PD IEC/TR 61788-20:2014

BSI Standards Publication

Superconductivity

Part 20: Superconducting wires — Categories of practical superconducting wires — General characteristics and guidance

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This Published Document is the UK implementation of IEC/TR 61788-20:2014.

The UK participation in its preparation was entrusted to Technical Committee L/-/90, Super Conductivity.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Published by BSI Standards Limited 2014

ISBN 978 0 580 87161 0
ICS 29.050

Compliance with a British Standard cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 August 2014.

Amendments/corrigenda issued since publication

Date	Text affected

IEC TR 61788-20

Edition 1.0 2014-07

TECHNICAL REPORT

Superconductivity –
Part 20: Superconducting wires – Categories of practical superconducting wires – General characteristics and guidance

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE **R**

ICS 29.050

ISBN 978-2-8322-1779-5

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

SUPERCONDUCTIVITY –

Part 20: Superconducting wires – Categories of practical superconducting wires – General characteristics and guidance

FOREWORD

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 61788-20, which is a technical report, has been prepared by IEC technical committee 90: Superconductivity.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
90/335/DTR	90/344/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 61788-20 series, published under the general title *Superconductivity,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

Superconducting (SC) wires are a central and often enabling technology of many important industrial products. Consensus-based standards for SC wires greatly facilitate the creation of procurement specifications, design and engineering of components, certification of quality, description of operating devices, and generalization of use in industrial technologies.

The present technical report (TR IEC61788-20) provides a description of the general features of practical SC wires. The practical low temperature superconducting (LTS) wires have been used extensively in a variety of applications since the late 1960s. These applications include magnetic resonance imaging magnets, research and accelerator magnets, and systems for cutting-edge scientific research. High temperature superconductors (HTS), discovered in 1986, allow operation of superconductor-based technologies with less expensive and more efficient refrigeration systems. These new materials will provide wires that will enable new applications, some of which may not be possible with LTS wires. Many fabrication routes and conductor architectures are well established for superconducting wires, and these engineering routes have a number of general characteristics that are fundamental to enabling industrial products.

Practical superconducting wires are those forms of SC wires that are nearly identical to other common electrical conductors such as those made from copper or aluminium. The appearance of low temperature superconductive wires is, for instance, very similar to commercial electrical copper wires or tin-plated copper wires, because they are covered with stabilization or reinforcing components consisting of metallic elements. Often practical SC wires are supplied in long lengths on wire spools. As such, practical SC wires can be used in products and applications almost interchangeably with common wires. The technical aspects of superconductivity impose, however, certain considerations that might be taken into account in specifications for procurement, design and engineering, testing and certification, quality control, and other commerce. These aspects can be complicated, making practical SC wires less accessible to the non-technical user despite the best efforts of SC wire suppliers to market their products. This document intends to provide descriptions of the technical aspects of practical SC wires in terms of simple general characteristics to assist in the specification and use of superconducting wire products. It might be noted that this document gives some general characteristics of practical SC wires at the present state, but not any type of specifications for the wires or for the processing of the wire.

Thus the present technical report that provides general characteristics and guidance with respect to practical SC wires is recommended as a first priority for both producers and users of superconducting technology.

SUPERCONDUCTIVITY –

Part 20: Superconducting wires – Categories of practical superconducting wires – General characteristics and guidance

1 Scope

This part of IEC 61788, which is a technical report, provides general characteristics and guidance on practical SC wires. Particular focus is given to the characteristics that are different from those of ordinary copper and aluminium wires, since practical SC wires have appearance nearly identical to common electrical wires and can be used interchangeably with them. On the other hand, the practical SC wires are typically composite materials consisting of several functional materials as described in Annex A.

Many forms of SC wires are described in Section 4 of IEC 60050-815, including single core wires, multi-filamentary superconducting wires, composite superconductors and coated conductors. These wires as well as others that might be described as monolithic composite superconducting wires will be the focus in this technical report. A wire is considered as being practical if it can be procured in sufficiently continuous lengths under ordinary commercial transactions to build devices.

Conductors made of multiple wires, such as cables, for example, are not included in this scope.

Since this report only addresses the characteristics of practical wires, other wires such as prototype, test sample and developmental wires are not included in the scope of this technical report.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at: <http://www.electropedia.org>)

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-815 apply.

4 Categories of practical SC wires

Industrially available SC materials are classified into two categories by IEC 60050-815. The low temperature superconductors have a critical temperature less than 25 K. They are typically in the Nb-Ti group and Nb_3Sn group, which is an intermetallic compound. The other category consists of high temperature superconductors such as BSCCO and REBCO and the intermetallic compound MgB_2. In the present document, the five types of SC wire based on the aforementioned five superconductor materials may be prescribed as practical SC wires, of which the additional details are mentioned in Annexes A and B. When a new superconducting material is industrialized into wire form in the future, the current general requirements should be modified by introducing it as a new practical SC wire.

5 Technical sheet assisting in the specification and the use of practical SC wires

General items to agree between the supplier and the customer at the time of contract or purchase order are listed as follows. Except the recommended items mentioned here, additional items providing for the specification are described in Annex C. The technical sheet may be executed.

6 Class of practical SC wires

One of the practical SC wires described in Clause 4 may be specified.

Additional informative items are mentioned in Annex B.

7 Product parameters

– Dimension may be settled in terms of the diameter of the round wire or the width / thickness of the rectangular wire together with the tolerance.
– Length and/or weight may be definitely settled.
– The necessity of insulation may be designated.
– The type of spooling may be designated.
– The shipping label designated in Clause 13 may be attached on the shipped product.

Additional informative items are mentioned in Annex C.

8 Joints

Unless otherwise agreed upon by a customer and a supplier, no joints may be made in the completed wire. If joints are permitted within the wire, the customer and supplier are required to agree on the quantity and properties of the joints.

9 Appearance

The appearance of the wire should be free from any imperfection not consistent with commercial practice.

Additional informative items are mentioned in Annex C.

10 Quality assurance

A representative critical current value may be designated together with tolerance.

Additional informative items are mentioned in Annex C.

11 Test methods

Tests to determine conformance to requirements on product parameter and quality may be performed according to the instruction of the document (see Bibliography).

12 Inspection

Unless otherwise specified in the contract or purchase order, the supplier may be responsible for the performance of all inspection and test requirements specified.

Unless otherwise agreed upon between the customer and the supplier, conformance of the wire to the various requirements listed in this specification may be determined on samples taken from each lot of wire presented for acceptance.

13 Shipping label

The following information may be supplied with the product shipping label:

– a heading title “Superconducting wire” and/or the name of the principal SC material, and/or product identification such as a trade name;
– manufacturer;
– manufacturing date;
– country of origin;
– information guaranteeing traceability by the manufacturer, such as lot number or billet number.

Further information is mentioned in Annex C.

Annex A
(informative)

Structural characteristics of practical SC wires

A.1 General

Practical SC wires are designed with a composite structure to meet the desired engineering characteristics by expert selection of materials and design of the architecture. SC wires typically possess a complicated internal architecture, the constituents of which include the SC material plus additional functional components, such as a metal matrix material and stabilizers or reinforcements. The functional components are engineered so that the SC wire possesses electrical and mechanical integrity to withstand fabrication into equipment and operating conditions in application.

An overview of the types of SC materials and the role of the functional components are explained below in Clauses A.2 and A.3, respectively. As mentioned above, low temperature superconducting wires are typically similar in appearance to standard copper wire. Practical high temperature superconducting wires come in a variety of shapes. Their cross section is flat or round in accordance with fabrication techniques. Some HTS wires are also covered by stabilization or reinforcing components. Descriptions of the construction of low temperature and high temperature superconducting wires, including typical choices of materials for the functional components, follow in Annex B.

A.2 Overview of SC materials

Five types of superconducting materials are designated as members of practical SC wires, of which the details are described in Annex B. Practical SC wires are used at temperatures sufficiently lower than their inherent critical temperature and under magnetic fields lower than an irreversibility magnetic field.

Practical SC wires also differ from common electrical wires by having the ability to carry hundreds or thousands of times higher electrical current for the copper wire with the same diameter. Under such conditions, the energy stored in the form of currents and their associated magnetic fields can exceed other thermodynamic energies, leading to the possibility of spontaneous and uncontrollable energy release. Since the electromagnetic energy per unit volume is proportional to the physical dimension of the superconductor, it is often common practice to sub-divide the superconductor material into small volume. Therefore, practical SC wire architectures sub-divide the superconducting material, usually by the formation of parallel superconducting filaments, resulting in multifilamentary superconducting wire.

Some uses of practical SC wires require the electric current to vary with time, or for the electric current to be carried under time-varying external magnetic field. Certain losses arise from superconducting behaviour under these conditions, which can be minimized by twisting the wire about its axis so as to impart a helical pattern to the filaments.

A.3 Overview of functional components

A.3.1 Matrix materials

Often a plurality of the superconducting material in a composite wire is present as filaments or thin layer. The filaments can have a diameter ranging between sub-micrometers to tens or even hundreds of micrometers or thin layers with thickness between one to tens of microns. The superconducting filaments are embedded in, and in direct contact with, matrix materials.

The function of the matrix materials with respect to the filaments can be multi-purpose, including: to support them mechanically, facilitate their formation, provide conductive electrical connections, promote transfer of heat to the cooling environment, and/or limit degradation of superconducting properties. In the case of MgB_2, the superconducting mulitifilaments are surrounded by sheath, outer sheath and/or barrier materials. In the case of REBCO group (see Clause B.4), the matrix consists of substrate, buffer layer, cap layer and protection layer. The details for individual SC wires are described more precisely in Clause B.5.

A.3.2 Stabilizer

A stabilization component can absorb the Joule heat and allow the supercurrent to reroute around a local break-down of superconductivity. At very low temperatures such as 4,2 K, there is greater necessity for a stabilization component because the heat capacity of all materials is generally lower as temperature decreases, even though the resistivity also changes with temperature.

Practical SC wires attain the superconducting state when cooled below their critical temperature. A good thermal conductor, called the stabilizer, is required to transmit heat to a refrigerant or some other cooling agent. Since good conductors of electricity are also good conductors of heat, pure copper, silver, or aluminium components of composite superconductors also serve as the stabilizer. Moreover, since most applications surround the wire with the coolant, the stabilizer typically forms the outside of the wire.

All practical SC wires are designed to carry electrical current through the stabilizer. Therefore, it is permissible to refer to the intended electrical conductor in the normal conducting state as the stabilizer.

As mentioned above, the contribution of the stabilizer is essential for designing the practical SC wires. The following indexes are usually designated.

– Copper volume fraction and superconductor volume fraction, which are used to specify the volume fraction of components in a composite wire, for the example where the stabilizer is copper.
– Copper to non-copper volume ratio and copper to superconductor volume ratio, which are the ratios of the volume of stabilizer to the volume of other components in a composite wire for the example where the stabilizer is copper.

In the case of Nb-Ti wires, in order to improve the thermal and/or flux jump stability as well as to reduce the coupling loss, a Cu alloy such as Cu-Ni and/or aluminium are composed as a stabilizer.

In the case of MgB_2, the stabilization components can be provided through materials inside and/or outside the outer sheath and/or with electro-deposition or soldering on the outer sheath surface.

A.3.3 Reinforcing component

Some metallic components are used in order to increase the strength. A high strength thin layer can be distributed in the interior of the low temperature superconducting wire. Thin metallic sheets can also be used to increase the strength of high temperature superconductors, which are soldered or electrodeposited on the surface of wires.

A.3.4 Insulation

The surface of practical SC wires is often coated by an insulating resin or wound with an insulating tape in order to prevent short-circuiting caused by contact between wires with the surrounding conducting substances, and to avoid dielectric breakdown or arcing depending on the voltage requirements of the application.

Practical SC wires can be supplied with insulation. Insulation materials that are used for common electrical wires may also be applied to practical SC wires. Also, the heat treatment and end use of the practical SC wire may determine other materials for insulation.

Annex B
(informative)

Classes of practical SC wires

B.1 Nb-Ti group

The Nb-Ti practical SC wires usually contain two components composed of SC Nb-Ti-based filaments and Cu matrix, as listed in Table B.1. The most practical Nb-Ti alloy is the simple Nb-Ti two-component system, with a composition of 46 % to 48 % titanium by mass, but for specific applications, ternary and multi-component alloys such as Nb-Ti-Hf and Nb-Ti-Ta-Zr were developed. The role of the matrix is to provide conductive electrical connections and promote transfer or conduction of heat to the cooling environment: for instance, copper is in direct contact with the Nb-Ti filaments of a multi-filamentary wire composite. In order to improve the thermal and/or flux jump stability as well as to reduce the coupling loss, the Cu alloy such as Cu-Ni and/or the aluminium are composed as stabilizer.

The fabrication process of Nb-Ti wires is applied to common electrical wires, using similar machinery and tooling, including: forging, swaging, rolling, extruding, and drawing. Heat treatments may be applied to assist the forming process; however, special properties of the superconducting material will generally govern the applicability of heat treatment as described below.

Raw material specifications apply to forms of Nb-Ti alloy used at the beginning of the manufacture of practical SC wire. These specifications also address methods of manufacture, chemical composition, physical and mechanical properties, dimensions and mass of product, workmanship and appearance, tolerances and variations, and other issues of direct commerce between the industrial supplier of practical SC wires and the raw material supplier.

Table B.1 – Constituents composing the Nb-Ti group SC wires

Constituent	Material
Superconductor	Nb-Ti alloy
Matrix	Copper or copper alloy
Stabilizer	Aluminium, copper or copper alloy
Insulation	Resin for coating Tape for winding Braided fiber for sheathing

B.2 Nb_3Sn group

This category of superconductors belongs to A15 type intermetallic compounds including Nb_3Sn, Nb_3Al and so on. Several kinds of manufacturing processes have been developed, including among them, the bronze process, the internal/ external diffusion process, the jelly roll process, and the powder-in-tube process. In the case of Nb_3Sn practical SC wires as shown in Table B.2, the matrix contacting directly with the superconductor is the Cu-Sn alloy and niobium. In order to operate stably, high conductivity copper is utilized as stabilizer, while the niobium or tantalum thin layer is inserted as diffusion barrier between the matrix and the copper stabilizer because it prevents contamination from the matrix during the heat treatment. Due to the final heat treatment at high temperature during the fabrication process, the SC wire becomes soft mechanically. To enhance mechanical strength, the SC wire is reinforced by adding a copper alloy component. Due to the brittleness of Nb_3Sn components, the so called “wind and react” process is adopted for many cases, by which the unreacted wire is finished in the final shape of the product prior to the heat treatment for forming the Nb_3Sn compound.

Several standard specifications for niobium, copper, and copper-tin alloy (bronze) raw materials exist. These specifications address many issues of direct commerce between the supplier of practical SC wires and the raw material suppliers.

Three sub-classes of practical Nb_3Sn wires exist: internal-tin wires, bronze-route wires, and powder-in-tube wires. In most circumstances, the details of the sub-class do not affect the end use.

All sub-classes of practical Nb_3Sn SC wires require a heat treatment to form the intermetallic compound by a diffusion reaction between a source of tin and a source of niobium. Because the wire is brittle after heat treatment, all Nb_3Sn wires are received in the state before heat treatment. Vendors should provide a recommendation for the time and temperature schedule for the heat treatment as well as the acceptable heat treatment environments.

Table B.2 – Constituents composing the Nb_3Sn group SC wires

Constituent	Material
Superconductor	Nb_3Al intermetallic compound or Nb_3Sn intermetallic compound
Matrix	Copper, copper alloy or niobium
Diffusion barrier	Niobium or tantalum
Stabilizer	Copper
Reinforcing member	Copper alloy
Insulation	Resin for coating Tape for winding or wrapping Braided fiber for sheathing

B.3 MgB_2

The MgB_2 practical wires are fabricated by means of in-situ or ex-situ techniques by using as starting materials an Mg and B precursor or an MgB_2 reacted compound. As shown in Table B.3, the materials contacting directly with the MgB_2 core and forming the monofilament should have no reactivity, or a well-controlled reactivity, with Mg, B and MgB_2. Usually, as a barrier, a material with no reactivity at all can be used. At the present state, the materials mostly used in the MgB_2 wire architecture are listed in Table B.3.

MgB_2 practical SC wire can be specified for delivery in a heat-treated or a non heat-treated state.

Table B.3 – Constituents composing the MgB_2 SC wires

Constituent		Material
Superconductor		MgB_2 or doped MgB_2
Matrix	Sheath and outer sheath	Iron, nickel, nickel alloy, niobium, stainless steel or titanium
	Barrier	Niobium or titanium
Stabilizer		Copper or copper alloy
Insulation		Resin for coating Tape for winding

B.4 BSCCO group

As shown in Table B.4, two types of bismuth-based oxide superconductors with the chemical formula ($(Bi, Pb)_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$), where n = 2 or 3, are used as practical SC wires. In either case, superconducting filaments are embedded into a pure silver matrix.

- Bi-2223

In the Bi-2223 wires, a silver alloy outer sheath surrounds the matrix for increasing mechanical strength. Bi-2223 wires are exclusively made in flat tape-shaped form. Wires are commercially available in which thin metallic sheets of copper alloy or stainless steel are soldered on both sides of the SC tapes in order to improve the strain dependence of the critical current and the mechanical properties.

- Bi-2212

According to the characteristic feature of microstructure control for Bi-2212 wire, its outer shape is round, while superconducting filaments are embedded into a pure silver matrix. In principle, the wire is so soft that the wind and react process is adopted to fabricate final products such as Rutherford cables.

Bi-2212 may be specified as round wires or as conductors with a high aspect ratio. It is recommended to clarify the form of the conductor as part of the procurement documentation.

Table B.4 – Constituents composing the BSCCO SC wires

Constituent	Material
Superconductor	Bi-2212 ($Bi_2Sr_2Ca_1Cu_2O_8$) or Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_{10}$)
Matrix	Silver or silver alloy
Reinforcing member	Copper alloy or stainless steel
Insulation	Resin for coating Tape for winding

B.5 REBCO group

The rare-earth-based oxide superconductor with the chemical formula, $RE_1Ba_2Cu_3O_7$ is used as a practical SC wire, where the rare-earth element RE is Y, Gd, Nd, Ho and Sm. This type of practical SC wire is usually called a REBCO coated conductor. As shown in Table B.5, a typical architecture consists of a substrate of Hastelloy, stainless steel or Ni-W alloy, and a few thin oxide layers including a buffer layer of Al_2O_3, Y_2O_3, CeO_2, YSZ, MgO, a cap layer of CeO_2 or $LaMnO_3$, an SC layer, and a protection layer of Ag. The cap layer acts as a template to facilitate the well-oriented epitaxial growth of the SC layer. Although not all components of substrate, buffer layer, cap layer and protection layer are in direct contact with the superconducting material, for convenience they are categorized as matrix material since they are either critical for the proper growth of the superconducting material (substrate, buffer layer and cap layer) or in direct contact with the superconductor (cap layer and protection layer) and provide thermal and/or electrical contact to the rest of the composite structure.

Table B.5 – Constituents composing REBCO SC wires

Constituent		Material
Superconductor		RE-123 ($RE_1Ba_2Cu_3O_7$:RE=Y, Nd, Sm, Gd, Ho)
Matrix	Substrate	Hastelloy, Ni-W alloy or stainless steel
	Buffer layer	Al_2O_3, CeO_2, $Gd_2Zr_2O_7$, MgO,Y_2O_3, or YSZ
	Cap layer	CeO_2 or $LaMnO_3$
	Protection layer	Ag
Stabilizer		Copper, copper alloy or other material for stabilization
Reinforcing member		Ferrous alloy, nickel alloy or stainless steel
Insulation		Resin for coating Tape for winding

Annex C
(informative)

Technical information assisting in the specification and use of practical SC wires

C.1 General

When contracting or ordering, further informative terms are selected from the following lists for fixing the specification, because it depends on individual application. Their technical meaning is interpreted in Annexes A and B.

C.2 Product parameters

– Constituent materials include the additional terms of matrix, barrier, reinforcing member, insulation and others.
– The interior structure is characterized by the following terms of filament diameter, number of filaments, twisting, twist pitch, matrix ratio, Cu/non-Cu ratio, silver ratio, and snapping rate.
– Insulation is complemented by the additional terms of thickness and dielectric strength.
– Length and/or weight are definitely settled in terms of single length, number of pieces, total length, weight of piece and/or total weight.
– The type of packing is complemented by the following additional terms of drum or reel, regular winding, pancake winding, and/or wrapping.
– The shipping label is additionally recommended to include the following terms when it is requested: (i) purchase order number, (ii) gross, tare, and net weights, (iii) number of pieces, (iv) diameter and length, (v) stabilizer material, etc.

C.3 Appearance

Inspection of the finished product may find the exterior free from harmful defects, wrench, billowing, stains, and other imperfections, as much as possible.

C.4 Quality assurance

– Properties referring to the operation of SC wires include the additional terms of *n* value, their bending and/or tensile stress/strain tolerance, critical temperature, critical magnetic and irreversibility fields, AC loss, etc.
– Properties related to implementation and engineering include dielectric strength, RRR, modulus of elasticity, tensile strength, etc.

Test methods necessary for quality assurance are described in the IEC 61788 series (see the Bibliography).

C.5 Test methods

Tests to determine the conformance to requirements necessary to the product parameter and quality may be performed according to the direction of the IEC 61788 series.

C.6 Technical record

A technical record is required to demonstrate compliance with the procurement specifications, in which additional informative items described in Clause C.2 and Clause C.4 might be included. The technical record can be added together with the technical sheet.

Bibliography

IEC 61788-1, *Superconductivity – Part 1: Critical current measurement – DC critical current of Nb-Ti composite superconductors*

IEC 61788-2, *Superconductivity – Part 2: Critical current measurement – DC critical current of* Nb_3Sn *composite superconductors*

IEC 61788-3, *Superconductivity – Part 3: Critical current measurement – DC critical current of Ag- and/or Ag alloy-sheathed Bi-2212 and Bi-2223 oxide superconductors*

IEC 61788-4, *Superconductivity – Part 4: Residual resistance ratio measurement – Residual resistance ratio of Nb-Ti composite superconductors*

IEC 61788-5, *Superconductivity – Part 5: Matrix to superconductor volume ratio measurement – Copper to superconductor volume ratio of Cu/Nb-Ti composite superconducting wires*

IEC 61788-6, *Superconductivity – Part 6: Mechanical properties measurement – Room temperature tensile test of Cu/Nb-Ti composite superconductors*

IEC 61788-8, *Superconductivity – Part 8: 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 61788-10, *Superconductivity – Part 10: Critical temperature measurement – Critical temperature of composite superconductors by a resistance method*

IEC 61788-11, *Superconductivity – Part 11: Residual resistance ratio measurement – Residual resistance ratio of* Nb_3Sn *composite superconductors*

IEC 61788-12, *Superconductivity – Part 12: Matrix to superconductor volume ratio measurement – Copper to non-copper volume ratio of* Nb_3Sn *composite superconducting wires*

IEC 61788-13, *Superconductivity – Part 13: AC loss measurements – Magnetometer methods for hysteresis loss in superconducting multifilamentary composites*

IEC 61788-18, *Superconductivity – Part 18: Mechanical properties measurement – Room temperature tensile test of Ag- and/or Ag alloy-sheathed Bi-2223 and Bi-2212 composite superconductors*

IEC 61788-19, *Superconductivity – Part 19: Superconductivity – Part 19: Mechanical properties measurement – Room temperature tensile test of reacted* Nb_3Sn *composite superconductors*

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