Standardization of Test Methods for Practical Superconducting Wires

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***Abstract* - Growth of the worldwide market of superconductivity applications, leads inevitably to products involving superconductivity (SC) being regulated by international standards. As the first priority, the general guidance for practical SC wires should be provided, which delineates the direction for a series of successive detailed standards. Some such standards have been already approved by the International Electrotechnical Commission (IEC). The working group WG13 of IEC-TC90 is engaged in the development of such international standards and prepared a standard on general characteristics of practical SC wires, separated into two subdocuments: the description of general features of practical SC wires and the general guidance for measurement methods and test procedures for properties (attributes) critical to users. This document was most recently approved as the IEC IS 61788-21:2015, Edition 1. Part of this paper is devoted to an overview of that document. In closing, issues critical to promoting standardization of the practical SC wires are pointed out.**

***Keywords* – International standard, practical superconducting wire, test method, critical current**

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I. INTRODUCTION

The low-temperature superconducting (LTS) wires of Nb-Ti and Nb_3Sn superconducting materials have been used extensively in a variety of applications since the 1960s. Today, most of these are magnets such as magnetic resonance imaging magnets, other industrial magnets, accelerator magnets, as well as other magnets and large magnet systems for cutting-edge scientific research. High temperature superconductors (HTS), discovered in 1986, make it possible to utilize superconductor-based devices and systems with less expensive and more efficient refrigeration systems. Wires of these new materials may enable new applications, some of which not even possible with LTS wires.

Growth of the worldwide market in superconductivity applications is accompanied by procurement of large amounts of practical SC wires and their products. For instance, current large-scale international projects such as ITER purchase superconductors from different sources and countries. In order to ensure consistency in the measurement of parameters and the definition of terms, the development of international standards becomes important to facilitate the relevant projects and the international fair trade. These standards should be used by materials suppliers, system developers and manufacturers.

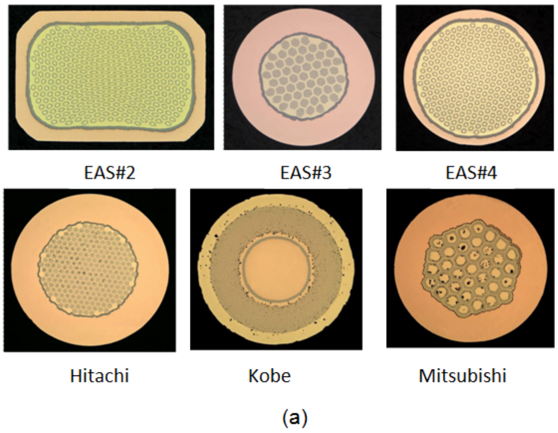
In 1989, International Electrotechnical Commission (IEC) took the intiative to establish the Technical Committee, TC 90, “Superconductivity”, which aims at standardization of superconducting Materials and devices by developing appropriate standards. We expect that such IEC standards will be widely used, because the IEC is the primary organization that is working on international standards development for superconductivity. Indeed, superconducting wires are the essential ingredients in all *large-scale* industrial products operated using superconductivity (SC). These SC products already are and shall be further regulated by international standards. Also, general guidance for practical SC wires should be provided, which outlines the general behavior and provides the direction for a series of successive, more detailed standards.

In practice, the primary purpose of practical SC wires is to carry electrical current. In the development of standards, particular focus should be given to wire design structure and characteristics that are different from those of ordinary copper and aluminum wires. Practical SC wires have appearance nearly identical to common electrical wires and can be used interchangeably with them at sufficiently low temperatures. However, in contrast to conventional wires, practical SC wires are typically composites of different materials performing different functions as described in Section II. In order to effectively utilize practical SC wires in a specified application, it is necessary to understand fully their characteristic properties (attributes). Section III describes various such attributes that shall be considered in commercial transactions. The present status of IEC standards for practical SC wires is given in Section IV. In Section V, we discuss some issues critical for promoting standardization of practical SC wires and emphasize that to develop internationally acceptable standards the collaboration is necessary with other societies and parties interested in standardization of superconductivity. The present status of such collaborations is briefly described.

II. PRACTICAL SUPERCONDUCTING WIRES

A SC wire is considered being “practical” when it can be procured by ordinary commercial transactions in continuous lengths sufficiently long to build devices. Conductors made of multiple wires, such as cables, are beyond the scope of the present consideration: we focus on characteristics of a single practical SC wire. Such a practical SC wire is designed as a composite structure to meet the desired engineering characteristics by proper selection of materials and the composite architecture. Figure 1 (a) shows the cross sections of several practical Nb_3Sn wires produced by various manufacturers. These wires are designed for use in a high field magnet. In the example of Figure 1(b), the SC wire possesses a complicated internal structure. The Nb_3Sn intermetallic compound (1) surrounds the residual Nb core (2), of which it has been grown. This superconducting composite (1+2) is embedded in the normal-conducting matrix (3). The barrier (4) is placed between the matrix and the external normal-conducting stabilizer tubing (5). All these functional components are engineered so that the SC wire exhibits electrical and mechanical integrity adequate to withstand fabrication into the equipment and to properly operate in the intended application.

Superconductor (1+2)	Nb_3Al 、 Nb_3Sn
Matrix (3)	copper or copper alloy
	niobium
Barrier (4)	niobium or tantalum
Stabilizer (5)	copper
reinforcing member	copper alloy
insulation	resin for coating
	tape for winding



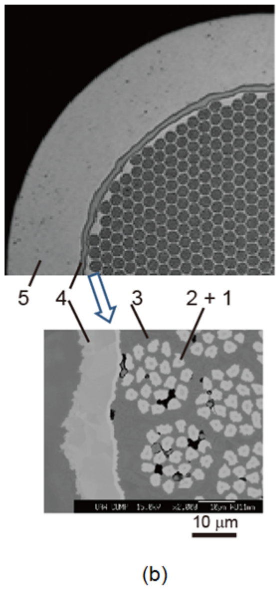


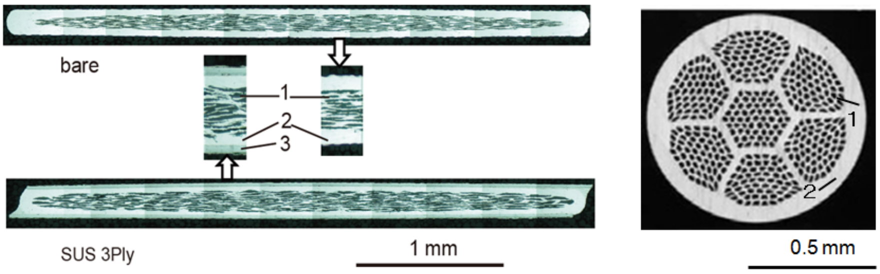
Fig. 1. (a) Cross-sectional view of practical Nb_3Sn wires produced by various manufacturers, (b) the detailed structure of a Hitachi composite wire, where the numerals correspond to those in the table (the lower photo in an enlarged view of a small segment of the upper photo). In the table, the niobium matrix refers to Nb_3Al wires fabricated by the "niobium tube" and "jelly roll" methods.

Presently, SC wires industrially available in sufficiently long continuous lengths are limited to five kinds of superconductors. Two of them belong to the LTS category (critical temperature T_c less than 25 K [1]): the Nb-Ti alloys and Nb_3Sn intermetallic compounds. Another category includes HTS compounds, such as the BSCCO ($Bi_2Sr_2Ca_nCu_{n+1}O_{6+2n}$; n=1 and 2) and REBCO ($REBa_2Cu_3O_{6+x}$; RE= Y, Gd and Sm) oxides, and the MgB_2 intermetallic compound. In the present standardization step, the five types of SC wires based on these five superconductors are termed "practical SC wires". An overview of the types of SC materials and the role of the functional components is explained in the technical report IEC 61788-20 [2]. When a new superconducting material will be industrialized into such long wire form in the future, it should be included by modifying that document.

Two types of practical BSCCO wires are shown in Figure 2 as examples of HTS wires. In the bare wire of BSCCO-2223, the SC filaments (1) are embedded in the silver matrix (2). In the SUS 3ply flat wire of Figure 1 (a), the stainless steel foil is soldered on the bare wire as the reinforcing member (3). In the round BSCCO-2212 wire shown in Fig. 2(b), the SC filaments (1) are embedded in the silver matrix (2).

As mentioned above, the practical Nb_3Sn and also Nb-Ti wires are covered by copper and insulation thus being often similar in appearance to commercial electrical copper wire. However, while any normal copper wires haves round cross section, practical HTS wires may have a variety of shapes. In the examples of Figure 2, the cross section of BSCCO wires is flat or round depending upon the fabrication technique. Other practical REBCO and MgB_2 wires are also covered by stabilization or reinforcing components. Regardless of their outward appearance, all practical SC wires are designed based on the same principles which require functional components of filaments, matrix, barrier, stabilizer, reinforcing member and insulation.

superconductor (1)	Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_{10}$)
	Bi-2212 ($Bi_2Sr_2Ca_1Cu_2O_8$)
matrix (2)	silver and/or silver alloy
reinforcing member (3)	copper alloy
	stainless steel
insulation	resin for coating
	tape for winding



(a) BSCCO-2223 (b) BSCCO-2212

Fig. 2. (a) Cross-sectional views of practical BSCCO-2223 (a) and BSCCO-2212 (b) wires, where the numerals correspond to those in the table.

Industrialization of practical SC wires has progressed intensively since the first low-temperature SC industrial applications in the 1960's and following the discovery of high temperature superconductors in 1986. As a result, the architecture and fabrication techniques of industrially available superconductors have now been established and exhibit reproducible performance fully adequate for industrial materials.

III. CHARACTERISTIC ATTRIBUTES OF PRACTICAL SC WIRES

The primary purpose of electrical wires is to carry electrical current. Practical SC wires have the same intended purpose as common electrical wires, but posses the special ability to carry two or three orders of magnitude higher current than a common electrical wire of the same dimension. A standard test method becomes necessary to address the determination of current-carrying capacity, represented by the critical current. Several special properties of practical SC wires also necessitate additional test methods of mechanical and thermal properties as well as properties in high magnetic fields. Just as mentioned above, procurement of practical SC wires generally requires the specification of performance for one or many properties or parameters (attributes). The manufacturer, supplier, and customer should agree on which properties are important for their application, and then determine specifications of performance for those properties. Standards described in the next section are required for the measurement of actual performance, such as for certification or assurance that the specification is met. This section describes briefly all necessary properties that shall be considered in commercial transactions. Each of these properties must be unambiguously and precisely defined by an appropriate standard.

(1) Critical Temperature (T_c)

When a SC material is cooled down, it transforms from the normal to superconducting state at a given critical temperature. A large supercurrent can be carried with negligible or small Joule heat loss (depending on application), because the DC electrical resistance is almost zero and the AC resistance low in the SC state. The operation of SC wire in a given real application should be carried out at temperatures lower than T_c with sufficient enough temperature margin, because the instability such as flux creep increases rapidly as the temperature becomes close to T_c. There are also certain types of application, such as fault current limiters, that make use of the wire transition from the superconducting state to the normal conducting one. In such applications, the SC wire will experience temperatures above T_c and the electrical and thermal stabilization of the wire are considered individually with regards to specific application requirements, also above T_c.

(2) Critical Magnetic and Irreversibility Fields

When an external magnetic field higher than the lower critical field (B_{c1}) is applied to a practical superconductor, a so-called mixed state appears where quantized magnetic flux is introduced into the SC material. In this mixed state, large supercurrent can flow steadily in the superconductor without the generation of voltage. The ability of the SC material to carry large supercurrents without dissipation in the mixed state makes it possible to design a SC magnet operating at high magnetic field. However when the external magnetic field exceeds the irreversibility value (B_{irr}), the supercurrent is accompanied by a voltage. The mixed state is destroyed once the external field is above the upper critical magnetic field (B_{c2}).

(3) Critical Current (I_c) and *n*-Value

Theoretically, the critical current is defined as the maximum direct current that can flow without resistance. In practice, however, the critical current is determined using devices of finite measurement sensitivity in detecting dissipation by the SC wire. Therefore, the practical definition uses a criterion of finite value of resistivity or electric field. Electric voltage appears rapidly in proportion to $(I/I_c)^n$, when current I approaches and exceeds the critical current. The exponential index is called "*n*-value", which indicates the sharpness of transition to the magnetic flux flow state.

(4) Stability

When the SC state breaks down, some spot(s) or local segment(s) of the superconductor carrying a large supercurrent become normal and generate potential instability due to Joule heat. The practical SC wire is designed to avoid the expansion of such a current instability. In the case of Nb-Ti and Nb_3Sn composite superconducting wire, for instance, the high conductivity copper surrounds each superconducting core as stabilizer. Characterization of the heat-carrying capacity of the stabilizer is often performed via measurement of the residual resistivity ratio, (RRR).

(5) AC Loss

When an AC magnetic field or an AC current is applied to SC wires, heat generation takes place due to hysteresis, coupling between superconducting elements, and eddy current losses from complementary metallic components. In some important applications, a large heat generation is expected and the SC wires used are specifically designed to prevent the break-down of the SC state from the heat generated. For instance, in the case of Nb-Ti composite superconducting wire, the Nb-Ti filaments are twisted and the Cu matrix is replaced by a highly resistive Cu-Ni alloy element or divided by configurating a network of Cu-Ni alloy barrier.

(6) Strain-dependent Superconducting Properties

Due to the complicated composite structure of a conductor, the properties and architecture of the component materials affect the internal stress/strain exerted on the SC component, which significantly influences the SC properties. In practice, application of the SC wire occurs such that the strain incurred during fabrication or under operation is below the reversibility strain limit. If a large external strain is applied above the reversible strain limit, it causes a large permanent degradation of the critical current, e.g., due to the fracture of the SC component.

(7) Mechanical Properties

Practical SC wires are composites of multiple materials. Under strain, their mechanical properties until fracture depend in general on the rule of mixtures, according to which the weakest component breaks first. The end use of practical SC wires often introduces enormous mechanical forces, due to the ability of SC wires to carry high current densities even in high magnetic fields.

(8) Uniformity of Properties

For most cable and magnet applications, SC wires are utilized in kilometer lengths. Therefore it is necessary to ensure the uniformity of properties like critical current and *n*-value over the length of the wire, because the overall performance is limited by the local segment of the wire having the lowest properties.

IV. INTERNATIONAL STANDARDS

The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees. The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards (IS), Technical Specifications, Technical Reports (TR), Publicly Available Specifications (PAS) and Guides.

As mentioned in the Introduction, the technical committee, TC 90, “Superconductivity”, was established in August 1989. The first TC meeting was held in Tokyo in May 1990. At that first meeting, the scope of TC 90 was reviewed and it was decided to prepare international standards related to superconducting materials and devices [3]. The activity of standardization has been expanded to a variety of technical fields of superconductivity [4]. Nowadays, 14 working groups (WG) take charge of individual technical subjects.

The task of WG13 is to develop international standards on general characteristics for practical superconducting wires, which relate to the following two subjects: the description of general features of practical SC wires as mentioned in Section II and the general guidance for measurement methods and test procedures for properties critical to users as mentioned in the preceding Section III. The document on the general guidance for test methods was approved on May 1st, 2015 as the international standard [5], of which scheme is briefly overviewed below.

This new standard might be seen as "the roof document", which specifies the test methods used for validating the mechanical, electrical, and superconducting properties of practical SC wires. Fig. 3 explains the relation of this roof document to the standards for test methods.

The wire attributes necessary for the specification are subdivided as follows:

1. Attributes referring to the operation of SC wires, e.g., relevant during the initial cool-down to operating temperature, standard continuous operation, and under fault conditions.
2. Attributes related to implementation and engineering, e.g., relevant for the fabrication and installation of a device.

With respect to attributes belonging to these two categories, their principal test methods have been established as international standards of IEC 61788 series characterized below.

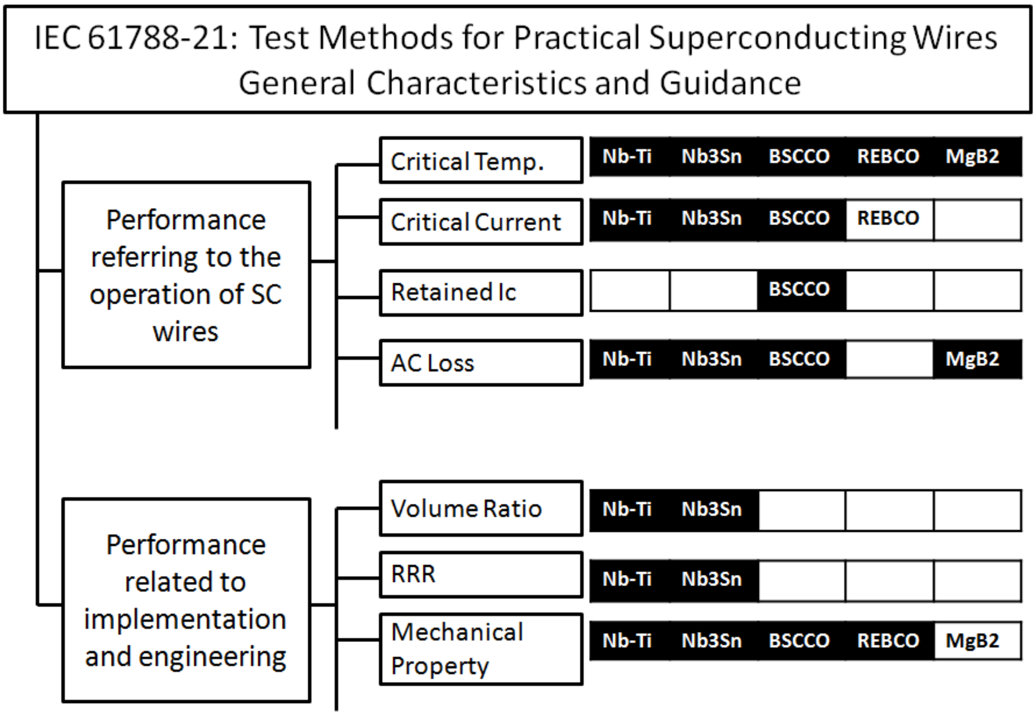


Fig. 3. Roof document and international standards for test methods of various attributes of practical SC wires. The black background boxes indicate international standards either published or under deliberation. Filled boxes with white background indicate the pre-standardization stage.

As indicated in Fig. 3, several attributes are addressed by individual standards of the IEC 61788 series. Each box with black background indicates the existence of an international standard or it being in the deliberation stage. Boxes with a compound's acronym on white background correspond to the pre-standardization stage. The detailed list of individual standards is presented below, where the number in parenthesis indicates the newest edition. When a new test method is established as the standard of IEC 61788 series, the newly approved roof document [5] should be modified by referring to it. Current standards of the IEC 61788 series related to specific properties shall be used to settle disputes. These standards are as follows:

(1) Attributes Referring to the Operation of SC wires:

i) Critical temperature:

- Critical temperature measurement – Critical temperature of composite superconductors by resistance method (IEC 61788-10:2006 Ed. 2.0).

ii) Critical current:

- Critical current measurement – DC critical current of Nb-Ti composite superconductors (IEC 61788-1: 2006 Ed. 2.0);
- Critical current measurement – DC critical current of Nb_3Sn composite superconductors (IEC 61788-2: 2006 Ed. 2.0);
- Critical current measurement – DC critical current of Ag- and/or Ag alloy-sheathed Bi-2212 and Bi-2223 oxide superconductors (IEC 61788-3: 2006 Ed. 2.0).

iii) Retained critical current

- Critical current measurement – Retained critical current after double bending at room temperature of Ag - sheathed Bi-2223 superconducting wires (IEC 61788-24: 2015 Ed. 1.0 NP) This document is under deliberation as a new work item proposal.

iv) AC loss:

- AC loss measurements - Total AC loss measurement of round superconducting wires exposed to a transverse alternating magnetic field at liquid helium temperature by a pickup coil method (IEC 61788-8: 2010 Ed. 2.0)
- AC loss measurements - Magnetometer methods for hysteresis loss in superconducting multifilamentary composites (IEC 61788-13: 2012 Ed. 2.0).

(2) Attributes Related to Wire Implementation and Engineering:

i) Matrix to superconductor volume ratio:

- Matrix to superconductor volume ratio measurement – Copper to superconductor volume ratio of Cu/Nb-Ti composite superconducting wires (IEC 61788-5: 2013 Ed. 2.0)
- Matrix to superconductor volume ratio measurement – Copper to non-copper volume ratio of Nb_3Sn composite superconducting wires (IEC 61788-12: 2013 Ed. 2.0).

ii) Residual resistance ratio:

- Residual resistance ratio measurement – Residual resistance ratio of Nb-Ti composite superconductors (IEC 61788-4: 2011 Ed. 3.0);
- Residual resistance ratio measurement – Residual resistance ratio of Nb_3Sn composite superconductors (IEC 61788-11: 2011 Ed. 2.0).

iii) Mechanical properties:

- Mechanical properties measurement – Room temperature tensile test of Cu/Nb-Ti composite superconductors (IEC 61788-6: 2011 Ed. 3.0);
- Mechanical properties measurement – Room temperature tensile test of Ag- and/or Ag alloy-sheathed Bi-2223 and Bi-2212 composite superconductors (IEC 61788-18: 2013 Ed. 1.0);
- Mechanical properties measurement – Room temperature tensile test of reacted Nb_3Sn composite superconductors (IEC 61788-19: 2013 Ed. 1.0);
- Mechanical properties measurement – Room temperature tensile test on REBCO wires (IEC 61788-XX: 2015 Ed. 1.0 NP). This document is under deliberation as a new work item proposal.

Terms used in all these standards are those defined by the International Electrotechnical Vocabulary (IEV), which by itself is considered a standard [1].

V. Towards Full Standardization

As mentioned in Section III, procurement of practical SC wires generally requires the specification of performance for all aspects of each attribute. The manufacturer, supplier, and customer should agree on which attributes are important for their application, and then determine specifications of performance for those attributes. We thus need to provide all kinds of standards on test method for attributes delineated in Section III. However, as indicated in Figure 3 and discussed in Section IV, the present status of wire standardization can be seen as "work in progress", with only some of the necessary attributes being already standardized. To further promote systematic international standardization, international collaborations are highly required. Indeed, it is absolutely necessary to collaborate with other international organizations to conduct standardization in the scientific and engineering areas of applied superconductivity. At present, the IEC-TC90 has kept liaison relationships with VAMAS TWA1[1] and CIGRÉ/SC D1[2] [3]. Specifically, of IEC standards published by TC90, most were studied technically in VAMAS and then completed in TC90 as IEC standards.

Until now, the collaboration with IEEE, Council on Superconductivity (CSC), has been rather informal, although effective in building a consensus on directions of future standards development. It is generally true that IEEE and IEC can launch parallel efforts, and the charter of each side recognizes other standards organizations and the need to work together. At present, the only parallel effort is in electronics, and there it is working well as a joint standards activity [6]. In SC wires and magnets, IEEE has not begun any standards work of significance, because IEC already initiated the standardization effort and plays the leadership role. Nevertheless, IEC wishes to establish a formal liaison relationship with IEEE

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[1] VAMAS in the acronym of the Versailles Project on Advanced Materials and Standards. This project supports world trade in products dependent on advanced materials technologies, through International collaborative projects aimed at providing the technical basis for harmonized measurements, testing, specifications, and standards.

[2] The International Council on Large Electric Systems (in French: Conseil International des Grands Réseaux Électriques, abbreviated CIGRÉ) is a global organization in the field of high voltage electricity. It was founded in Paris, France, in 1921. The scope of its activities includes the technical and economical aspects of the electrical grid, as well as the environmental and regulatory aspects.

and believes it should be very effective in accelerating and avoiding duplication of international work.

The procedure to develop an international standard of a test method is as follows. At first, a preliminary draft describing the test procedure is provided. By using this preliminary draft, a group of international experts from various laboratories carry out the test on the same specimens and then discuss their experience to improve the test method. This action is called the international round robin test (RRT). The established test method is then proposed to IEC-TC90 as a new item work proposal (NP). In principle, the relevant experts are recruited to participate in RRT as volunteers. Through the accomplishment of RRT, it becomes easier to summarize opinions and to attain agreement on the standard to be established.

By collaboration of IEC TC90 WG3 and VAMAS TWA16 [7], an international RRT on DC critical current testing of REBCO wires is just now in progress with participation of experts from the US, Asia and Europe. A preliminary draft of room temperature tensile test for MgB_2 wires is prepared for international RRT under the activity of TC90 WG5. Accordingly, that status is reflected in Figure 3 as the "pre-standardization stage".

One of most important future problems in standardization of superconductivity is to create product standards, which mean the specifications of practical SC wires related to different type of applications, for instance, for DC, AC and pulse operated devices, MRI, accelerators, ITER, and so on. Product standards are a sensitive issue. In fact, however, various forms of SC wires for such applications are presently distributed by manufacturers on the worldwide market. It seems to be possible to define the general and common characteristics among those practical SC wires currently on the market.

As mentioned in Section II, the general features of practical SC wires can be described in terms of the common structural requirements. At present, the five types of SC wire can be considered as practical [2]. That technical report might be accessed as a roof document for framing a systematic series of product standards.

VI. Concluding Remark

Further progress in superconductivity science and technology can be expected in the near future. In a variety of new applications, the SC products will be distributed and consumed by either experts or non experts via sales, deliveries and assembling of devices. Consensus-based standards are indispensable for developing a commercial market and accelerating the distribution of products. For new materials in the form of SC wires, the process of standardization disseminates knowledge about their characteristic features and provides recommendations on how to use them in applications.

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