Columbus (USA) Single core Bi cable (13.2kV, 3kA, 200m)
		Albabny (USA) Three-phase sharing from the same Bi coaxial cable(Bi/Y) (34.5kV, 800A, 350m/30m(Y)
		KEPCO Three-phase sharing from the same Bi coaxial cable (22.9kV, 1.25kA, 100m)
		Three core integrated Y cable *(NEDO Project)* (66kV, 1kA, 20m)
	2007	DAPAS Project (Korea) Three core integrated Bi cable (22.9kV, 1.26kA, 100m)
		Three core integrated Bi cable *(NEDO Project)* (66kV, 3kA, 200~300m)
	2008	LIPA (USA) Three core integrated Bi cable (138kV, 2.4kA, 600m)
		HYDRA (USA) Single core Y cable (13.8kV, 4kA, 300m)
		M-PACC Project *(NEDO)* (66kV, 5kA, 15m)
		M-PACC Project *(NEDO)* (275kV, 3kA, 30m)
		GENI Project (Korea) Single core three-phase Y cable (22.9kV, 1.26kA, 500m)
	2009	Russian Project (Russia) Single core three-phase Bi cable (20kV, 1.5kA, 200m)
		Super 3C (EU, Spain) Single core Y cable (10kV, 1kA, 30m)
	2010	New Orieans (USA) Single core Y cable (13.8kV, 2kA, 1760m)
	2012	Beijing Project (China) Y cable (110kV, 3kA, 1000m)
In the planning stage		Neuon Project (Amsterdam, Holland) Single core Y cable (50kV, 3kA, 6000m)

There are several benefits in the development of a Y-based superconducting cable and include, conventional underground transmission cable losses, which can be reduced by 1/3 and contribute to energy savings and a significant reduction in CO_2 emissions. Additionally, large-current capable power transmission cables can be realized, which are compact and are able to carry large amounts of electricity. These and other merits and characteristics of Y-based superconducting cables are shown in figure 4. In advanced countries the future vision of transmission lines is to switch to underground transmission lines, both from a safety point of view and the impact they have on the surrounding landscape. In major cities conventional power cables have been installed in cable tunnels with diameters of 2~3 m. Assuming a further increase in future electricity demands, the construction costs in the installation of new cable tunnels is expected to be immense. If however, the cable tunnels carry superconducting power cables it will be possible to install this cable in a duct with an approximate inner diameter of 150 mm, housed within an approximate 760 mm diameter conduit pipe buried underground. As shown in the diagram, the effective utilization of existing conduit pipes would allow the installation of more compact cables with larger capacities. On the other hand, amongst those existing power cables, it is estimated that many OF (oil-filled) cables and POF (pipe-type oil-filled) cables will be over 40 years old by 2020. This raises concerns about possible oil leakages from these old pipes and with the future plans for the installation of more and more underground transmission lines, these will have to be replaced in due course. Furthermore, the power transmission cables would make use of the large current-carrying capabilities of superconducting power to prevent overloading local power grids, as well as possibly simplifying power grids by replacing the existing 154kV circuit with a 66kV high-current transmission circuit.

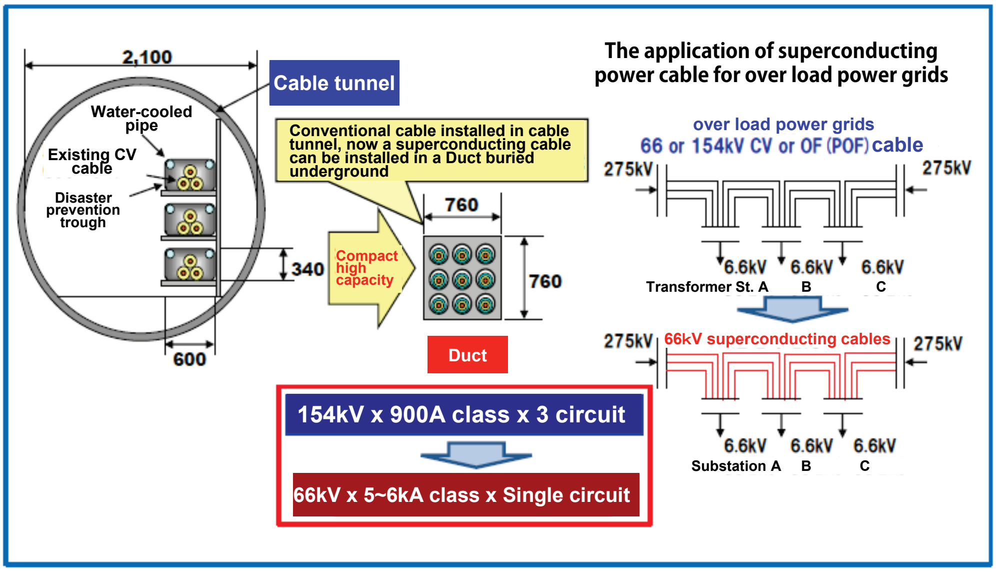

Fig. 4 Merits and characteristics of superconducting cables

Although the magnetic field generated during current transmission is small, the AC loss of a superconducting transmission cable could be almost in proportion to the square of the operating currents. Factors to reduce AC loss in superconducting cables would be to reduce the numbers of layers by significantly improving the critical current of the superconducting tapes, reduce the load factor (operating current (I_{OP})/ critical current (I_C)), and design a cable with a perfect circular cross-section as well as forming a spiral-shaped conductor, and thinning the superconducting layers of the tapes. Such factors are driving the research efforts of Y-based superconducting wires. For example, when the cross-section of the cable is made perfectly circular, it is then thickness of the superconducting tapes that determines the fluctuation -width (moving distance) for the fluctuation of magnetic fluxes when an AC current is supplied. For Y-based superconducting tapes, the thickness of the superconducting layer, including the Ag stabilization layer is a few tens of μm, compared to a thickness of approximately 250 μm for Bi-based wires (commercially available Bi-based superconducting wires excluding a BZO barrier layer between the 2223 superconducting filament/Ag matrix), Y-based tapes are 1/10-1/5 the thickness of Bi-based wires and

therefore a significant reduction in AC loss is expected.
In Japan, until now the development of cable technology has aimed larger current capabilities and low AC loss. Reducing AC losses has involved structural design of a "four-layer superconducting tapes and two-layer superconducting shield tapes," tested using short current test and joint tests, resulting in a cable loss of 1.5 W/m phase @5 kA and 0.4 W/m-phase@5 kA for the four-layer conductors and shield layers, respectively. There were no signs of degraded operational performance or other abnormalities. The development of high voltage and low dielectric loss cable technology has produced positive results in successfully reducing cable loss (AC loss and dielectric loss) down to 0.70 W/m. These tests also confirmed that joints made between strands at the midpoint of the superconducting cable has realized a low electrical resistance of several nΩ, and voltage impression tests showed that there were no abnormalities with the cables and the joints.

2.2 Superconducting transformer

Table 2 shows the history regarding the development of superconducting transformers up to present time. Since the discovery of high temperature superconducting materials in 1986, developments over the first half of the 2000s have seen countries such as Japan, Europe, USA, Korea and China all involved the development of superconducting transformers utilizing Bi-based superconducting wires. Especially in Japan, from the figure, Kyushu University has been at the forefront in the research and development of transformers aimed for train and carriage applications. It is also worth pointing out that there is a shift in research focus from 2006 onwards, which sees development efforts directed towards the fabrication of a Y-based superconducting transformer.

Table 2 R&D Trend in development of superconducting transformers

	Year	Superconducting transformer
1900	1911	Hg Discovery of Superconductivity
	1986～	Discovery of high temperature superconductor (YBCO: 1987, BSCCO: 1988)
≀	～	･Kyushu Univ., Bi-2223 Superconducting single-phase transformer: 630kVA, 6.6/3.3kV@77K
	1993	･ABB (EU), Bi2223 Superconducting three-phase transformer : 630kVA, 115/13.1kV, @77K
	1997	･SPI (USA, Waukesha et.al.), Bi2212 Superconducting single-phase transformer : 1MVA, 13.8/6.9kV, @25K
	1998	･Fukuoka PREF. Consortium (Kyushu Univ., Fuji Electric), Bi-2223 Superconducting single-phase transformer: 1MVA, 22/6.9kV, @66K
2000	2001	･Siemens (EU), Bi-2223 Superconducting single-phase transformer (for train/carriage) 100kVA, 5.5/1.1kV, @77K
	2003	･SPI (USA, Waukesha et.al.), Bi2223 Superconducting three-phase transformer : 5/10MVA, 24.9/4.2kV, @25K
	2004	･Super-Ace (Kyushu Univ., Fuji Electric), Bi-2223 Superconducting single-phase transformer: 2MVA, 66/6.9kV, @66K
		･DAPAS Project (Korea), Bi-2223 Superconducting single-phase transformer: 1MVA, 22.9/6.6kV, @65K
≀		･RTRI (RTRI, Kyushu Univ., Fuji Electric), Bi-2223 Superconducting single-phase transformer: 4MVA, 25/1.2kV, @66K
		･TBEA (China), Bi-2223 Superconducting three-phase transformer:630kVA, 10.5/0.4kV, @77K
	2005	･Siemens (EU), Bi2223 Superconducting single-phase transformer (for train/carriage) 1MVA, 25/1.4kV, @66K
	2006	･M-PACC project (NEDO: Kyushu-EPCO, TAIYO NIPPON SANSO, ISTEC, Kyushu Univ.) YBCO Superconducting three-phase transformer: 2MVA, 66/6.9kV, @66K
	2008	･SPI (USA, Waukesha et.al.), YBCO Superconducting three-phase transformer: 25MVA, 115/13.1kV, @70K

There are several advantages in developing Y-based superconducting transformers and include, an efficiency improvement compared to conventional-type oil-filled transformers, compactness, lightweight, requiring less installation space and noninflamable. Additionally, the use of Y-based superconductors for transformer conductor windings increases the current density allowing for a more compact design of transformer itself. Although these advantages have been realized with the development of Bi-based superconducting transformer, large AC losses still remained to be solved. To circumvent such AC losses it has been necessary to extract the corresponding heat load to the conductors by cryocooling. However, there were issues reported that suggested the cryocooling system needed to be increased in size. In the

USA, research on a superconducting transformer operating at cryogenic temperatures (~25 K), aiming for larger current densities, was temporarily halted due to significant problems associated with insulation. Figure 5 shows the merits and characteristics of Y-based superconducting transformers. Since Y-based superconducting tapes have superior critical current densities at high temperatures and high magnetic fields, it is possible to maintain its insulating characteristics by liquid nitrogen as coolant. In such cables, measures to reduce AC loss are different to the above-mentioned case where the AC loss is attributed to fluctuations in magnetic fluxes. These losses are due to the coil shape and mainly the loss caused by the fluctuations in the magnetic fluxes applied perpendicular to the surface of the tapes/wires. Thus, a filament with no electrical coupling is an effective measure to be able to reduce the fluctuation-width (moving distance). From the point of view of structural characteristics, Y-based superconducting tapes are composed of insulating buffer layers sandwiched between a metal substrate and a superconducting layer. There is a foreseeable possibility then to reduce the AC loss by striation (filament process) of grooving to be able to realize a width reduction of the Y-based superconducting tapes. For the first time, in Japan, by applying special winding technology and transposing the tape winding has proven to be successful with a coil using the tapes scribed into five filaments having 1/5 the hysteresis (magnetization) loss than a coil used non-scribed tapes. As mentioned above, the attributes for the development of a more compact, lightweight, high efficiency superconducting transformer system, including the cryogenic cooling system is highly expected from the utilization of Y-based superconducting tapes. As Japan instigated the development of Y-based superconducting transformers, the assumption is that this has prompted the USA to restart their development activities in this field.

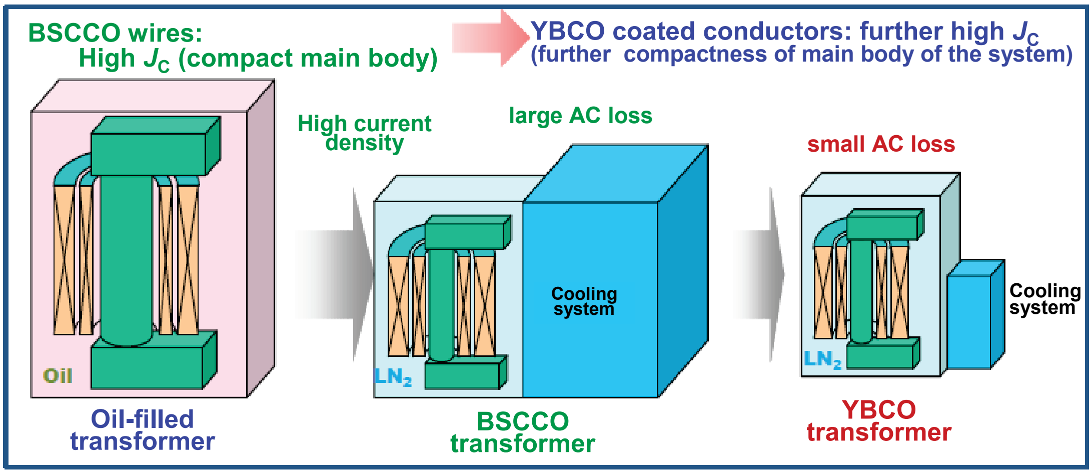

Fig. 5 Merits of transformer utilizing YBCO superconducting coated conductors

In Japan, current developments for a superconducting transformer utilizing Y-based superconducting tapes involve a prototype 400 kVA transformer, which is undergoing short-circuit evaluation trials. The trials confirm healthy characteristics of the transformer at six-times the rated value, as well as positive current carrying characteristics at 2 kA, revealing no deterioration in the tape windings and no abnormalities with short circuits tests. A verification test of a 2 MVA-class superconducting transformer model was performed. Investigation was carried out designing a 66kV/6.9kV-2MVA-class model as well a cooling system study, resulting in the system design of a 66kV/6.9kV-20MVA-class transformer utilized for a distribution system. Figure 6 shows a small-type tape -winding model that successfully limited a 1200 A fault current to 43 A, corresponding to 1/30 of the fault-current-limiting efficiency. A short circuit event results in the flow of a large current, and by taking advantage of the phase transition phenomenon of a superconductor in going from the superconducting state to the normal conducting state, the small-type wire-winding model successfully handled such an event by limiting the current supplied to the coils, (during transformer operation it is essential to protect the transformer from inrush current – the transformer does not limit the inrush current), thus not affecting transformer performance.

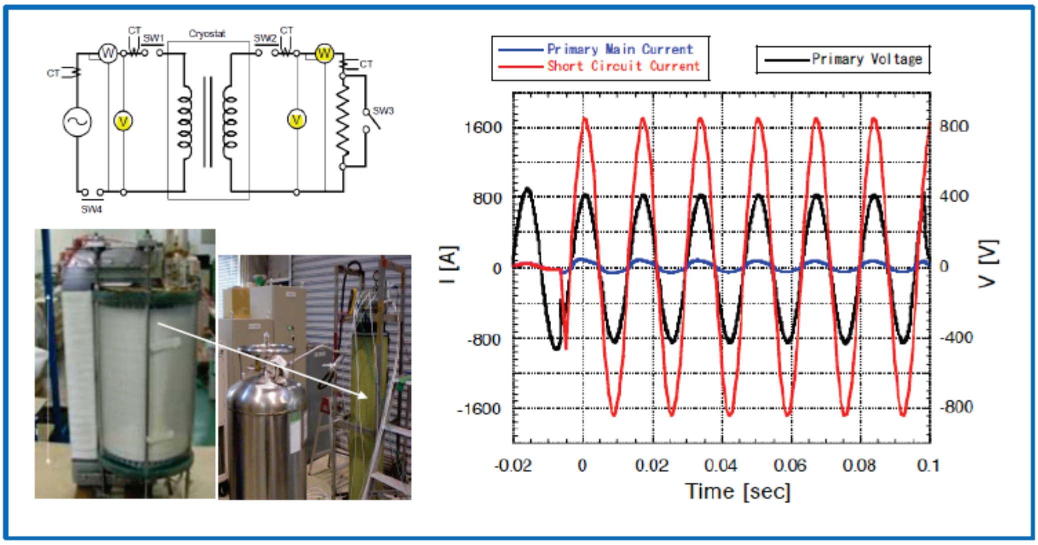

Fig. 6 Verification of current-limiting function additional to transformer

2.3 Superconducting Magnetic Energy Storage (SMES)

Worldwide development efforts for superconducting power devices are focusing upon Superconducting Magnetic Energy Storage (SMES) and current limiters, excluding the above-mentioned AC current transmission cable and transformer. In Japan, the developments of current limiters have advanced in parallel with the developments in transformer technology under the national projects. SMES system developments on the other hand, are required to adapt to the power grid control technology. The systems are widely expected to diffuse into industrial applications, utilizing small-scale SMES as well as voltage-sag mitigation technology required for high-tech industries where high quality and reliability in electrical energy are of upmost importance. In Japan, the research having led to the technological development for the fabrication of a high-magnetic field and compact coil, as well as the coil conduction cooling technology offering easier maintenance, has been followed by the development of highly reliable components with excellent tolerances, essential for the coil of the SMES system. The aims now are for the development of a 2 GJ-class SMES.

Up until now the largest scale SMES was rated at 20 MJ and employs NbTi-based wires. The development of a SMES utilizing Y-based superconducting tapes has only just begun. At the ARPA-E project launched last year by the Department of Energy (DOE) in the USA, reported a 3-year project for the development of a 3.4 MJ SMES operating @4.2 K and 30 T, and employing Y-based superconducting tapes. Although the development of a superconducting SMES (2.5 MJ), utilizing Y-based superconducting wires has been advancing in Korea as well, the scale of Japan's development of a 2 GJ-class SMES outshines them all. Several components coils for the 2 GJ-class SMES were already fabricated and tolerance tests involving

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carrying the large-current, hoop stresses (BJR calculated from magnetic field B, current density J, half-diameter R) were evaluated during operations. The results show hoop stresses exceeding 600 MPa for a multilayered coil, with a current capacity large enough to exceed 2.6 kA for 4-bundle conducting coil.

2.4 Applications for Industrial superconducting equipment

Y-based superconductors have strong critical current characteristics at high magnetic fields. Therefore further developments towards devices for various applications are greatly anticipated. Europe and the USA have both seen a considerable number of development activities for electric motors employing high temperature oxide-based superconducting wires. In Japan, this activity has primarily focussed on the development of ship-propulsion motors that utilize Bi-based superconducting wires. Additionally, activities to replace permanent magnet (PM) rotors in a synchronous electric motor with Y-based superconducting field coil (electromagnet) are ongoing, and are largely aimed at reducing the consumption volume of rare earth elements or rare earth metals used in PM such as, Nd and Dy. The power output of the rotors in a synchronous electric motor increases proportionally to the numbers of revolutions. However, the development of industrial electric motors exceeding 1000 rpm and ship-propulsion motors with 100~300 rpm, are likely to contribute energy saving effects in the future and the further development is anticipated. Moreover, the development of wind turbine generators (several 10's rpm) for sources of renewable energy and the reduction of CO_2 emissions are currently being advanced in Europe and the USA. The use of Y-based superconducting tapes is expected to give rise to more compact, lightweight and high-capacity generators. In particular further weight reduction of the wind turbine nacelle has been instrumental in the realization of a large-scale wind turbine generator (>3 GW), and further promoting the introduction of offshore wind turbine generators into the mainstream. Therefore, development efforts have focussed on at least replacing the field coil with Y-based superconducting electromagnets in order to improve efficiencies, eliminate the need for speeder gear (speed-changer) and reduce weight.

Device applications developments utilizing the characteristics of Y-based superconducting tapes such as high critical current characteristics in high magnetic field, are gathering such expectations. It was about 50 years ago since Nuclear Magnetic Resonance (NMR) was discovered, and NMR spectroscopy has made possible the analysis of complex organic molecular structures. Research interests in this field are now centred on the structural analysis of natural/artificial highly polymerized compounds, proteins and DNA. Such high performance NMR equipment employs superconducting magnets that generate intense magnetic fields. In Japan in recent years, such a superior NMR system has been developed to analyze complex proteins with high molecular weights. To further improve upon the performance characteristics, more intense magnetic fields are required to improve resolution and instrument sensitivity, and high spatial uniformity is required to improve signal separation and high time stability is required to allow signal accumulations to be made,

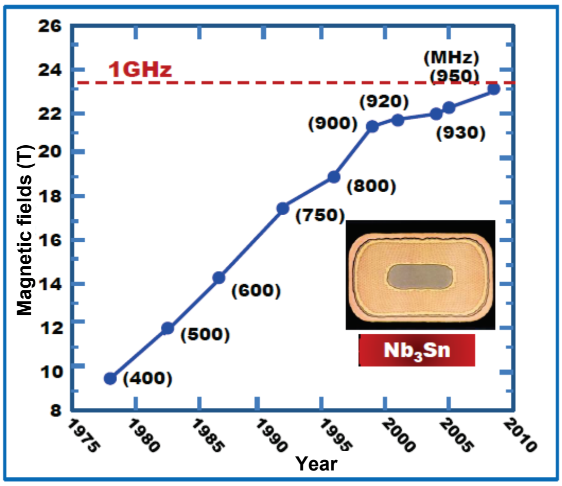

Fig. 7 Progress in the development of higher-magnetic fields for NMR magnets

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reduce in-field drift caused by the shielding current generated within the superconducting wires by utilizing the excitation and demagnetization control. Figure 7 shows the progress in the development of a High field NMR magnet. The magnetic field for high resolution NMR at 1 GHz, requires fields exceeding 23.5T. Current worldwide NMR development efforts are being undertaken to improve resolution (higher magnetic field).

Such endeavours, which have been impossible until now, can only be realized by using Y-based superconducting tapes, which have the added bonus of realizing possible NMR systems with magnetic fields exceeding 1 GHz (23.5 T) and achieving a more compact magnet. As mentioned previously, for an NMR instrument, a high magnetic field (=high frequency), this equates to higher resolution and greater sensitivity. However, whilst it has been possible to increase the sensitivity and instrument resolution for an NMR system using a high field magnet, this has come at the expense of the magnet size. By utilizing mechanically strong Y-based superconducting tapes allows for a more compact NMR magnet with greater magnetic field strengths than conventionally available NMR instruments. Focusing on this point, the developments of next generation NMR magnets are currently advancing in Japan.

Figure 8 shows a comparison of the industrial standard critical current densities measured in high magnetic fields (J_e: the value of critical current I_C divided by the cross-sectional areas of the conductors) for each type of conductors. What are noticeable from this figure are the remarkable high-magnetic field characteristics of Y-based superconducting tapes. The J_e characteristics of Y-based superconducting tapes at 20 K are superior to Nb_3Sn at 4.2 K (liquid helium temperatures), which are considered to have the best performance amongst metal-based low temperature superconducting wires. Additionally, this J_e value implies that it is at a practical application level in 30 T magnetic fields. In the future, it is expected that the development of a system utilizing Y-based high temperature superconducting tapes aimed at 1 GHz (23.5 T) operations will be competed in Japan, USA and Europe. Thus, for the time being the developmental competition for a superconducting electromagnet with an ultra- high magnetic field aimed for high resolution NMR will likely intensify.

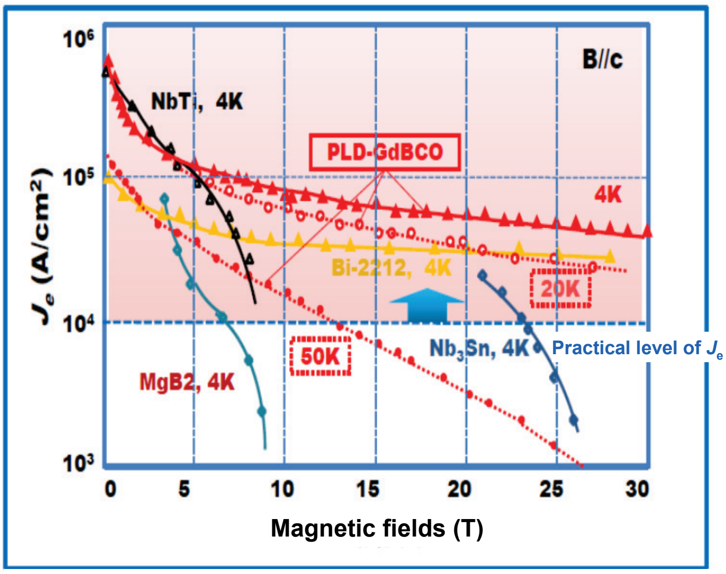

Fig. 8 Engineering Critical Current densities as a function of magnetic fields for several different superconducting wires/tapes

3. Future developments

The Materials and Power Applications of Coated Conductors (M-PACC) project using Y-based superconducting tapes, have now reached the midpoint having completed the first three years of the project. The remaining two years will see the efforts made towards individual themes, (SMES, cable, transformer, Y-based superconducting tapes) and achieving the final targets as early as possible. Technical developments satisfying practical requirements will be undertaken (verification tests such as long-term

reliability) after the project ends, and will trigger the start of practical assessments such as system introduction and penetration into the market from 2020 onwards. Furthermore, together with a review of the execution structure of the research and development, the entire project will be progressed with collaborations between various research institutions and other national projects, by sharing research outcomes as well as consolidating research and development efforts.
It is superconductor technology that holds the key to realizing the benefits of greater device efficiencies and system compactness resulting in technologies that remarkably lead the way to solve environmental issues such as the reduction of CO_s emission and energy savings. Additionally, the technology is expected to sustain the superiority of Japan's technology as the leader in this field becoming a strategic growth area. Moreover, by 2020, it is equally important to establish an all-Japan research and development structure in order to advance technological development aimed at successful, practical applications and take up the business opportunities afforded by the superconductor industry.

This article partially refers to the research outcomes of the "Materials and Power Applications of Coated Conductors (M-PACC) project" supported by the New Energy and Industrial Technology Development Organization (NEDO).

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Feature Article: Forum on Superconductivity Technology Trends - History and Future of Superconducting Wires/Tapes

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Considering the array of potential applications for superconductors, wire development is anticipated for large-scale applications especially power devices. Historically wire development has been ongoing since the early discovery of metal-based superconducting materials in 1911. The 1950s saw the commercialization of NbTi wires. In this report, the historical and recent developments that were introduced at the Forum on Superconductivity Technology Trends are summarized. The historical and development trends elaborated in this report pertain to metal-based and the recent wave in oxide-based superconducting wires.

The most common metal-based superconducting wires are composed of NbTi materials. This material has a T_C of 9 K, although not considered high, it has superior processing characteristics and the majority of superconducting equipment applications currently utilize this material. Initially, research and development activities were devoted towards solving issues such as superconducting quenching caused by AC loss. Today, improving mechanical stability of the wire material, multifilament, thinner filaments and twisting are favoured topics. NbTi wires are the only superconducting materials that have been widely commercialized and are extensively used for MRI applications. The most familiar superconducting material application is the maglev train. As a similar metal-based superconductor to NbTi, Nb_3Sn superconducting wires are chosen particularly for their superior characteristics and are employed in applications where they are subjected to severely high magnetic fields. These materials have a higher T_C than NbTi, of 18 K, with greater critical magnetic field characteristics such as H_c of 28 T compared to 10.5 T for NbTi, allowing them to be utilized in applications requiring high resolution (high magnetic field) NMR and ITER. The development of wire fabrication technology has mainly involved external diffusion as well as bronze methods. As with NbTi wire development, the progress of extremely thin multifilament Nb_3Sn wires has involved ternary additions with a view to further improve in-field characteristics. Contrary to these Nb-based superconducting wires, a new group of metal-based materials, namely MgB_2, recently discovered by Professor Akimitsu and his research group, have shown promising results with the top T_C characteristics of 39 K. Fabricating methods of MgB_2 superconducting wires have developed mainly from the PIT method, with the technological development of higher densities having been actively carried out by mechanical alloying and diffusion methods, resulting in the improvement of the wire characteristics. Recently, an Italian company has begun production of long wires and developing equipment aimed for applications operating at 20 K.

The widespread dissemination of equipment applications mentioned above that employ metal-based superconducting materials, are hampered by the massive cooling loads required to reach the cryogenic temperatures and thermal instabilities due to the small specific heat. There are possible swift resolutions available that involve using high temperature superconducting materials. Such developments utilizing Bi-based superconducting materials, discovered by Dr. Maeda, and Y-based superconducting materials discovered by Dr. Chu in the USA, have become the mainstream worldwide. Although other materials such as Tl- and Hg-based superconductors, which have superconducting characteristics with even higher T_C's have been discovered, their poisonous nature detracts from mainstream use and Bi- or Y-based materials have thus proved more attractive. Amongst the two, wire developments utilizing Bi-based superconducting materials have progressed. The major factor behind the preference of Bi-based over Y-based wire fabrication is due to the well-researched PIT method of utilizing a silver tube. Of importance of the PIT method is the major breakthrough by the process development of the sintering method under high pressure that is able to realize high-density superconducting materials at the last stage of heat treatment. The higher density has promoted reactions in forming a superconducting phase and achieving an almost 100 % superconductivity volume fraction, and at the same time introducing other merits such as homogeneity and mechanical strength. Short wires produced using this method have already achieved an I_C value of 250 A with mass-produced long wires achieving 180 A. The development of Bi-based materials started earlier, and aimed at a particular application. Several projects for transmission cable developments are ongoing, with an operational power grid test at the Asahi substation of Tokyo Electric Power Company currently in planning, in order to evaluate performance, under the "Superconducting Transmission System Verification Project". These wires are currently supplied for the development of an array of ship motors as well. Recently, a new application field has been opened up in the use of magnets for billet heating, which has already been successfully put to practical use.

On the other hand, the development of Y-based superconducting wires has too been rapidly advancing, as they have a number of advantages over their Bi-based counterparts, such as future cost, in-field characteristics, mechanical strength and low AC loss properties. Even though there were superior materials characteristics of Y-based superconducting wires since the time of their discovery, employing the same silver-sheath method resulted in Y-based superconductors with poor process characteristics relative to Bi-based materials. Thus, alternative, small-scale research for Y-based wire development has been undertaken at laboratory level to continuously investigate the fabrication of longer wires using technology and fabrication methods usually utilized for thin film materials. The national project launched in 1998, has led the remarkable progress in the development of Y-based superconducting wires. The grain boundary orientation structure is essential to realize high performance characteristics of Y-based wires. To achieve this, several methods were suggested, but amongst these the most appropriate and valid method currently involves a buffer layer deposited by IBAD or a method utilizing a metal substrate to achieve the necessary grain orientation. Several methods were attempted as well to form the superconducting phase, at present the ability of alternative methods such as PLD, MOD, and MOCVD has progressed with the fabrication of long wires. Full-scale development efforts during the past ten years or so, have led to initial achievements of 1m and a few tens of amps, to now where an 816 m-572 A has been demonstrated by Fujikura. In the past it was both Japan and USA who were the world leaders in the developments of Y-based superconducting wires, with both countries having competed to secure the top spot. Recent trends in development of Y-based wires are application specific. Until now, the benchmarking characteristic of wire development was the product of self-field I_C and length. As presented in the "M-PACC" project, since the start of full-scale development of application-specific equipment, it has emerged that these application specifications are more diversified and specialized. This opens up further avenues of development work towards components technology to respond to those specifications requirements. For example, developments for in-field applications involve the improvements in I_C characteristics in a magnetic field. Such developments have realized in-field characteristics (@77 K, 3 T) of 40A-90m and 30A-60m, respectively by using an approach to improve the self-field as well as in-field characteristics by thick film fabrication as well as adopting methods to disperse $BaZrO_3$ nano-sacaled rods as artificial pinning centre (APC). Recent developments investigating APC in new materials has resulted in the realization of 70A@77K at 3 T, even for short wires. Furthermore, as component technology is being developed for AC applications, it has become essential that AC losses in the wires be reduced. To address this issue, a wire scribing process has been developed to achieve uniform wire characteristics and wire thinning process technology. For a 5 mm-wide, 50 m-long wire scribed into five filaments, demonstrated that AC losses reduce by 1/5 compared to non-scribed wires. Worldwide research efforts also confirmed the reduction of AC losses in short wires, however results have not yet been proven in any other longer wires. It is only recently discovered that AC losses can be minimized in wires that have remarkably high grain boundary orientations. This phenomenon is still at an early stage of understanding and seems to be limited to short wires under specific conditions such as temperature and magnetic field. However, this phenomenon itself is able reduce AC losses without the need of employing a scribing process. There still remain many unanswered questions to the theory, however the phenomenon does open the possibility in the realization of reducing AC losses in many applications without the need for additional processing such as scribing.

This article reported the history and present situation regarding metal and oxide-based superconducting wires utilized in practical applications, and those wires that are almost ready for practical applications. Figure 1 summarizes the characteristics and the historical background to each type of wire. Following the successes achieved by metal-based superconducting wires leading to practical applications, MgB_2, Bi-, Y-based wires each have the potential to become the future application forerunner.

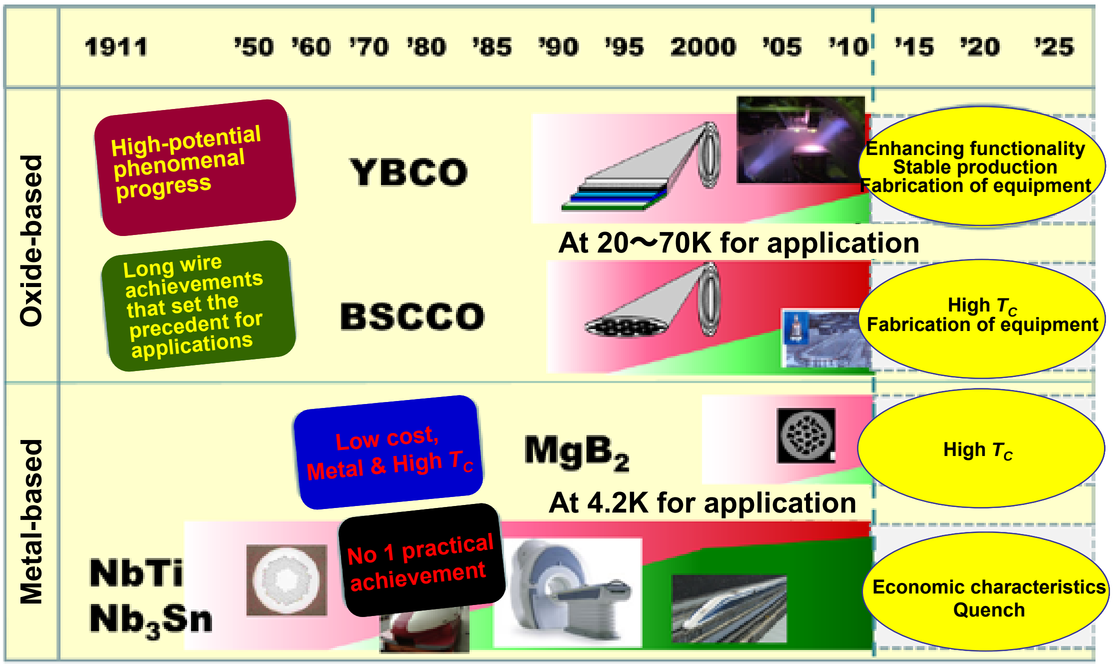

Fig. 1 A summary of the history and trends of superconducting wire development

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Feature Article: The Forum on Superconductivity Technology Trends - The past, Current and Future for Low AC Loss Technology in Superconducting Wires

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At this Forum on Superconductivity Technology Trends, the progress and trends for low AC loss technology for superconducting wires and conductors were reported together with the research and development of associated superconducting applications.

AC losses in superconducting wires and conductors are fundamentally owing to hysteresis and coupling current losses in wires. Additional AC losses are due to superconducting Joule-losses generated by the inter-strain coupling current induced between the strands, (please refer to page 3 of the PDF document). The dynamic resistance loss occurs during the simultaneous application of an AC transport current and an AC transverse magnetic field. However, the hysteresis loss is usually reduced when the dynamic resistance loss is induced and therefore does not need to be considered when estimating the AC loss.

For the case of multifilamentary wires with circular cross sections, the hysteresis loss (per unit volume of the superconducting strands per cycle) is described by the following formula:

$$W_h = \frac{16}{3\pi} J_c(B_m) d_f B_m \quad (for\ B_m >> B_p)$$

$$B_p = \frac{2}{3\pi} \mu_0 J_c d_f$$

The coupling loss (per unit volume of the superconducting strands per cycle) is described by the following formula:

$$W_c = \frac{2\pi\omega\tau_c}{1+\omega^2\tau_c^2} \frac{B_m^2}{\mu_0}$$

$$\tau_c = \frac{1}{2}\sigma_{\perp}\mu_0 \left(\frac{l_p}{2\pi}\right)^2$$

Here, B_m is the magnetic field amplitude, d_f is filament diameter, B_p is full penetration magnetic field, l_c is coupling constant, σ is the traverse electrical conductivity in the conductor, l_p is the twist pitch, ω is the angular frequency.

The above equations have been tested quantitatively from research and standardization studies conducted over a number of years. The equation of hysteresis loss is in accord with the critical state model (this is where the electromagnetic phenomenon that occurs within the superconductor, when the critical current density, J_c, is determined at the point where the Lorentz force at the fluxoids and the pinning force are equal, and the current density of the superconductor is limited to J_c or 0). Metal-based low temperature superconducting wires with NbTi or Nb_3Sn, and high temperature Bi-based oxide superconducting wires display this electromagnetic phenomenon. However, apart from this, in such material-based superconducting wires the fluxoids are able to reverse within the pinning potential, the so-called reversible behaviour of the fluxoids, (this reversible behaviour is only observed at low magnetic fields with submicron-diameter multifilamentary wires). The above-mentioned equations show that low AC loss or low hysteresis loss occurs when the filament diameter is made small, and also that a low coupling loss is achieved by having a high resistivity matrix in the conductors as well as a short twist pitch (P5 of PDF documents). Using this knowledge, the fabrication of low temperature superconducting wires for low AC loss applications has been advanced. A typical example is shown (P6 of PDF documents), with the fabrication of extremely thin multifilamentary wires for AC use.

However, for large-current capacity conductors (wires strands), reducing AC losses proved always challenging, (PDF document, p7-9), where additional AC losses occurred relating to the conducting structure or the coupling loss between the strands, which far exceeded the total hysteresis and coupling loss of the individual wires. The only solution was to insulate between the strands or maximize the contact resistance between the strands. However, low AC losses were achieved at the expense of increasing wire instability. Owing to its monolithic superconducting structure, wire strands fabricated from low temperature superconducting materials have AC losses that can be ignored or do not need to be considered as having much AC loss. Hence the reasons why such wires are currently utilized for DC or pulsed current applications are only where stability is of paramount importance.

Furthermore, when using low temperature superconducting wires for power devices applications, the issues associated with the operating temperatures cannot be avoided. A superconducting magnet for DC or pulse applications is driven by its own power supply, however for the case of power devices, the interference from the power grid caused by excess current and voltage relentlessly intrudes the superconducting windings. An example of this is when a lightening surge penetrates the transformer's windings leading to current and voltage oscillations. For conventional high-voltage transformers with normal conducting windings, a damper winding such as interleaved windings are usually adopted as a means to reduce any electrical gradients generated within the windings. The principle of operation is to reduce electrical gradients along the wire windings occurs by rapid charge transfer, leading to the reduction of potential oscillations at the cost of intensifying the current oscillations. Even by using extremely thin multifilamentary wires designed specifically to minimize AC losses, the AC losses due to current oscillations are more than two-digits larger than commercially used frequencies at normal operation. By introducing test waveforms as defined by JEC, the temperature of the superconducting windings exceeds the critical temperature, T_c, causing superconducting quenching to occur, (PDF document, p11-15). Even if current oscillations did not occur, any type of electrical surge is equivalent to a unipolar impulse voltage applied on the superconducting windings. Additionally, when a switching surge with a long-duration wave-tail penetrates, the current monotonously increases and rapidly exceeds the rated critical current, I_c, (PDF document, p16-17). The reasons behind this are due to the low temperature operation of the superconducting wires, 4-6 K, resulting in the specific heat being 1/1000th compared to that of room temperature. In fact realizing power devices using low temperature superconducting wires proved to be extremely difficult and challenging.

Even by fabricating extremely thin, sub-micron diameter, low temperature metal-based multifilamentary wires aimed for electrical equipment applications, which displayed low AC loss characteristics with a Cu-30Ni high resistance conductor, and a 1-2mm short twist pitch could not fully realize the performance characteristics of equivalent copper wires. The desired low AC loss characteristics had to satisfy wire-level as well as conductor-level performance, and additionally the stability of superconducting conductor. To satisfy all these conditions was challenging using superconducting wires fabricated from low temperature superconducting materials as the specific heat in these materials is small. Thus, the only hope was left to replace conventional copper wires was to utilize high temperature oxide-based superconducting wires.

Therefore, back in 1992, when research and development efforts for the Super-GM project were vigorous, at our research team a clear-cut attitude was adopted towards the use of low temperature superconducting wires; they could only be used for DC and pulse applications. This shifted the research objectives leading to the development of high temperature superconducting wires and conductors aimed for wide applications in superconductor technology industries.

High temperature superconducting wires operating at liquid nitrogen temperatures of 64-77 K, were utilized, and any power surge invading the superconducting windings from the power-grid fluctuations would be greatly reduced since the specific heat is 1000 times larger that at 4.2 K, allowing more stable operation. Actually, a prototype-superconducting transformer utilizing Bi2223 wires have been employed to verify the safety and stability by subjecting it to a lightening impulse voltage of 100 kV and 350 kV, against the transformer rating of 22 kV and 66 kV, respectively, as defined by JEC protocols.

Oxide-based superconducting wires do not have a large current capacity. However, wires were fabricated utilizing the tape-type oxide superconducting wires technology and transposing parallel conductors conventionally used for copper winding wires for normal conducting equipment applications were adopted (PDF document, p18-28). The strands were transposed only at the minimum number of points. A fundamental theoretical and experimental study to analyse the AC loss characteristics of the transposed parallel conductors was undertaken (PDF document, p23-25). Each of the prototype transformers, as well as the conduction-cooling system pulse coils, was made up from an oxide superconductor, utilizing superconducting windings with transposed parallel conductors. For superconducting windings composed of transposed parallel superconductors, these tests verified that there was no fundamental additional AC loss occurred during the conduction, and showed that the AC loss density in these superconducting parallel conductors is equal to that of a single stand under identical conditions, (PDF document, p26-27). Moreover, a prototype-testing coil composed of 24-parallel conductors was fabricated and verified that the structure of having transposed parallel conductors was adaptable to Y-based wires too (PDF document, p30-31).

Having realized the fabrication of a stable conductor with a high specific heat, as well as the suppression of additional AC losses with the development of transposed parallel conductors, the only challenge of reducing AC losses remained in the individual superconducting-oxide wire strands. However, Bi-based wires with a multifilamentary structure having a low AC loss have not yet been realized because of a superconducting junction between each individual filament. Thus, testing to realize low AC loss was undertaken using Y-based taped wires. A new method to reduce the AC loss of the superconducting tapes was investigated. The process involved the combination of scribing a superconducting layer into a multifilamentary structure and a bespoke wire-winding fabrication process. The process was successful and a world's first, reducing AC loss in wire windings, pro-rata to the filament width (PDF document, p32-38). Up to this point the research and development of low AC loss conductors was based upon conventional theory and a critical state model.

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In recent years, we have discovered a new phenomenon of the magnetization of Y-based wires and a significant reduction in AC loss (PDF document, p39-50). Employing 10 mm-wide wires without a multifilamentary process, AC loss was reduced by two-digits compared to that predicted by conventional theory. This phenomenon is not explained by either Maxwell's equations or conventional theory, but we believe it is due to the magnetic phase transition phenomenon attributing to the structure of REBCO superconductor and its superconductor characteristic anisotropy. By introducing CuO_2 superconducting layers, multi-laminated and parallel with the surface of the tape, the REBCO superconducting layers formed (PDF document, p49). When fluxoids penetrate perpendicular to the CuO_2 superconducting layer, the system energy increases only by the amount of condensation energy due to the fact that the fluxoid is at which point the superconducting electron density is zero, and is a normal conducting core. On the other hand, regardless of what effects arise, when the fluxoids enter parallel to the CuO_2 superconducting layer, the layer remains superconducting and thus no increases in energy occur. When parallel to the CuO_2 superconducting layer, the fluxoid penetrates easily. Future efforts to quantitatively clarify the AC loss when this phenomenon occurs will be undertaken.

A combination of a scribing process with a bespoke wire-winding process, or either taking advantage of the new phenomenon has enabled the reduction of AC losses of Y-based superconducting tapes. The application of transposed parallel conductors verified that additional AC losses were not induced during conduction. A high specific heat allowed stable operation of the wires, essential for power equipment and device applications. Now full-scale research and development should be made for both superconducting DC and AC power applications, and electrical equipment employing Y-based superconducting wires, which have almost reached the point of possible practical applications.

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Feature Article: The Forum on Superconductivity Technology Trends - The Possibilities of Y-based Superconductors for Rotating Machine

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SRL/ISTEC

In this presentation, the development of the “Superconducting Applications by Y-based superconductor” was introduced, and mainly focussed upon recent research and development activities in superconducting rotating machines; motors and generators.

1 Background

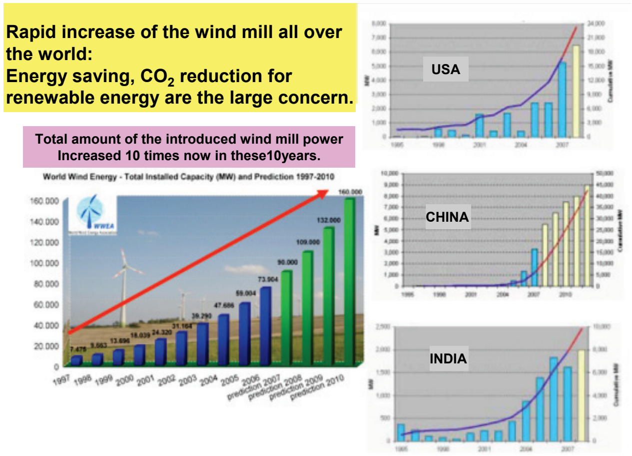

Fig. 1 The progression in the worldwide numbers of wind turbines

The world population has been increasing rapidly, with population projections by the United Nations over 50 years ago, increasing from 2 billion to 6.9 billion (2010) during 50 years. Thus considering the demands on energy consumption due to improving world living standards, the utilization of natural resources and energy needs to be managed more effectively. At the same time, methods to save energy and natural resources are aimed towards being more considerate to the environment by reducing CO_2 emissions. In light of this, the demand for renewable energies such as wind power generation has increased significantly worldwide. Figure 1 shows the numbers of wind power generators introduced in the USA, China, India and the rest of the world, the number has increased 10 times during the past 10 years.

If the superconductor is applied in such a field as wind mill or rotating machines described here, the efficiency of the machine will be expected to be improved drastically, which can benefit for the future energy-saving society.

2 Superconductors

Many superconducting rotating machines have been already developed using Bi-superconducting conductors. A superconductor does not generate heat during the operation because of its zero resistance, benefitting the efficiency rating of electrical equipment and resulting in energy savings. Typical example is shown in Figure 2 and the Bi-superconductor has been used in the field coil (center). The superconducting field coil can generate a

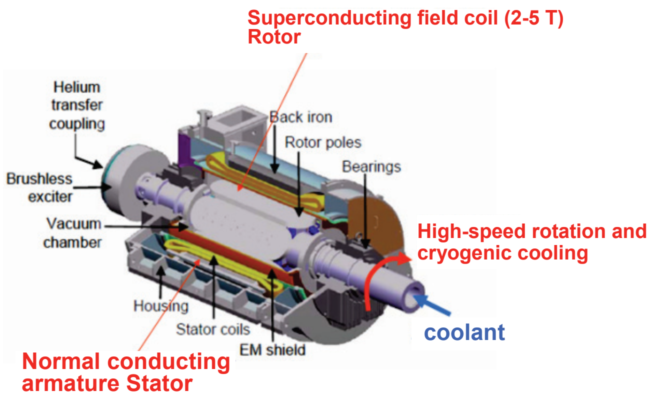

Fig. 2 An example of superconducting motor by AMSC

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stronger magnetic field to rotate with high operating current and zero resistance. So the machine generates lower electric loss and show high efficiency. Up to now, such superconducting rotating machines have been already fabricated, for example, aiming at electrical ship propulsion system by AMSC, Siemens, Doosan (Korea), and Kawasaki Heavy Industries utilizing Bi-based superconductor. The electric ship system is now becoming popular to save the energy resources even by using a normal conducting electric motor (see typical example of Figure 3). When replacing the normal motor to the superconducting one, the efficiency will be increased more and then the industry has been trying to use the superconductor in the motor.

Fig. 3 Example of an electric-propelled ship: 70,000ton class gorgeous large passenger carrier ship equipped with "Elation"42.8 MW motor. Applying the electric propulsion system, the motor was placed outside the ship and the ship was created more spacious inside. Vibration and noise as well were largely reduced.
http://www.cruise-mag.com/db/profile.cgi?_v=1204176961&tpl=view

3 The movement toward Y-based conductors

Instead of the above Bi-based superconductor, Y-based one is now being considered for the application of the rotating machine. Recently, there have been significant advance in the length of Y-based conductors and their critical current characteristics. This has initiated Y-based high-performance rotating machine applications. "Converteam" in UK and "AMSC" in USA have both carried out design investigations in of a superconducting wind mill generator for l8-10MW-class. In the background mentioned the section 1, there are many development plans in Europe and the USA for a large-scale offshore wind-park utilizing large wind turbines (Figure 4). This proves that there are demands for such large size wind turbines. However, the current mainstream of the wind turbines commercially available are typically 1.5-2MW-class. When increasing the capacity using a conventional normal conducting generator, the weight and the size of the wind turbine would increase significantly. Thus difficulties arise in the installation and placement if it would be placed in the tower as high as 100m. The size and weight are increased drastically with increasing its power. Then, a permanent magnet instead of current Cu conductor windings is now trying to be used in a larger one as shown in Figure 5, because permanent magnet system can reduce the size and weight.

Fig. 4 Example of off-shore wind turbine generators in the USA: Large-scale plan is advancing. Planned to install several hundreds of MW class system.(Renewable Energy Focus, HP
http://www.renewableenergyfocus.com/

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According to the companies above, the use of Y-based conductors has led to a significant reduction in both the weight and size compared to a conventional induction generator utilizing Cu windings and the permanent synchronous system. For example, a 10 MW-class generator has a weight of 800 tons using a conventional Cu winding. However, if realized a superconducting generator, it would have a weight of only 500 tons approximately, with a 120 m tower height and a 190 m blade diameter.

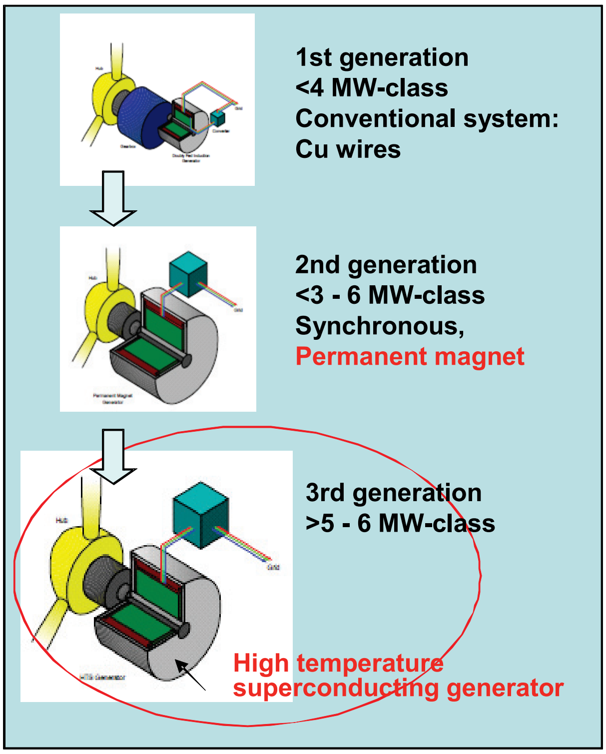

Fig. 5 Trend in wind turbine generator with increasing the power (sourced from Converteam)

4 The present situation of Y-based superconductor and its application

Like the example of the wind turbines, the Y-based applications have until now only been at the design stage. Actual fabrication has recently started. Siemens, following the former Bi-based 400 kW-class motors since 2000, of late have started research on Y-based coils. Also, Doosan in Korea, are currently undertaking Y-based ship motor using a large amount of Y-based conductors. In Japan, Industrial Superconductivity Technology and Research Associations (iSTERA) recently commenced a study on Y-based rotating machines. As shown in Figure 6, the study of the fabrication of a simple coil as well as irregular shaped coils was done and all aim at realizing a practical rotating machine. The R&D items in this study are 1) the transporting characteristics such as critical current, I_c, of the practical long wires for rotating machine applications, (considering the I_c homogeneity along the length with a Cu stabilizer and a insulator). 2) mechanical characteristics required to fabricate the coil, 3) coil fabrication method considering the irregular shape optimal to the motor field-coil, 4) coil stability under conduction cooled conditions, and so on. Recently we have made a field coil using 600m Y-based conductor and the coil was excited successfully without any degradation of the conductor.

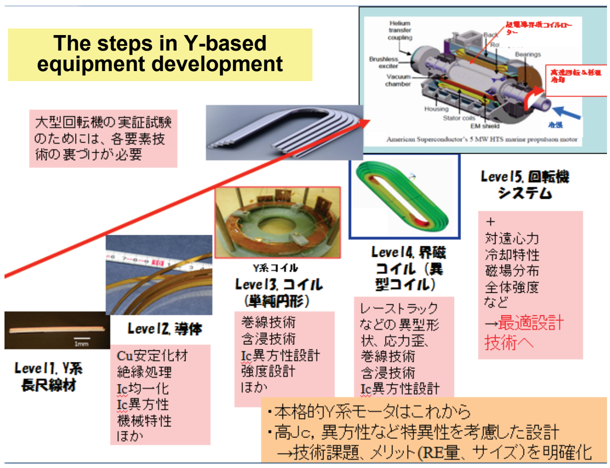

Fig. 6 R&D using Y-based conductors (by iSTERA)

5 Rare earth issues for motors

Motors are now widely used in our daily life and dominate a large amount of our electric power consumption (recent data 57% of the total domestic consumption in Japan). Namely, the improvement of the motor

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efficiency should be a significant issue for our future energy problem. For this improvement, a number of small to large-scale permanent magnets (PM) synchronous motors are now being introduced in many application fields. Such motors are employed from the automobile to the recently opened Tohoku Shinkan-sen in Japan. However, in recent years there has been an international strategy to preserve natural resources and to reduce the consumption of rare-earth materials in each country. Although PM systems have been applied because of the better efficiency, the superconducting magnets can improve motor or generator efficiency further and, at the same time, significantly reduce the amount of rare-earth consumption. Thus, iSTERA has carried out investigations to design a rotating machine using Y-based superconductor and coils.

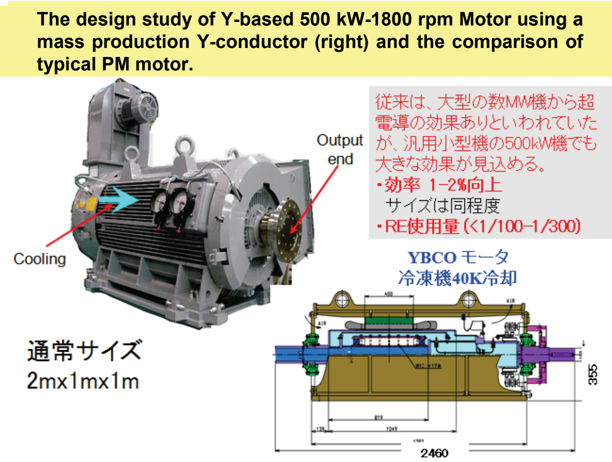

Fig. 7 Example of Y-based superconducting motor design (by iSTERA)

Figure 7 shows the result of a Y-500 kW motor design for industrial use. The Y-based windings in the motor can carry current densities of 150 A/mm^2, 50 times higher than conventional Cu windings that can carry only 3 A/mm^2. This resulted in the motor efficiency increase by 1-2 % without the increase in motor size. Of course, it was confirmed that the consumption of rare-earth materials would be reduced by a hundred, compared to the conventional PM motors when using Y-based conductor for the winding.

6. Summary

The current status of Y-based applications for rotating machines was introduced in this report. In anticipation of the high in-field I_c of the Y-based conductor, and the recent developments for the length, many groups worldwide have been intensively investigating the Y-based applications. In particular, applications relating to ship propulsion and wind power are focussed in Japan, USA, Europe and Korea. Y-based application equipment consumes far less rare earth materials and at the same time improves efficiencies, producing equipment that is compact and light, compared to conventional equipment.

The results mentioned in this report were partially carried out as the NEDO projects, “Yttrium-based superconducting power application technology development,” as well as, part of “Rare metal substitute materials development-Development of an Yttrium-based composite material for ultra-light high performance motor”.

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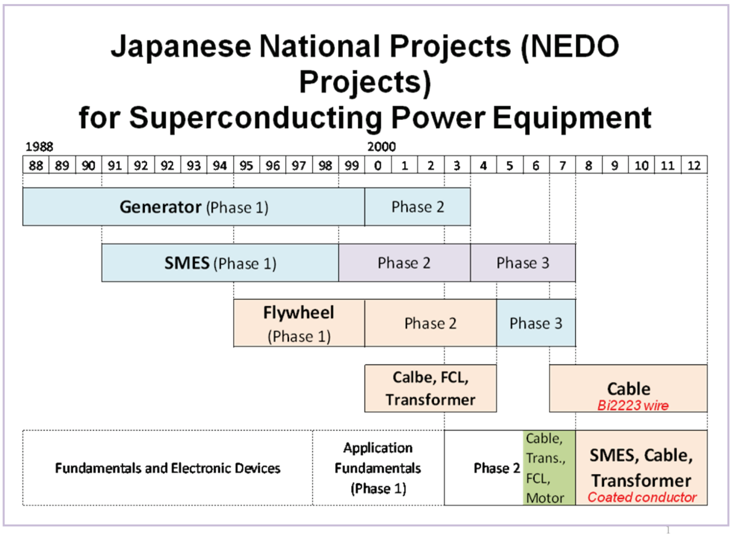
Feature Article: The Forum on Superconducting Technology Trends - Electric Power Equipment for Energy Applications

Hiroyuki Ohsaki, Professor
Graduate School of Frontier Sciences
The University of Tokyo



A large-scale project aimed for the technological development of superconducting power equipment was launched in 1988, soon after the discovery of high temperature superconducting materials. From 1988 to 1999, the project was undertaken by Super-GM who was commissioned by the New Energy and Industrial Technology Development Organization (NEDO) as one of the New Sunshine projects held by the Agency of Industrial Science and Technology, from the Ministry of International Trade and Industry. Super-GM demonstrated the world's first successful operation of a 70 MW-superconducting prototype generator, realizing the future possibilities of 200 MW-class power generators. In addition to this, they were instrumental in the development of low-loss NbTi superconductor and oxide superconducting wires, and in the research and development of a cryocooling system. Since the launch of the Super-GM project, research and development into SMES, flywheel energy storage, power cables, current limiters, transformers and motors have been undertaken. In 2011, NEDO projects for power cables, SMES, transformers and ship motors are ongoing. Initial research and development activities for power equipment applications centered on the use of metal-based superconducting wires fabricated from NbTi. However, with advances in high-temperature superconducting technology such as Bi2223 and Y-based wires, the research and developments efforts have shifted towards utilizing these superior materials. In particular, high temperature superconducting power cables were tested in Japan, USA, Korea and China, with repeated results and achievements leading to the testing standard development in IEC and CIGRE. Recently, applications utilizing DC superconducting cables have gathered attention, with SMES devices utilizing an NbTi superconducting coil as a practical voltage-sag compensation device.

At present it is difficult to envisage the future of electric power systems considering the recent East-Japan earthquake disaster on March 11, 2011, which led to a major nuclear plant accident. However, important issues relating to the proper combination of central and dispersed power generation, the realization of high-efficiency power transmission, the introduction and expansion of renewable energies and the realization and operation of flexible networks will remain the same for the future. It is thus considered that the realization of the future can only be envisaged with power cable, energy storage and current limiter devices, making them important devices for future development. To validate the suitability of superconducting equipment for practical use it is imperative that it is subjected to repeated power grid

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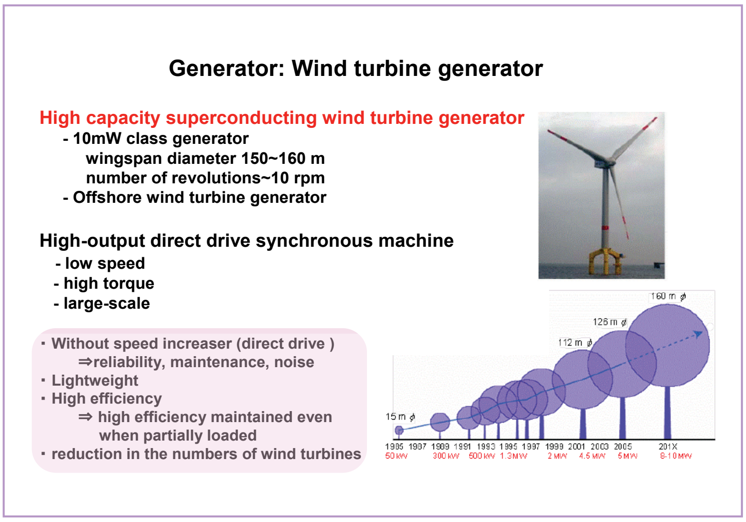
evaluation and verification testing demonstrations as well as risk assessment.

Moreover, the introduction and expansion of more natural forms of energy are desired for the future. Superconducting technology still has its place in the future, offering the potential of a large-scale wind turbine generator rated at 10-20MW. Since the launch of Super-GM project there have been no full-scale development of large rotating machines. However, rotating machines are generally used in an array of applications, with ongoing developments for ship propulsion motors and large wind turbine generators currently under investigation. It is through these efforts that the future development potential of superconducting rotating machines for wide practical use are to be realized.



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Feature Article: The Forum on Superconductivity Technology Trends - The History and Future of Superconducting Digital Circuits

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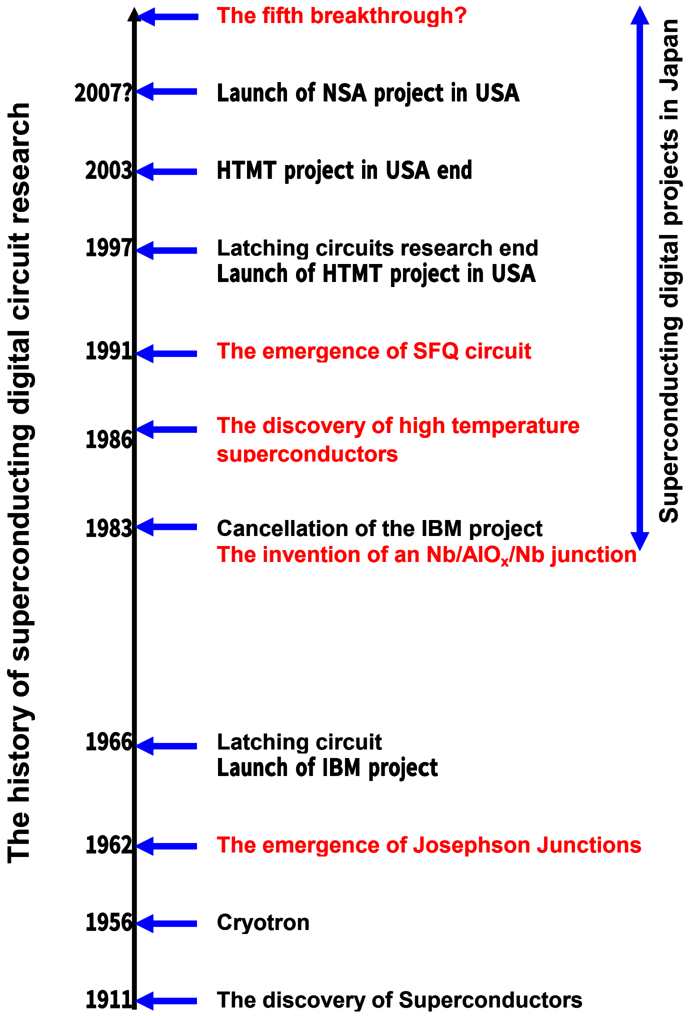
The superconducting digital circuit has continued its development over more than half a century since the first switch "Cryotron" utilizing the superconductor was invented back in 1956. There have been a number of challenges over the years, which have hindered technological progress however there have been four major technological breakthroughs that have made this technology possible and the findings are reported here.



The initial challenge was the formulation of the "0" and "1" state, which has become the basis of all digital circuits. The cryotron initially proposed utilized a superconducting/normal-conducting transfer, and the challenge was the time taken to remove heat energy generated and thus transform from a normal-conducting state to a superconducting state. The first breakthrough occurred after the discovery of Josephson effects and the fabrication of Josephson junctions (JJ) utilizing this effect. Superconducting circuits could have high-speed switch by the JJs.

In 1966, IBM first launched a large-scale superconducting computer project with JJs, utilizing lead as a superconducting material for the development. With elaborate methods involving Pb-In-Au and Pb-Bi in the lower and upper electrodes, respectively, the mixture of PbO and In_2O_3 for tunnel barriers, resulted in JJ showing acceptable characteristics. However, there were many issues associated with lead, not to mention its toxicity, its deterioration rate, its weak mechanical properties and its thermal cycle damages in going from room temperature to liquid helium temperatures, and the remarkable deterioration of characteristics caused by secular change, all leading to a number of poor characteristics. Additionally, it proved rather difficult to minimize JJ critical

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current scattering. The difficulties in improving the lead JJ characteristics were the main reason that forced IBM to cancel the project in 1983.

It was rather fortunate considering that in the same year when IBM cancelled the project, a second breakthrough appeared, with the invention of an Nb/AlO_x/Nb junction. Since Nb is chemically and mechanically stable and is not toxic, from an early stage it drew the attention of researchers as a potential material for use in superconducting circuits. However, the downside at that time was that optimum JJ characteristics were not forthcoming. For a Nb/AlO_x/Nb junction, stable tunnel barrier layers of AlO_x are formed by oxidation of a thin film of Al on the Nb lower electrode. This results in stable JJ with ideal characteristics and high uniformity.

The initial method of utilizing a JJ switch for a superconducting digital circuit was the so-called latching circuit, which diverted the current to a load resistance by JJ switching. The initial numbers of latching circuits employed allowed the fabrication of an 8-bit processor and a 4 kb memory. It was inevitable that AC bias would be required to reset the latching circuits, however supplying a large AC current at high speeds proved extremely difficult. This limited the clock frequency at several GHz, which was inferior compared to CMOS circuits, which had superior clock speeds at that time. It was gradually concluded that the latching circuits were not good enough for future development prospects and therefore the research and development stagnated in the latter part of the 1980s.

It was the discovery of high temperature superconductors that provided the third breakthrough, which reignited the research and development activities of digital circuits and resulted in improvement of the Nb circuit technology. During this time, the fourth breakthrough came about in the development of single flux quantum (SFQ) circuit, which shifted the research direction. The SFQ has high-speed characteristics exceeding 100GHz, and low power consumption characteristics of 0.1μW per gate, all made by DC bias. This device has superior characteristics that cannot be realized in other technologies. This accelerated the progress in the research and development activities of superconducting digital circuits, resulting in the current position today.

As introduced above, superconducting digital circuits have come about due to four major breakthroughs, leading to a SFQ circuit with a Nb/AlO_x/Nb junction as a switch. However, in the midst of all these activities, the world demands for electron-based devices have intensified year on year, and a fifth breakthrough is desired, i.e. the transfer to an even higher stage of superconducting digital circuits. Presently, it is difficult to surmise what the fifth breakthrough will be however, some potential candidates are considered.

Firstly, SFQ circuits need to reduce their current power consumption. Because this requirement has been less than other devices (In fact, since the SFQ circuit consume less power compared to other devices), studies to reduce power consumption have not yet to been fully undertaken. Recently investigations to this aim have focused on lowering power consumption by improving the circuit design, and initial experimental results look promising with power consumption more than two digits lower than what is possible presently. Superconducting digital circuit applications have until now focused on supercomputers and routers. However, current investigations have begun applying circuit technology to multiplex output from an array of ultra-sensitive superconducting detectors. From the multiplexing, it is thus expected that the market for superconducting detector devices will expand rapidly. The new application market and/or lower power consumption would be the desired fifth breakthrough.

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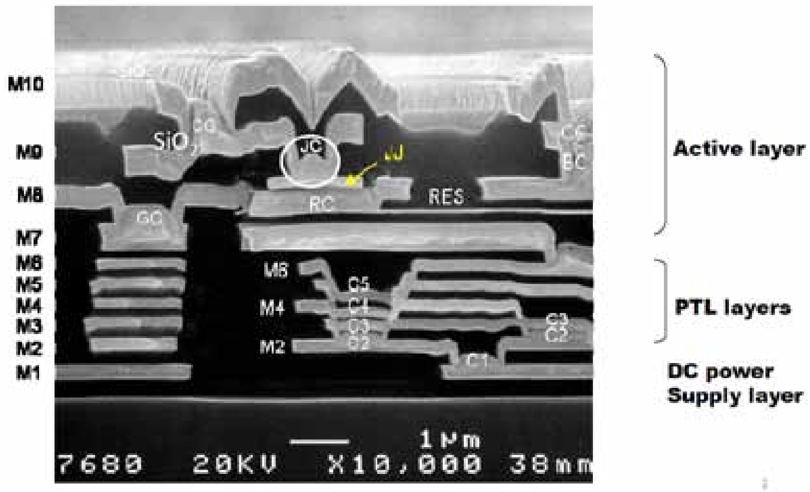
Improvement in Niobium processing: Multilayer planarization (ADP)
Cross-section of a Niobium 10-layer Niobium device utilizing ADP process



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Feature Article: The Forum on Superconducting Technology Trends - Materials Analysis using a Scanning Electron Microscope equipped with a Superconducting X-ray Detector

Keiichi Tanaka
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1. A high-energy resolution X-ray detector required for electron microscope

A Scanning Electron Microscope (SEM) is widely employed to interrogate material surfaces. Equipped with an X-ray analysis system it undertakes compositional analysis by measuring characteristic X-rays generated when a sample surface is irradiated with a beam of electrons. The resulting X-rays are analyzed using either Energy Dispersive Spectrometer (EDS) or a Wavelength Dispersive Spectrometer (WDS). EDS is able to analyze a full spectrum of X-rays up to 20 keV in a short time interval, and with the energy resolution being a benchmark for elemental identification, in EDS this is at best only 130 eV, and therefore lacks resolution. WDS on the other hand, has a greater resolution but cannot measure the full spectrum of X-rays quickly. Additionally, the higher resolution dictates that WDS needs higher probe currents than in EDS. The downsides to requiring higher probe currents are the deterioration of the spatial resolution during observational analysis and damage to the sample. The needs of microscopists are to have a greater degree of elemental determing ability without shortfalls in spatial resolution. This article reports a superconducting X-ray detector system, which has been developed in response to user demands and requirements.

2. A SEM equipped with a TES-type X-ray detector

The developed system is a TES-type system based upon a superconducting X-ray detector. TES is the abbreviation of Transition Edge Sensor, so-called as the system uses the transition edge of a superconductor as a thermometer. EDS is employed to detect the generated X-rays, enabling analysis to be undertaken at the same current level as conventional EDS systems. Figure 1(left-hand side) shows the SEM equipped with a TES-type X-ray detector system. It consists of the detector, the gas handling system and a liquid helium tank. The TES-type X-ray detector is

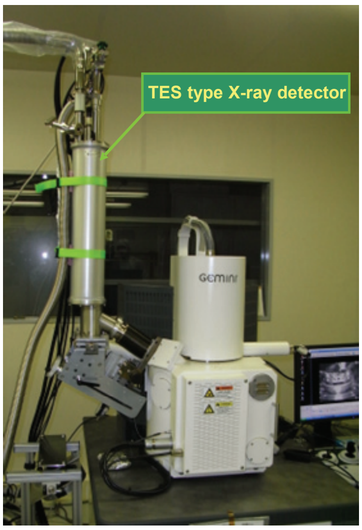

Fig. 1 (left): picture of the SEM equipped with a TES type X-ray detector, (right): picture of the superconducting X-ray detector system

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connected to the SEM, with the gas handing system, a source of vibration, located separately, (shown on the right-hand side of figure 1). Furthermore, in order to reduce the weight of the TES-type X-ray detector, liquid helium is always fed from the tank to the detector via a transfer tube. The gas handling system consists of a pump to transport the liquid helium, the gas-mixing tank to cryocool the TES-type X-ray detector to 100mK, and a gas-mixing circulation pump.

3. The system operational performance

Recently, copper wirings are utilized for LSI device. The left-hand side picture in figure 2 shows the cross-sectional image area of a recent LSI device. For an LSI device a tantalum barrier layer, with a thickness of 12 nm, is required between the copper wiring and the oxide film. To evaluate the spatial resolution of the superconducting X-ray detector system, a cross-section of the LSI sample was prepared using FIB, and the signal from the tantalum barrier analyzed. LSI's have tungsten vias, which when analyzed using low-acceleration, 3 keV X-rays show only M-lines from both tungsten and tantalum, which are both heavy elements. The Kα line of SiO at 1740 eV, and the Ta and W Mα lines at 1710, 1775 eV, respectively, are very close in energies and thus difficult to resolve using conventional EDS. However, these energies are clearly resolved when utilizing the superconducting X-ray detector system. The right-hand side of figure 2 shows the dotted parts (Area1), of the images mapped using a 3 kV accelerating voltage, with an image pixel of 64 x 64. The image shows the 12 nm tantalum layer and the tungsten via at the bottom half of the copper wiring, which is clearly distinguished from the silicon.

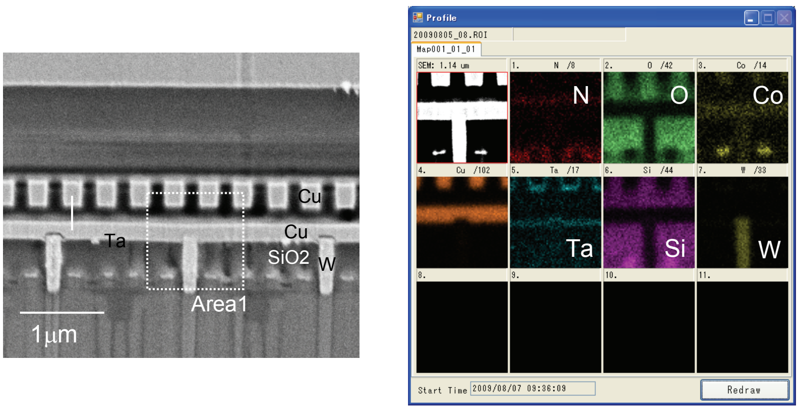

Fig. 2 (left): SEM image of the LSI device, (right): a mapping image of Area 1 in figure 2 (left)

4. Summary

A SEM equipped with a superconducting X-ray detector system was introduced. Employing only conventional SEM analysis with EDS allowed a spatial resolution of 10 nm, thanks due to the superconducting X-ray detector system. Further research endeavors are currently ongoing to investigate cryogen-free system operation, and high-count rate mapping using multiple devices.

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Feature Article: The Forum on Superconductivity Technology Trends - The Advancement of High Temperature Superconducting Device Technology and SQUID Applications

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International Superconductivity Technology Center

2011 marks the 100th anniversary since the discovery of the superconducting phenomenon, as well as marking the 25th anniversary since the discovery of oxide-based high temperature superconducting (HTS) materials. Furthermore, next year will mark the 50th anniversary since the discovery of Josephson effects in superconductors, back in 1962, which now form the basis of all superconducting electronic applications. A thin (1-2 nm thick) insulator or even thicker metal-barrier layer separating two superconductors forms a so-called Josephson Junction (JJ), and is the point at which Josephson effects occur. The junction with an insulating barrier is called a superconductor-insulator-superconductor (SIS) Josephson Junction, and exhibits current-voltage (*I-V*) characteristics with a steep rise of quasiparticle current at a v oltage corresponding to the superconducting energy gap as well as hysteresis.

The fabrication technology for SIS junctions based on low-temperature superconductors was established in the first-half of the 1980s when Nb/AlO_x/Nb SIS junctions showing ideal *I-V* characteristics were developed. Since the discovery of oxide-based high temperature superconducting materials, many researchers have attempted but failed to demonstrate an HTS SIS junction due to several reasons, including the extremely short superconducting coherence length, and the insulating characteristics of disordered materials with a lack of carriers. Additionally, the unusual characteristics of the superconducting gap exhibiting “d-wave” symmetry negate the fabrication of an ideal SIS junction for the present time. On the other hand, overdamped or weak link type JJs, which exhibit no hysteresis, allow the fabrication of SQUID and Single Flux Quantum (SFQ) circuits. For example, the grain boundary JJs, which take advantage of the exponential drop in the critical current density with the mis-orientation angle are easy to be fabricated and are commonly used, however a large spread of characteristics and flux-trapping issues occur frequently and thus still require resolution. Contrary to this are ramp-edge JJs, developed in the latter part of the 1990s that have surface modified barriers and un iform characteristics, with little tendency of flux-trapping occurrence. During the project supported by the New Energy and Industrial Technology Development Technology (NEDO) in Japan, the fabrication technology of ramp-edge JJs and the integration technology required for HTS SFQ circuits were extensively developed and advanced very much. The technology developed for the fabrication of integrated circuits composed of three superconducting layers and several insulation layers, was firmly established at ISTEC and it is this what has been inherited to the present day.

A SQUID is an ultra sensitive magnetic sensor that utilizes superconductivity for its operation. By utilizing high temperature superconducting materials in SQUIDs, various testing equipments are expected to emerge, which are more compact and cheap to operate, as only cryocooling with liquid nitrogen is required. Until now, the developments of HTS SQUIDs have been under taken for applications such as magnetocardiogram, immunological testing, metallic contaminant detection and metals exploration systems. The latter two have been realized for practical use but have yet to diffuse widely into the marketplace. One of the reasons behind their lack of market acceptance is due to their inferior performance such as low field sensitivity when compared to Nb-based SQUIDs. The difference in performance is attributed to the

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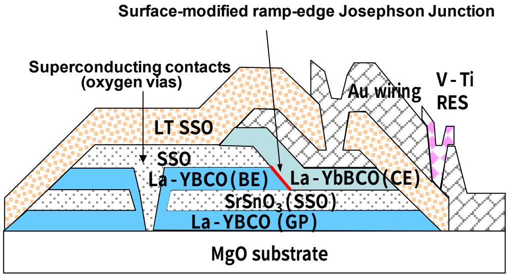
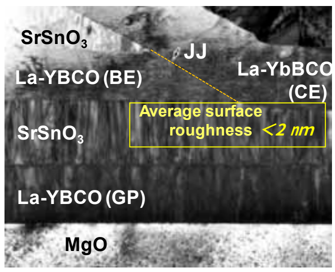
grain-boundary JJs employed in HTS SQUID sensors and the simple structure composed of a single-layer HTS thin film.

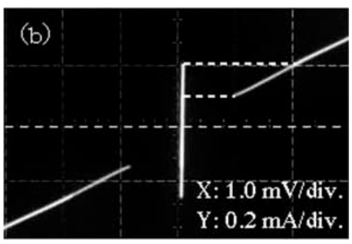
ISTEC has been developing thin film multilayer-type HTS SQUIDs for the past four to five years by employing fabrication knowledge and technology gained from their experience in HTS integrated circuits. For example, ISTEC developed and fabricated a magnetometer composed of a multi-turn input coil (magnetic flux transformer) that was integrated on the SQUID loop, demonstrating low field noise performance characteristics at 77 K of 10 fT(femto-Tesla=10^{-15} T)/$Hz^{1/2}$, equivalent to commercially available Nb-based SQUIDs. Furthermore, the sensor has a strong magnetic field tolerance since it employs ramp-edge JJs, and we can fabricate complex sensors utilizing crossover wiring. A defect inspection system to investigate the performance of long-length superconducting tapes was developed by employing a 5-channel SQUID magnetic field gradient sensor (gradiometer). This system is employed to evaluate the performance of multi-filamentary-processed Y-based long-length tapes under the "Materials and Power Application of Coated Conductors (M-PACC)" project, supported by NEDO. Additionally, the development of highly-sensitive SQUID magnetometers for practical applications such as the next generation metals exploration systems, and the development of high-performance, HTS SQUIDs to be employed for advanced bio-sensing and non-destructive evaluation systems are ongoing, commissioned by Japan Oil, Gas and Metals National Corporation (JOGMEC) and the Japan Science and Technology Agency, (JST), respectively. If these endeavors prove fruitful by verifying the effective cost performance of systems employing thin film multilayer-type HTS SQUIDs, it is then expected that there will be a rapid acceptance and diffusion of HTS SQUID applications into the marketplace.

Integration technology for high temperature superconducting devices

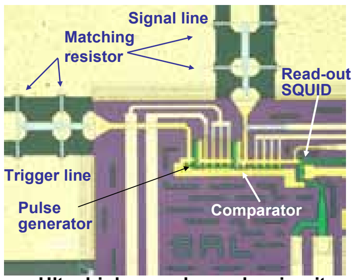




Cross sectional schematic view of the HTS integrated circuit fabricated by ISTEC



I-V characteristics of a surface-modified ramp-edge Josephson junction (4.2 K)



Ultra high-speed sampler circuit
(15 junctions, 40 K operation)

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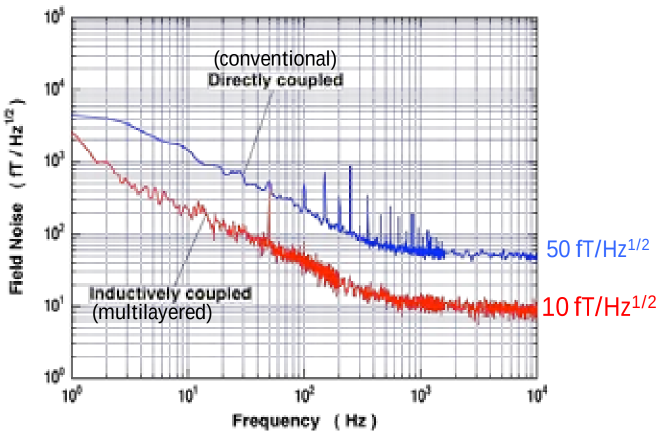
Improvement in the sensitivity of the multilayered HTS magnetometer



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微弱磁気センサー

高温超電導材使い安く

医療機器を小型化

超電導工学研

Multilayered magnetometer with a reproducible field noise of 10fT/Hz½
(equivalent to commercially available low temperature SQUID)
Owing to optimization of junction fabrication conditions

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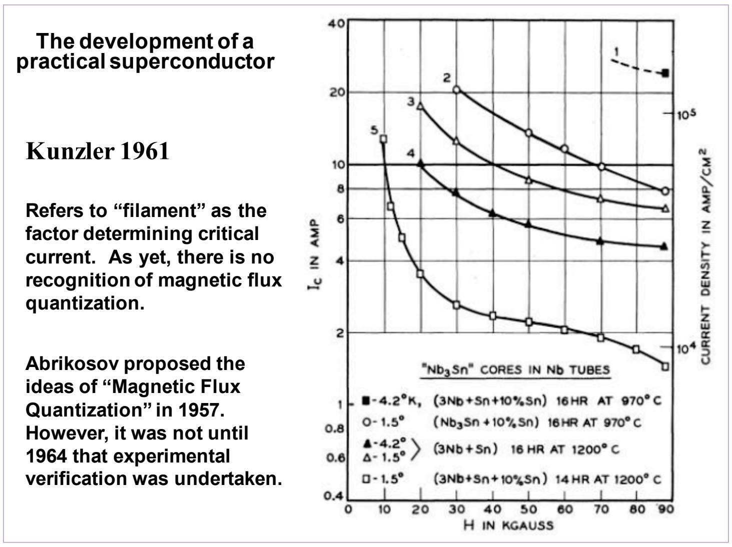
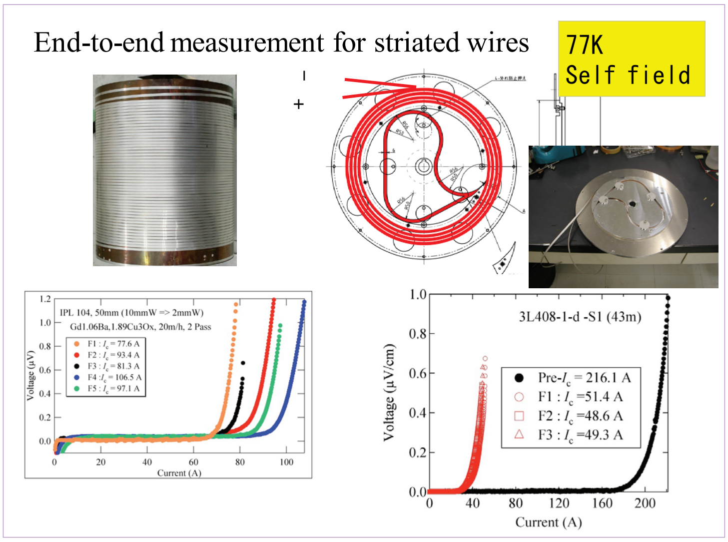
Feature Article: The Forum on Superconductivity Technology Trends - The Critical Current Capabilities of Y-based Superconducting Wires and Its Evaluation Methods

Koichi Nakao, Senior Research Scientist
R&D Division of Applied Materials and Physics
SRL/ISTEC

Since the discovery of superconductivity by Kamerlingh Onnes in 1911, it was conceived that the very first applications would be for the generation of strong magnetic fields. A coil composed of superconducting wires generates no heat and the natural perception was that it would have greater current-carrying capacities, resulting in intense magnetic fields. However, the original tests carried out by Kamerlingh Onnes were disappointing. The superconducting wires generated magnetic field strengths of only a few tens of mT, losing their superconductivity because of electrical resistance. It was weaker than expected magnetic fields that were blamed for the loss in superconducting characteristics. It was not until half a century later that superconductors with large critical magnetic fields were discovered, and resulted in superconducting wires able to produce magnetic fields exceeding 10 T.



Superconducting wires that are able to carry large currents are type II superconductors. The majority of these superconductors have a high (upper) critical magnetic field, however this does not always equate to large current-carrying capabilities due, in the majority of cases, to the in-field critical current value, which is determined by quantum flux pinning. The critical magnetic field of a superconductor is a material constant and its characteristics are not dependent upon manufacturing process routes. Contrary to this is the critical current density, which is affected by the types and densities of the pinning centres and is significantly dependent upon manufacturing processes.



Therefore, there is still scope for the critical current values to be improved by optimizing the manufacturing process. This can be achieved by providing feedback to the manufacturing process of the measured critical current values precisely and promptly. In case of Y-based high temperature superconductors, the critical current value is often measured at liquid nitrogen temperatures. There is an enormous advantage of cooling using liquid nitrogen rather than cooling using liquid helium, which is used to cool conventional low-temperature superconductors. This is because liquid nitrogen is far easier to use rather than liquid helium. For the case of Y-based high temperature superconducting long-wires, the measurements are taken along the complete length of the wire in addition to measurements for short samples. There are several methods to measure the critical currents along the complete length, such as measuring the critical current every meter-length in a reel-to-reel manner, or measuring a single value of end-to-end critical current. In the latter case, the wire is wound in a single layer around a drum in order to prevent an excessive self-field, or the wire is wound in a reel in a bifilar manner. Additionally, induction methods exist to measure critical currents, in which electric currents are induced in the wire with the application of a magnetic field and an external current source is not required. At ISTEC, the Hall sensor array method as well as the magneto optic method has been used as variants of the induction method to measure wire critical currents. The former method has high-speed measurement characteristics, while the latter has greater spatial resolution.

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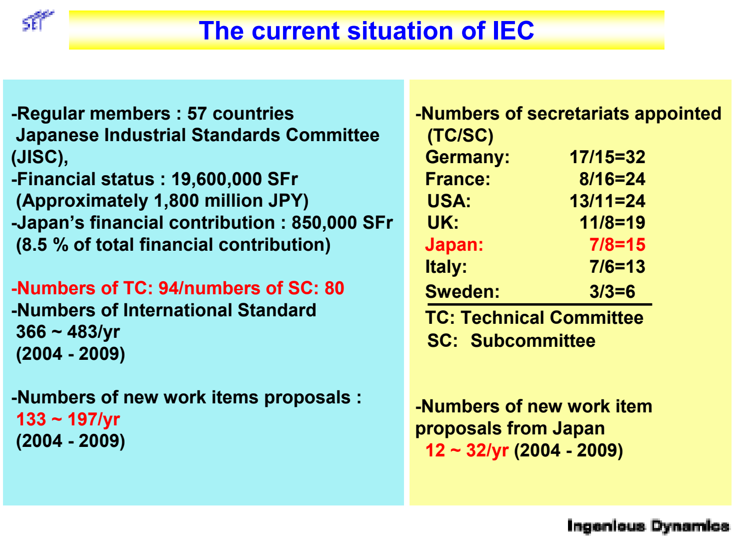
Feature Article: The Forum on Superconductivity Technology Trends - Trends in the International Standardization of Superconducting Technology

Ken-ichi Sato, Fellow and Chief Engineer - Superconductivity
Material and Process Technology R&D Unit, R&D Group
Sumitomo Electric Industries, Ltd.

De jure standards set by International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO), as well as forum standards set by industry groups are recently referred to as “consensus standards”. The following highlights the positive and negative attributes of those standards.

- Negative attributes: As there is no single company allowed in deciding these standards, obtaining a consensus can often be time consuming compared to de facto standards and there are regulations governing standards used in patented technology.
- Positive attributes: There is an obligation that each country adopts and uses these standards as stated by the “Agreement on Technical Barriers to Trade” of World Trade Organization (WTO). Thus, to expand corporate activities globally, the international standards’ activities together with securing the rights to one’s own patented technology are powerful drivers for, 1) international market expansion at the initial stage of product development, and 2) reducing costs during periods of business expansion for the products.



An important aspect requires that each company have a technology development strategy part of which is standardized, or not standardized (Black Box), by adopting business models that include intellectual property.

Historically, the events surrounding superconductivity and IEC are thus: 1906, Foundation of IEC; 1908, Heike Kamerlingh Onnes successfully liquefied helium; 1910, Japan joined IEC; 1911, Kamerlingh Onnes discovered superconductivity; 1986, J. G. Bednorz & K. A. Müller discovered high temperature superconductors; 1989, Establishment of TC 90 (Superconductivity). There is some overlap observed between the events.

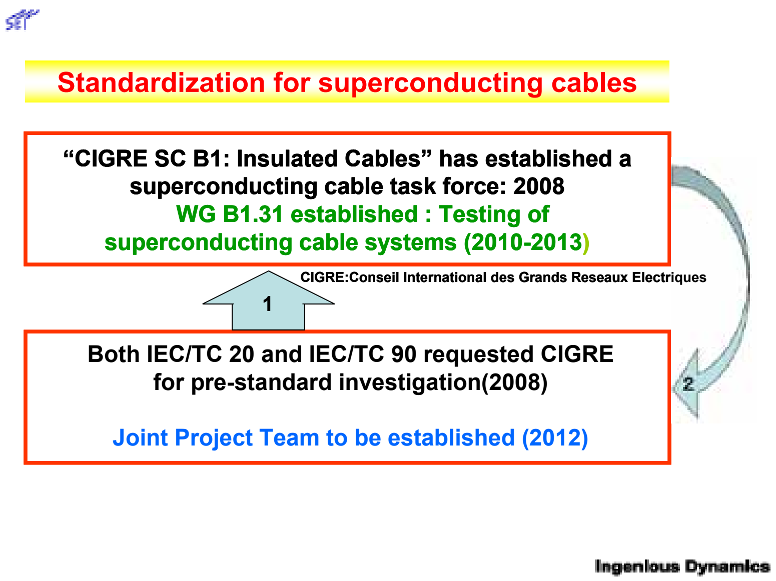
Japan was at the centre of the activities involved in the establishment of TC 90 in 1989. What follows is an explanation of the process undertaken. Japan, for the first time was entrusted as secretariat at the TC-level of the IEC.

- In 1988, the approaches to superconductivity adopted by the IEC were discussed at the “Special WG – Superconductivity,” directly controlled by IEC Committee of Action (now, Standardization

Management Board). (Secretariat: Japan (Representative: Professor Sekine, The University of Tokyo), Secretary: Ken-ichi Sato)

- Received guidance from former Technical Regulations, Standards, and Conformity Assessment Policy Division of Ministry of Economy, Trade and Industry, IEC approached the following issues:

1) At that time there was Japan-USA trade conflicts. Japanese domestic standards had to be justified so as not to cause potential trade barriers.
2) It was IEC standards that formed the framework for the Japanese standards, which resulted in the formation of the Japanese Industrial Standards (JIS).
3) At that time, only ASTM standards existed in the vocabulary in the field of superconductivity and standard for measuring critical current of NbTi. With the expectation of high temperature superconductors, discovered in 1986, a wide-range of international standards was desired.
4) The data from research and development activities was compared to single benchmarking standards, which triggered a flurry of research and development activities.
5) Since Japan was producing world-leading research results in the high temperature superconductor field, Japan should positively participate the activities toward a future international standardization.
6) Strengthening the Japan's presence in the IEC.



At TC 90, up until now, 15 of the IEC standards were published with 13 WG working members, involving 150 specialized experts, who initially instilled the vocabulary and the testing methods involved for the standards and guidelines for superconductivity. Recently, investigations for the standards and guidelines were progressing for categories including the materials level of wires, thin film and bulk materials, as well as component and production level such as current leads and power cables, respectively.

Looking back over the past 22 years since 1989, the following can be summarized:

1) The manufacturers have made international standards. We too can follow suit.
2) Some ten years of run-up approach periods have been required to set up international standards in new field.
3) Beneficial in cooperation with institutions that have worked on pre-standards (VAMAS, CIGRE)
4) Efforts with related people are required to form agreements towards the future direction of standardization (International Standardization Panel)

5) A government's involvement is indispensible to gain international standardization in an industry that has yet to mature, for example the superconductor industry. (It is difficult to think that only beneficiaries are responsible for standardization activities).

We will greatly appreciate your further guidance and continued encouragement.

The current situation of TC 90

The International Electrotechnical Commission (IEC)
TECHNICAL COMMITTEE No.90 : SUPERCONDUCTIVITY

TC90 established	1989
Secretariat country	Japan (Secretary: Ken-ichi Sato, Assistant Secretary: Jun Fujigami) (Committee member･Secretariat:The International Superconducting Technology Center)
Chairman	USA (Dr. L.F. Goodrich, NIST)
Scope	- To deal with technical aspects, problems and standards activities related to superconducting material and devices. - All classes of superconductors will be covered.
Liaison member A)	VAMAS (Versailles Project on Advanced Materials and Standards)
P-member	Austria, China, France, Germany, Italy, Japan, Korea, Poland, Romania, Russia, USA (11 countries)
O-member	14 countries

The first time Japan was entrusted as secretariat at the TC-level of the IEC

Ingenious Dynamics

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Feature Article: The Forum on Superconductivity Technology Trends -The History and Future of Superconductor

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National Institute for Materials Science

This year marks 100 years since the discovery of superconductivity. It is therefore an opportune moment to historically reflect upon the material and application developments and gain an insight into the future. Looking back over this time the foremost developments can be roughly divided into four major time periods.

The first major time period, up until 1961, covers 50 years since the discovery of superconductivity in 1911, and can be considered as the dawn of the superconductor. It was during this time that a famous story took place involving, Onnes himself, who promptly after discovering superconductivity attempted to fabricate a superconducting magnet utilizing lead wires. Unfortunately, this experiment ended in failure because of the presence of a thermodynamical critical magnetic field, H_C. For the next half-century superconductors were deemed extremely weak in the presence of a magnetic field, and almost considered useless for any practical applications. However, it was during this time that the development of materials utilized in later applications took place. For example, in the exploration of new materials, there were two distinguished contributors; Meissner who was active during the 1920s (famous for the discovery of the Meissner effect) and Matthias, at Bell Labs, who was active during the 1950s. In particular, Matthias's research may well be likened to that of a carpet-bombing approach, however it was his results that led to the discovery of scores of superconducting materials. Amongst these, the discovery of Nb_3Sn, which has had the most significant impact for applications suitable for practical use.

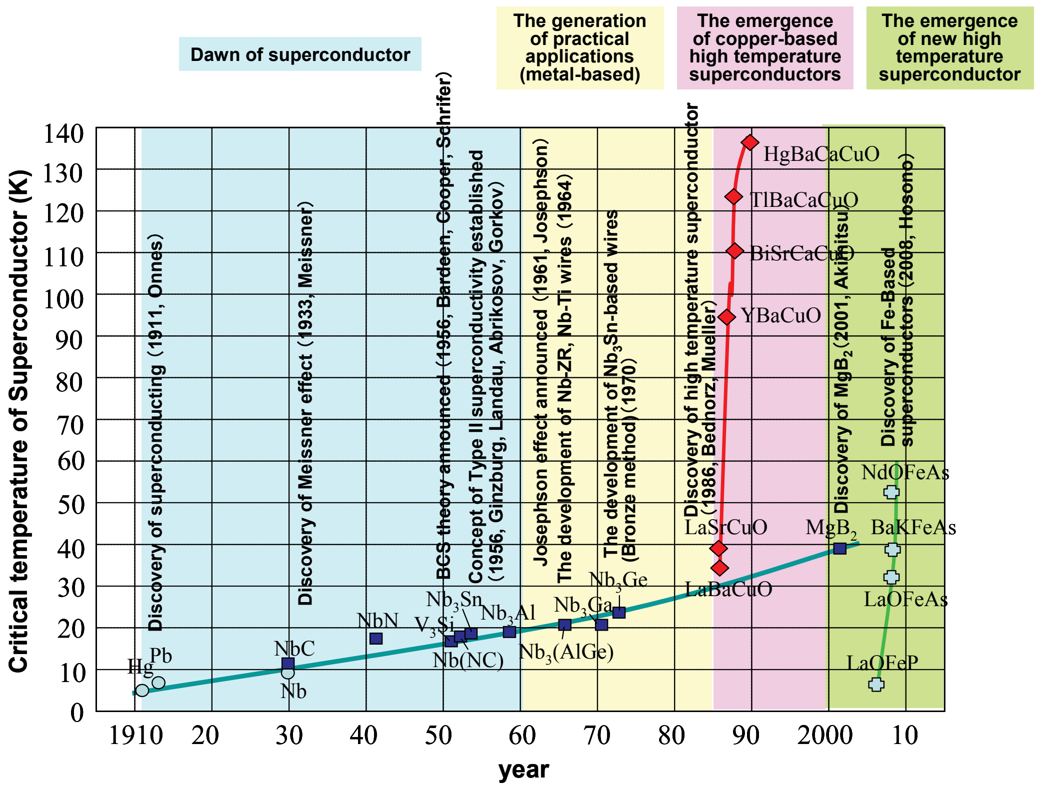

Fig.1 Changes in critical temperature T_C

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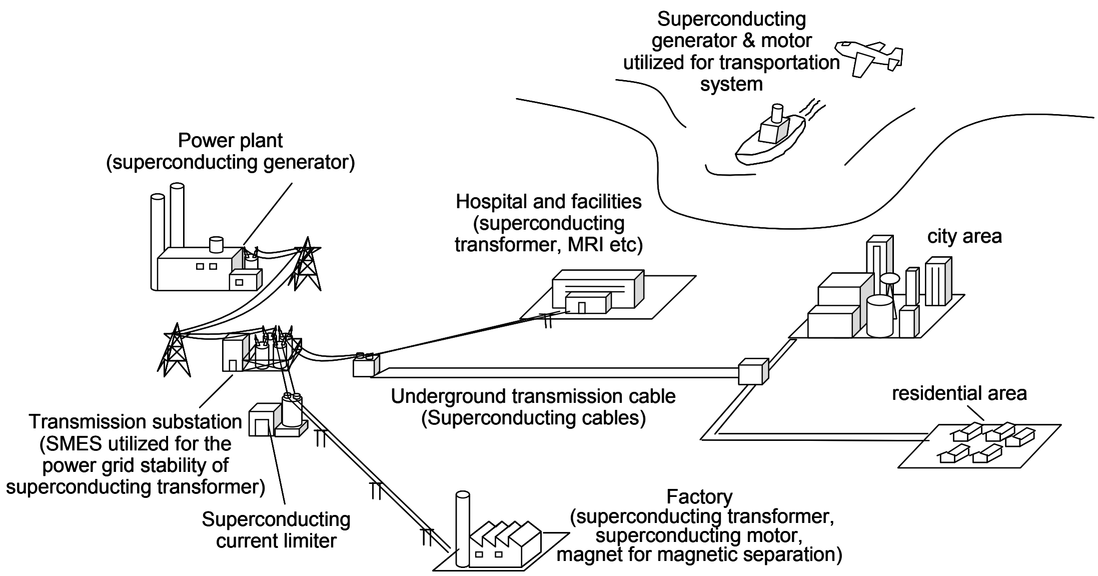
It was only after 1961 that research groups began to believe that superconducting applications could be a possibility, and this forms the second major time period in superconductor history. It was only this year that both Matthias and his colleague at Bell Labs, Kuntzler, fabricated Nb_3Sn wires from the so-called PIT (Powder-in-tube) method, confirming an extremely large in-field critical current at 8.8 T. The flow of such a large current was unexpected and caused a huge sensation in the research community. At the end of the same year, at an international conference held at MIT, there were reports of coils fabricated from, not only Nb_3Sn wires, but also Nb-Zr alloys, both successfully generating intense magnetic fields of 6-7 T – an epoch at that time. It was this conference that gained the world's attention and countries began realizing the importance of superconducting applications. This was exactly the starting year for superconducting applications. This was followed with the development of high-performance Nb_3Sn and NbTi wires for practical use, which still now form the mainstream of superconducting applications to the present day. On the other hand, A15-type compounds, representing Nb_3Sn, and B1-type NbN material groups, gained attention as part of materials exploration at that time. In 1973, a record for the highest recorded critical temperature was measured at 23 K for Nb_3Ge thin films. This prompted further investigations to find other materials with even greater critical temperatures, starting with the metastable compound state of Nb_3Si and MoN. However, over 13 years of research efforts, up until 1986, a T_C exceeding that of Nb_3Ge was not achieved.

It was not until the third time period when superconductor-fever hit with the discovery of LSCO in 1986. This was succeeded the following year with the discovery of YBCO, which had a T_C exceeding liquid nitrogen temperatures (77 K). Bi-based and Tl-based superconductors achieved a rapid increase in critical temperatures to over 100 K, however at the present time, the T_C of 135 K achieved by Hg-based superconductors still remains the highest value at normal pressures. The discovery of these copper-based high temperature superconductors facilitated liquid-nitrogen cooling, significantly impacting applications designed for practical use. For Bi-based superconductors, silver is employed as a sheath material and the PIT method has allowed the mass-production of wires for practical use. Moreover, Y-based superconductors having biaxial orientation enables them to have large critical current densities, and thus the development of a coated conductor has been progressing at the national project level.

The fourth time period begins in 2001, with the emergence of a new breed of high temperature superconductors, MgB_2, followed in 2008, by Fe-based superconductors. It is quite gratifying for us Japanese to know that these new breeds of superconductors were discovered in Japan. Looking back at the work Matthias undertook, it seems to suggest that he overlooked the existence of MgB_2, even though this material belongs to the conventional metal-based superconductor category. The grain boundary coupling in these metal-based superconductors is extremely strong and is therefore able to have large current-carrying capability without any characteristic orientation effects. As this is a huge benefit for the realization of practical applications, the research for wire fabrication employing PIT and diffusion methods has been advancing steadily, presently aiming for applications requiring medium temperature crycooling refrigeration systems. On the other hand, Fe-based superconductors have large variety in crystal structure that offer the possibilities to further improve T_C, and since they have a higher upper critical magnetic field, $Hc2$, it is expected to become the next high magnetic field superconductor. However, despite these positive attributes, future issues remain in solving the weak coupling.

As a conclusion to this report the future prospects of the superconductor is briefly explained. The NbTi and Nb_3Sn wires developed during the second time period still the mainstream for applications at present, being utilized by hospital MRI's that now play a familiar role in our lives. However, as superconductor applications are presently limited to superior equipment operating under liquid helium cooling conditions they have yet to mature in order for them to gain public recognition. This can only be achieved with the development of wires that have stable operation at temperatures greater than liquid nitrogen. Thus, these expectations are likely to be achieved using Bi-based 2223 wires and Y-based coated conductors. It is my belief that the development of materials with even greater T_C's, including the realization of a room temperature superconductor, have to be advanced strongly in the future in order to bring superconductor applications to the mainstream and be of benefit to the public.

At this 100th anniversary since the discovery of the superconductor, we Japanese faced the unprecedented East-Japan earthquake. It was from this disaster that we were made more aware about the importance of using electricity wisely. The superconductor research communities are thus required to further accelerate research activities by mutual cooperation of both material and application developments, so that the superconductor can significantly contribute to the social fabric in the near future.



Characteristics required

(Electric power system)
- High capacity
- Electromagnetic shielding
- Stability

(Electric equipment, industrial equipment, magneto and chemical transport)
- High temperature operations
(greater than the cooling temperature of a refrigerator)
-low cost
-high current density
(compact and lightweight equipment)

(Ultimate applications)
- High temperature operation
(at around room temperature)
- low cost

Under development

the future areas where development is required

Fig.2 Problem of the development and ultimate goal for applications of Superconductor

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