INTERNATIONAL STANDARD

IEC 61788-4

First edition
2001-07

Superconductivity –

Part 4:
Residual resistance ratio measurement –
Residual resistance ratio of Nb-Ti composite superconductors

Supraconductivité –

Partie 4:
Mesure de la résistivité résiduelle –
Taux de résistivité résiduelle des supraconducteurs composites au Nb-Ti

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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SUPERCONDUCTIVITY –

Part 4: Residual resistance ratio measurement – Residual resistance ratio of Nb-Ti composite superconductors

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the 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, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 61788-4 has been prepared by IEC technical committee 90: Superconductivity.

The text of this standard is based on the following documents:

FDIS	Report on voting
90/96/FDIS	90/104/RVD

Full information on the voting for the approval of this standard 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 3.

Annex A is for information only.

The committee has decided that the contents of this publication will remain unchanged until 2005. At this date, the publication will be

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- withdrawn;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

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

INTRODUCTION

Copper is used as a matrix material in multifilamentary superconductors and works as an electrical shunt when the superconductivity is interrupted. It also contributes to recovery of the superconductivity by conducting heat generated in the superconductor to the surrounding coolant. The cryogenic-temperature resistivity of copper is an important quantity, which influences the stability of the superconductor. The residual resistance ratio is defined as a ratio of the resistance of the superconductor at room temperature to that just above the superconducting transition.

In this International Standard the test method of residual resistance ratio of Nb-Ti composite superconductors is described. The curve method is employed for the measurement of the resistance just above the superconducting transition. Other methods are described in clause A.4.

SUPERCONDUCTIVITY –

Part 4: Residual resistance ratio measurement – Residual resistance ratio of Nb-Ti composite superconductors

1 Scope

This part of IEC 61788 covers a test method for the determination of the residual resistance ratio (*RRR*) of a composite superconductor comprised of Nb-Ti filaments and Cu, Cu-Ni or Cu/Cu-Ni matrix. This method is intended for use with superconductors that have a rectangular or round cross-section, *RRR* less than 350, and cross-sectional area less than 3 mm^2. All measurements shall be done without an applied magnetic field.

The method described in the body of this standard is the “reference” method and optional acquisition methods are outlined in annex A.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60050-815:2000, *International Electrotechnical Vocabulary – Part 815: Superconductivity*

3 Terminology

For the purpose of this part of IEC 61788, the definitions given in IEC 60050-815 and the following definition apply.

3.1
residual resistance ratio
the ratio of resistance at room temperature to the resistance just above the superconducting transition

4 Definition

The residual resistance ratio of the composite wire shall be obtained in equation (1) below where the resistance (R_1) at room temperature (20 °C) is divided by the resistance (R_2) just above the superconducting transition.

$$RRR = \frac{R_1}{R_2} \quad (1)$$

Figure 1 shows schematically a voltage versus temperature curve acquired on a specimen while measuring the cryogenic resistance. Draw a line in figure 1 where the voltage sharply increases (a), and draw also a line in figure 1 where the temperature increases but the resistance remains almost the same (b). The value of resistance at the intersection of these two lines, A, is defined as resistance (R_2) just above the superconducting transition.

5 Requirements

The resistance measurement both at room and cryogenic temperatures shall be performed with the four probe technique.

The target precision of this method is that the coefficient of variation (COV) in the inter-comparison test shall be 5 % or less.

The maximum bending strain, induced during mounting the specimen, shall not exceed 2 %.

6 Apparatus

6.1 Material of measuring mandrel or of measuring base plate

Material of the measuring mandrel for a coiled specimen or of the measuring base plate for a straight specimen shall be copper, aluminum, silver, or the like whose thermal conductivity is equal to or better than 100 W/(m·K) at liquid helium temperature (4,2 K). The surface of the material shall be covered with an insulating layer (tape or a layer made of mylar, polyester, teflon, etc.) whose thickness is 0,1 mm or less.

6.2 Diameter of the measuring mandrel and length of the measuring base plate

Diameter of the measuring mandrel shall be large enough to keep bending strain of the specimen less than or equal to 2 %.

The measuring base plate shall be at least 30 mm long in one dimension.

6.3 Cryostat for the resistance, R_2, measurement

The cryostat shall include a specimen support structure and a liquid helium reservoir for the resistance, R_2, measurement. The specimen support structure shall allow the specimen, which is mounted on a measurement mandrel or a measurement base plate, to be lowered and raised into, and out of, a liquid helium bath. In addition, the specimen support structure shall be made so that a current can flow through the specimen and the resulting voltage generated along the specimen can be measured.

7 Specimen preparation

The test specimen shall have no joints or splices, and shall be 30 mm or longer. The distance between two voltage taps (*L*) shall be 25 mm or longer. A thermometer for measuring cryogenic temperature shall be attached near the specimen.

Some mechanical method shall be used to hold the specimen against the insulated layer of the measurement mandrel or base plate. Special care shall be taken during instrumentation and installation of the specimen on the measurement mandrel or on the measurement base plate so that there is no excessive force, which may cause undesired bending strain or tensile strain, being applied to the specimen.

The specimen shall be instrumented with current contacts near each end of the specimen and a pair of voltage contacts over a central portion of the specimen. The specimen shall be mounted on a measurement mandrel or on a measurement base plate for these measurements. Both resistance measurements, R_1 and R_2, shall be made on the same specimen and the same mounting.

8 Data acquisition

8.1 Resistance (R_1) at room temperature

The mounted specimen shall be measured at room temperature (T_m (°C)), where T_m satisfies the following condition, $0 \leq T_m \leq 35$. A specimen current (I_1 (A)) shall be applied so that the current density is in the range of 0,1 A/mm^2 to 1 A/mm^2 based on the total wire cross-sectional area, and the resulting voltage (U_1 (V)), I_1 and T_m shall be recorded. Equation (2) below shall be used to calculate the resistance (R_m) at room temperature. The resistance (R_1) at 293 K (20 °C) shall be calculated using equation (3) for a wire with Cu matrix. The value of R_1 shall be set equal to R_m, without any temperature correction, for wires that do not contain a pure Cu component.

$$R_m = \frac{U_1}{I_1} \qquad (2)$$

$$R_1 = \frac{R_m}{[1 + 0{,}00393 \times (T_m - 20)]} \qquad (3)$$

8.2 Resistance (R_2*) just above the superconducting transition

Under a strained condition of the specimen, the measured cryogenic resistance, R_2*, is not a correct value for R_2. The corresponding correction of the strain effect will be described in subclause 8.3.

8.2.1 The specimen, which is still mounted as it was for the room temperature measurement, shall be placed in the cryostat for electrical measurement specified under 6.3. Alternate cryostats that employ a heating element to sweep the specimen temperature are described in clause A.2.

8.2.2 The specimen shall be slowly lowered into the liquid helium bath and cooled to liquid helium temperature over a time period of at least 5 min.

8.2.3 During the acquisition phases of the low-temperature R_2* measurements, a specimen current (I_2) shall be applied so that the current density is in the range of 0,1 A/mm^2 to 10 A/mm^2 based on the total wire cross-sectional area, and the resulting voltage (U(V)), I_2 (A), and specimen temperature (T (K)) shall be recorded. In order to keep the ratio of signal to noise high enough, the measurement shall be carried out under the condition that the resulting voltage above the superconducting transition exceeds 10 µV. An illustration of the data to be acquired and its analysis is shown in figure 2.

8.2.4 When the specimen is in superconducting state and test current (I_2) is applied, two voltages shall be measured nearly simultaneously, U_{0+} (the initial voltage recorded with a positive current polarity) and U_{0rev} (the voltage recorded during a brief change in applied current polarity). A valid R_2* measurement requires that excessive interfering voltages are not present and that the specimen is initially in the superconducting state. Thus, the following condition shall be met for a valid measurement:

$$\frac{|U_{0+} - U_{0\,rev}|}{\overline{U_2}} < 1\ \% \qquad (4)$$

where $\overline{U_2}$ is the average voltage for specimen in normal state at cryogenic temperature, which is defined at 8.2.10.

8.2.5 The specimen shall be gradually warmed so that it changes to the normal state completely. When the cryostat for the resistance measurement specified under 6.3 is used, this can be achieved simply by raising the specimen to an appropriate position above the liquid helium level.

8.2.6 The specimen voltage versus temperature curve shall be acquired with the rate of temperature increase maintained between 0,1 K/min and 10 K/min.

8.2.7 The voltage versus temperature curve shall continue to be recorded during the transition and into the normal state, up to a temperature somewhat less than 15 K. Then the specimen current shall be decreased to zero and the corresponding voltage, U_{20+}, shall be recorded at a temperature below 15 K.

8.2.8 The specimen shall then be slowly lowered into the liquid helium bath and cooled to the same temperature, within ±1 K, where the initial voltage signal U_{0+} was recorded. A specimen current, I_2, with the same magnitude but negative polarity (polarity opposite that used for the initial curve) shall be applied and the voltage U_{0-} shall be recorded at this temperature. The procedural steps 8.2.5 to 8.2.7 shall be repeated to record the voltage versus temperature curve with this negative current. In addition, the recording of U_{20-} shall be made at the same temperature, within ±1 K, where U_{20+} was recorded.

8.2.9 Each of the two voltage versus temperature curves shall be analyzed by drawing a line (a) through the data where the voltage sharply increases with temperature (see figure 2) and drawing a second line (b) through the data above the transition where the voltage is nearly constant with temperature. U_{2+}* and U_{2-}* shall be determined at the intersection of these two lines for the positive and negative polarity curves respectively.

8.2.10 The corrected voltages, U_{2+} and U_{2-}, shall be calculated using the following equations, $U_{2+} = U_{2+}^* - U_{0+}$ and $U_{2-} = U_{2-}^* - U_{0-}$. The average voltage, $\bar{U}_2$, shall be defined as

$$\bar{U}_2 = \frac{|U_{2+} - U_{2-}|}{2} \qquad (5)$$

8.2.11 A valid R_2* measurement requires that the shift of thermoelectric voltage be within acceptable limits during the measurements of the U_{2+} and U_{2-}. Thus, the following condition shall be met for a valid measurement,

$$\frac{|\Delta_+ - \Delta_-|}{\bar{U}_2} < 3\% \qquad (6)$$

where Δ_+ and Δ_- are defined as $\Delta_+ = U_{20+} - U_{0+}$ and $\Delta_- = U_{20-} - U_{0-}$. If the R_2* measurement does not meet the validity requirements in 8.2.4 and 8.2.11, then improvement steps either in hardware or experimental operation shall be taken to meet these requirements before results are reported.

8.2.12 Equation (7) shall be used to calculate the measured resistance (R_2*) just above the superconducting transition.

$$R_2^* = \frac{\bar{U}_2}{I_2} \qquad (7)$$

8.3 Correction on measured R_2* for bending strain

If there is no pure Cu component in the superconductor, then R_2 shall be set equal to R_2*.

For a specimen with a pure Cu component, the bending strain shall be defined by $\varepsilon_b = 100 \times (h/r)$ (%), where h is a half of the specimen thickness and r is the bending radius. If the bending strain is less than 0,3 %, then no correction is necessary, and R_2 shall be set equal to R_2*.

If neither of the above two situations applies, then the resistance R_2 just above the superconducting transition under the strain-free condition shall be estimated by

$$R_2 = R_2^* - \Delta\rho \times \frac{L}{S_{Cu}} \tag{8}$$

where $\Delta\rho$ is defined below and S_{Cu} and L are defined in 9.4. The increase in the resistivity of pure copper at 4,2 K due to tensile strain, ε(%), is expressed by

$$\Delta\rho\ (\Omega m) = 6{,}24 \times 10^{-12}\varepsilon - 5{,}11 \times 10^{-14}\varepsilon^2\ ; \quad \varepsilon \leq 2\ \% \tag{9}$$

The calculation of equation (9) shall be carried out assuming that the equivalent tensile strain ε is (1/2) ε_b and (4/3π) ε_b for rectangular and round wires, respectively. The bending strain dependency of residual resistance ratio for pure copper is described in clause A.1.

8.4 Residual resistance ratio (*RRR*)

The *RRR* shall be calculated using equation (1).

9 Accuracy and stability in the test method

9.1 Temperature

The room temperature shall be determined to an accuracy of ±1 °C, while holding the specimen, which is mounted on the measuring mandrel or on the measuring base plate, at room temperature.

9.2 Voltage measurement

For the resistance measurement, the voltage signal shall be measured to an accuracy of 0,5 %.

9.3 Current

The specimen test current shall be determined from a voltage-current characteristic of a standard resistor by the four-terminal technique.

A four-terminal standard resistor, with an accuracy of at least 0,5 %, shall be used to determine the specimen test current.

The fluctuation of d.c. specimen test current, provided by a d.c. power supply, shall be less than 0,5 % during every resistance measurement.

9.4 Dimension

The distance along the specimen between the two voltage taps, (L), shall be determined to an accuracy of 5 %.

In the case of the wire with pure Cu matrix, the cross-sectional area of Cu matrix (S_{Cu}) shall be determined using a nominal value of copper to non-copper ratio and nominal dimensions of the specimen.

10 Test report

The test report for the result of the measurements shall include *RRR* explicitly listed in 10.2 and also the following items if known.

10.1 Specimen

a) Manufacturer

b) Classification and/or symbol

c) Shape and area of the cross-section

d) Dimensions of the cross-sectional area

e) Number of filaments

f) Diameter of the filaments

g) Cu to Nb-Ti ratio, Cu-Ni to Nb-Ti ratio, or Cu, Cu-Ni to Nb-Ti ratio, or volume ratio among Cu-Ni, Cu, and Nb-Ti.

h) Cross-sectional area of the Cu matrix (S_{Cu})

10.2 Reported *RRR* values

10.3 Report of test conditions

10.3.1 The following test conditions shall be reported for the measurements of R_1 and R_2

a) Total length of the specimen

b) Distance between the voltage measurement taps (L)

c) Length of the current contacts

d) Transport current (I_1 and I_2)

e) Current density (I_1 and I_2 divided by the total wire cross-sectional area)

f) Voltages (U_1, U_{0+}, U_{0rev}, U_{2+}*, U_{20+}, U_{0-}, U_{2-}*, U_{20-}, and $\overline{U_2}$)

g) Resistances (R_m, R_1, R_2* and R_2)

h) Resistivities ($\rho_1 = (R_1 \times S_{Cu})/L$ and $\rho_2 = (R_2 \times S_{Cu})/L$)

i) Material, shape, and dimensions of the mandrel or the base plate

j) Installation method of the specimen in the mandrel or the base plate

k) Insulating material of the mandrel or the base plate

10.3.2 Report of R_1

a) Temperature setting and holding method of the specimen

b) T_m: Temperature for measurement of R_m

10.3.3 Report of R_2

a) Rate of increasing temperature

b) Method of cooling down and heating up

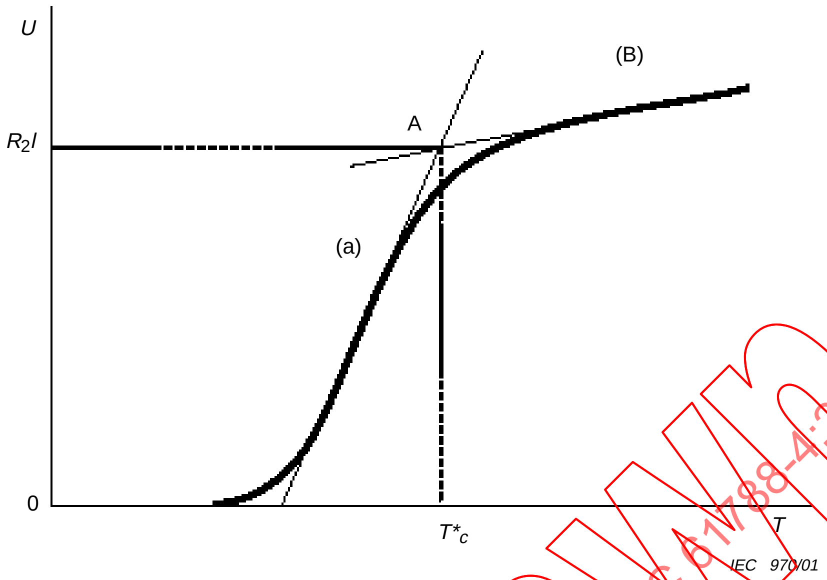
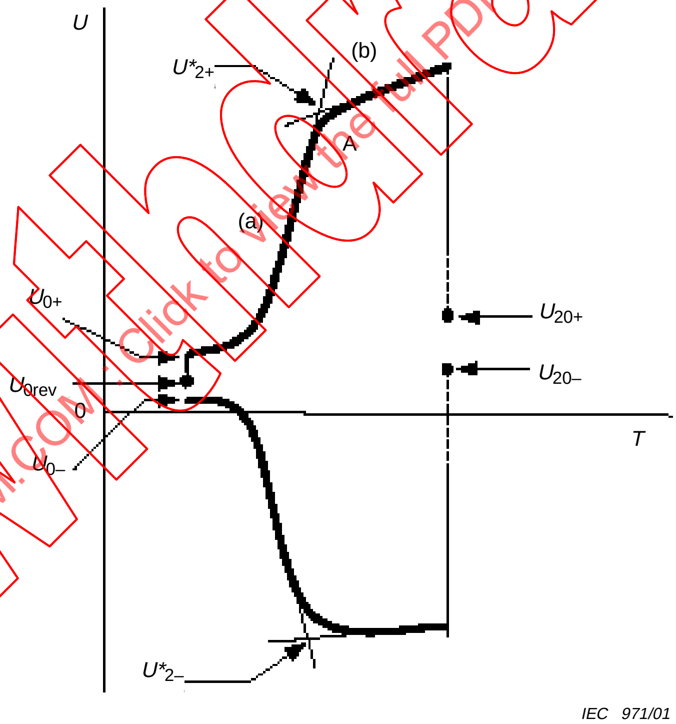


Figure 1 – Relationship between temperature and voltage



Voltages with subscripts + and – are those obtained in the first and second measurements under positive and negative currents, respectively, and U_{20+} and U_{20-} are those obtained at zero current. For clarity, U_{0rev} is not shown coincident with U_{0-}.

Figure 2 – Voltage versus temperature curves and definitions of each voltage

Annex A
(informative)

Additional information relating to the measurement of *RRR*

A.1 Bending strain dependency of *RRR*

In general, the resistivity (ρ) of a pure metal such as copper at a very-low temperature increases as its applied strain increases. In general, a lower ρ wire has a larger percentage change in ρ than a higher ρ wire. There is almost no effect of strain on the room temperature resistivity of a metal. This means that the change in *RRR* with strain is more significant for a material whose resistivity is low (whose *RRR* is high). According to the result of the intercomparison tests [1][1], the dependency of the bending strain is low for a specimen of low *RRR*. Bending strain is applied when the specimen is mounted on the measuring base plate or the measuring mandrel. Since the bending strain is inversely proportional to a radius of bent curvature, the smaller the diameter of the measuring mandrel is, the larger the bending strain being applied to the specimen is.

The increase in resistivity, $\Delta\rho$, at 4 K as a function of cold working ratio, *CW* (%), for pure copper is shown in Chapter 8 of reference [2]. Since the value of *CW* is approximately equal to the value of tensile strain, ε, when ε is small, the result is expressed as in equation (9). The dependency on bending strain can be obtained by replacing the bending strain by an equivalent tensile strain.

Figure A.1 shows the relationship between *RRR* and bending strain for Nb-Ti composite superconductors with pure Cu matrix, obtained from the measured values of the intercomparison test performed in 1993 and 1994. The lines in the figure are the relationships calculated according to equation (9) for each specimen. The measured values agree with the calculated values, and high *RRR* materials are sensitive to bending strain. Figure A.2 shows, using equation (9), dependency for round Cu wires where *RRR* with zero strain varies from 50 to 350. Figure A.3 shows bending strain dependency of *RRR* normalized by the value at zero strain. The same dependency of rectangular Cu wires is shown in figures A.4 and A.5. For the material with a *RRR* of 350, which can be a high limit of *RRR, the RRR* decreases by 10 % for a bending strain of 2 %, with respect to the zero strain value.

When the high-*RRR* data of specimen 6 shown in figure A.1 are corrected for various bending strain values using equation (9), the following results are obtained: an average value of 303,2, a standard deviation of 13,2 and a coefficient of variation (COV) of 4,36 %. The results show that the COV is kept at less than 5 % by using the correction equation even for high *RRR* values.

To evaluate a high-*RRR* material, it is therefore desirable to use a straight base plate or a mandrel with a large coil diameter so that the evaluation can be performed with the least possible bending strain being applied. In addition to this, special care should be taken with the specimen so that there is no significant strain applied to it during handling.

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[1] The figures in brackets refer to the reference documents at the end of this annex.

A.2 Measuring methods of resistance (R_2*) just above the superconducting transition

The following methods are also recommended for increasing temperature above the superconducting transition of the specimen. The rate of increasing temperature of the whole specimen within a range between 0,1 K/min and 10 K/min should be applied for these methods. In order to dampen the rate of increasing temperature and to avoid a large temperature gradient, special care should be taken in selecting heater power, heat capacity (the specimen with the measuring mandrel or the measuring base plate) and the distance between the heater and the specimen.

1) Heater method

   The specimen can be heated above the superconducting transition by a heater installed in the measuring mandrel or in the measuring base plate after taking the specimen out of the liquid helium bath in the cryostat.

2) Adiabatic method

   Using the cryostat in which the specimen and the measuring mandrel or the measuring base plate can be held stably around the liquid helium temperature (5 K or lower) by a thermal anchor, the specimen can be heated above the superconducting transition by a heater under adiabatic or quasi-adiabatic condition.

3) Refrigerator method

   In this method, an electromechanical apparatus (a refrigerator) is used to cool the specimen, which is mounted to a measuring mandrel or a measuring base plate, to a temperature of 5 K or lower. The specimen can be heated above the superconducting transition by a heater or by controlling the refrigerator power.

A.3 Summary of round robin test of *RRR*

The round robin test of *RRR* was carried out on a Cu/Nb-Ti composite superconductor. The specifications of the test superconductor are:

diameter: 0,80 mm, 0,86 mm including insulating layer

Cu/Nb-Ti ratio: 6,5

mean filament diameter: about 70 µm

number of filaments: 16

twist pitch: 30 mm

critical current: more than 185 A (3 T, 4,2 K)

RRR: more than 150

Participating institutes were provided with specimens that were nearly straight. Some specimens were measured in the as-received condition and some were measured wound on a bobbin under a strained condition. The number of participating institutes was 13 from five countries and the number of determinations was 77. R_2 was measured following the method defined in 8.2 and 8.3, and those in clause A.4. The details of the measurements are described in reference [3]. The effect of the strain was corrected using equations (8) and (9). The distribution of the measured *RRR* is shown in figure A.6. Almost all of the data, except for three, were concentrated fairly sharply. The average was 178,5, the standard deviation was 4,4 and COV was 2,44 %. If the three extraordinary data are omitted, the average was 178,2, the standard deviation was 3,1 and COV was 1,73 %. Since the target of COV is 5 %, this result shows that *RRR* can be measured correctly following the method described in this standard.

A.4 Alternative R_2^* measurement method

The following methods can optionally be used for acquisition of R_2^*.

a) Modified reference method.

This is a simplified method with acquisition of only one voltage-temperature curve. The voltage of the specimen is measured in the superconducting state under a desired direction of current and then with current in the opposite direction. These values are U_{0+} and U_{0rev} as shown in figure A.7. The current is then changed back to the initial direction. After the transition to the normal state, the voltage is measured as U'_{2+} in a plateau region of the curve within about 4 K above the transition. Then the voltage is read under a zero current (U_{20}). The current direction is then reversed and the voltage is measured again (U'_{2-}). The cryogenic resistance is obtained from

$$R_2{}^* = \frac{\overline{U_2}}{I_2}$$

with

$$\overline{U_2} = \frac{\left| U'_{2+} - U'_{2-} \right|}{2}$$

This approximately compensates the effect of thermoelectric voltage. The following conditions should be fulfilled for the assurance that the error due to the interfering voltage and the thermoelectric voltage is not appreciably large:

$$\frac{\left| U_{0+} - U_{0rev} \right|}{\overline{U_2}} < 1\ \%$$

$$\frac{\left| U''_{2+} - U''_{2-} \right|}{\overline{U_2}} < 4\ \%$$

where U''_{2+} and U''_{2-} are defined by $U''_{2+} = |U'_{2+} - U_{20}|$ and $U''_{2-} = |U'_{2-} - U_{20}|$, respectively.

b) Fixed temperature method

In this method R_2^* is directly determined at a fixed temperature in a plateau region within about 4 K above the transition instead of the method described in 8.2. In this case it is desirable to check that the whole specimen is at a uniform and fixed temperature. Also the U_{0+} and U_{0-}, which are defined in the body of the text, should be recorded as the zero voltage level in the fixed method. In order to eliminate the influence of thermoelectric voltage, two voltage signals of specimen, say U_{2+} and U_{2-}, should be acquired nearly simultaneously by reversal of the test current. For the fixed method the effect of thermoelectric voltage on determination of cryogenic resistance R_2^* can well be eliminated.

c) Computer-based method

A computer can be used to control the current direction and warming of the specimen and to measure the voltage-temperature curve. Changes in current direction by periodic current reversals or periodic current on and off cycles are used to correct for off-set voltages in order that the measurements can be made during one cycle of changing the specimen temperature. This method is useful when the transition to the normal state is not too fast. The effect of thermoelectric voltage should also be checked.

d) Other simplified methods with periodic checks

Simplified methods without temperature measurement might also be accepted, if an operator with sufficient experience performs the measurement using a given apparatus and if the following condition is satisfied. If a simplified laboratory practice can be shown, through periodic checks, to achieve the same result as the method in this standard, within its stated uncertainty, then the simplified practice can be used in place of this standard method. These periodic checks could be accomplished by doing one of the following:

1. an interlaboratory comparison where one laboratory uses the standard method and another laboratory uses their simplified method;
2. a single laboratory comparison where one laboratory "checks" their simplified method against the standard method;
3. periodic measurement of a small set of reference samples with well-known *RRR* values using the simplified method.

A.5 Reference documents

[1] MURASE S., SAITOH T., MATSUSHITA T., OSAMURA K., *Proc. of ICEC16/ICMC*, Kitakyushu, May 1996, p. 1795.

[2] SIMON NJ., DREXLER ES., REED RP., *Properties of Copper and Copper Alloys at Cryogenic Temperatures.* NIST Monograph, 1992, 177.

[3] MATSUSHITA T., OTABE ES., MURASE S., OSAMURA K., HUA CY., *Adv. in Superconductivity XI.* Tokyo: Springer, 1999, 1507.

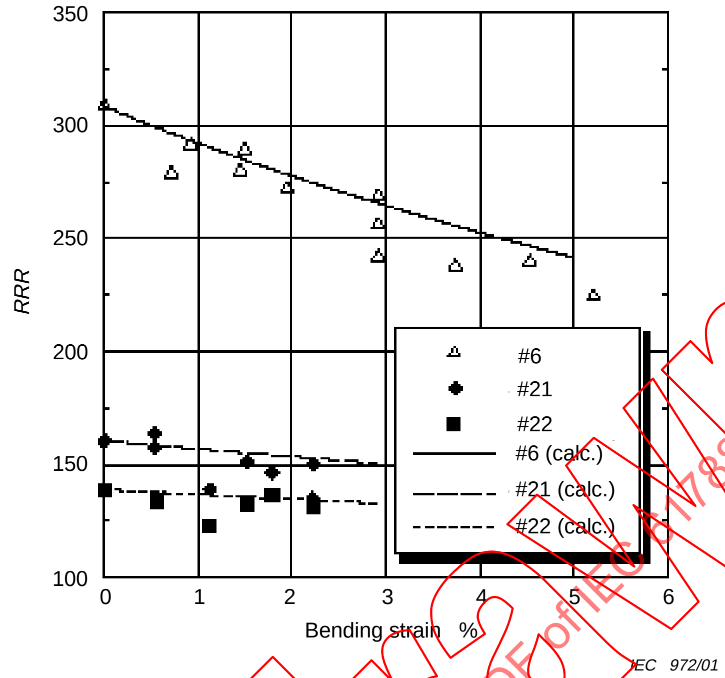

Figure A.1 – Bending strain dependency of *RRR* for pure Cu matrix of Nb-Ti composite superconductors (comparison between measured values and calculated values)

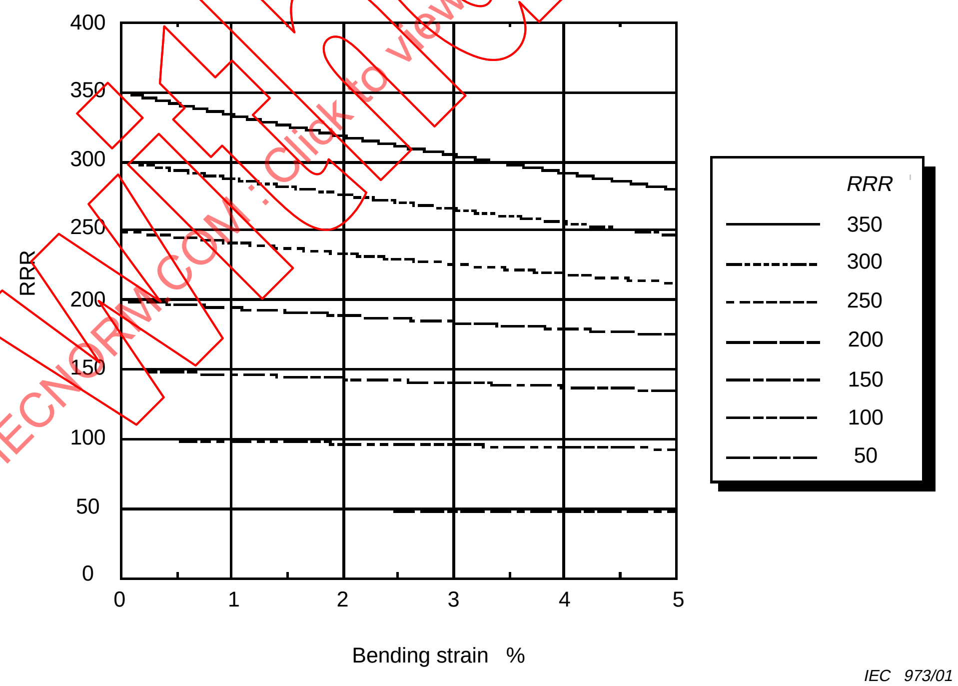

Figure A.2 – Bending strain dependency of *RRR* for round Cu wires

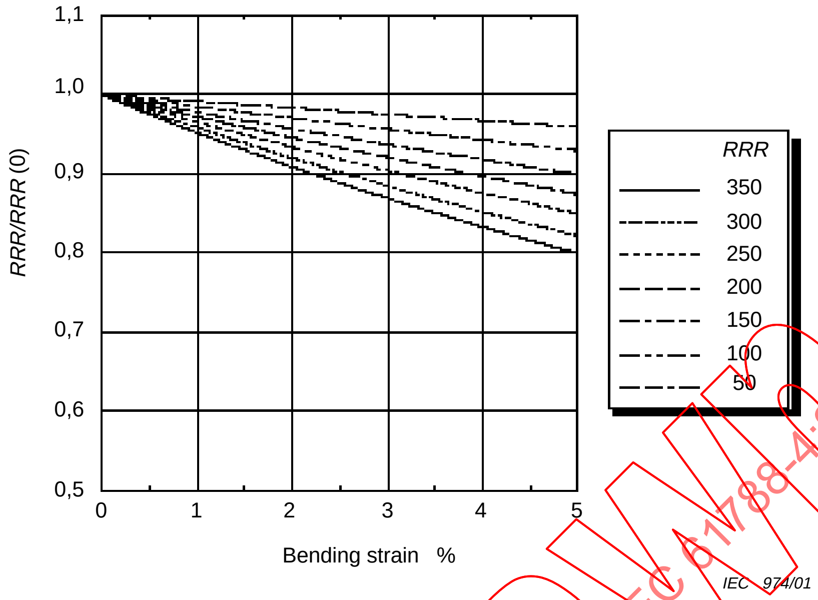

Figure A.3 – Bending strain dependency of normalized *RRR* for round Cu wires

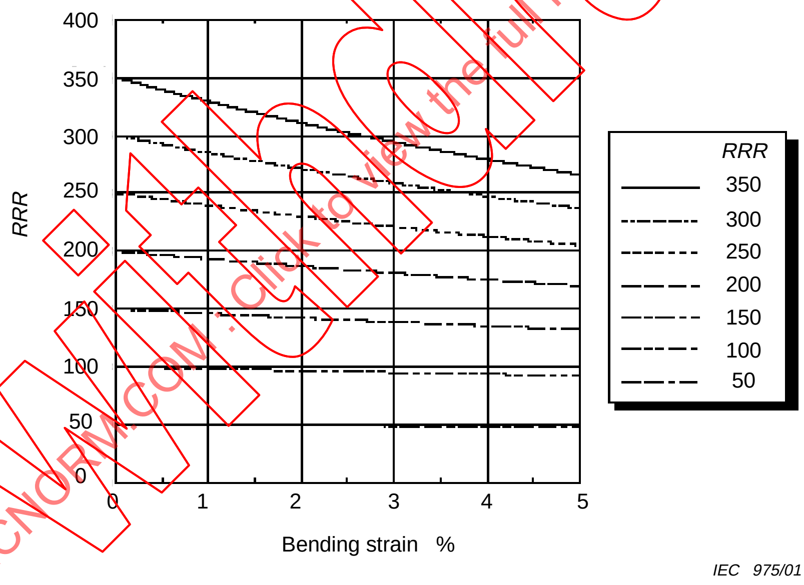

Figure A.4 – Bending strain dependency of *RRR* for rectangular Cu wires

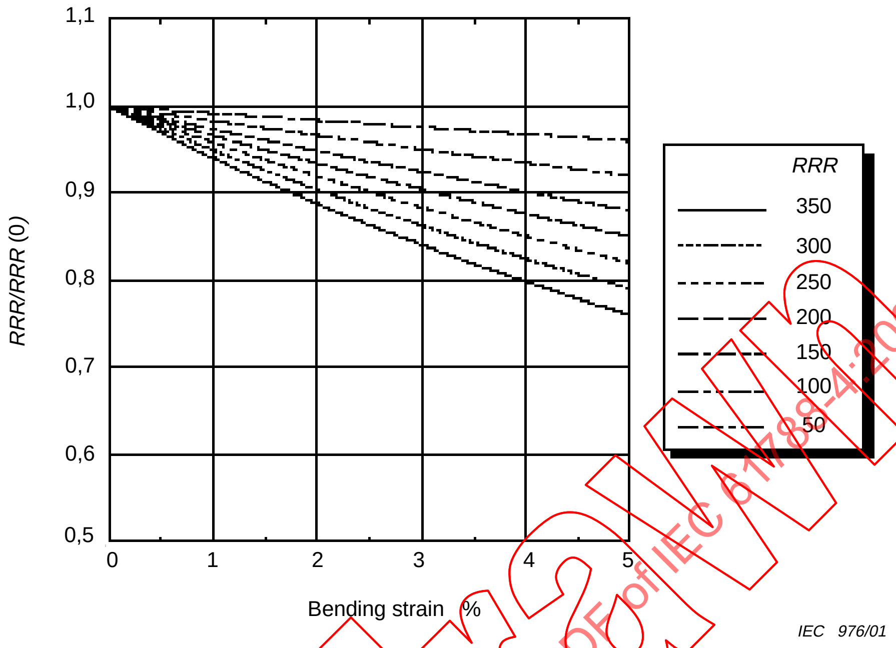

Figure A.5 – Bending strain dependency of normalized *RRR* for rectangular Cu wires

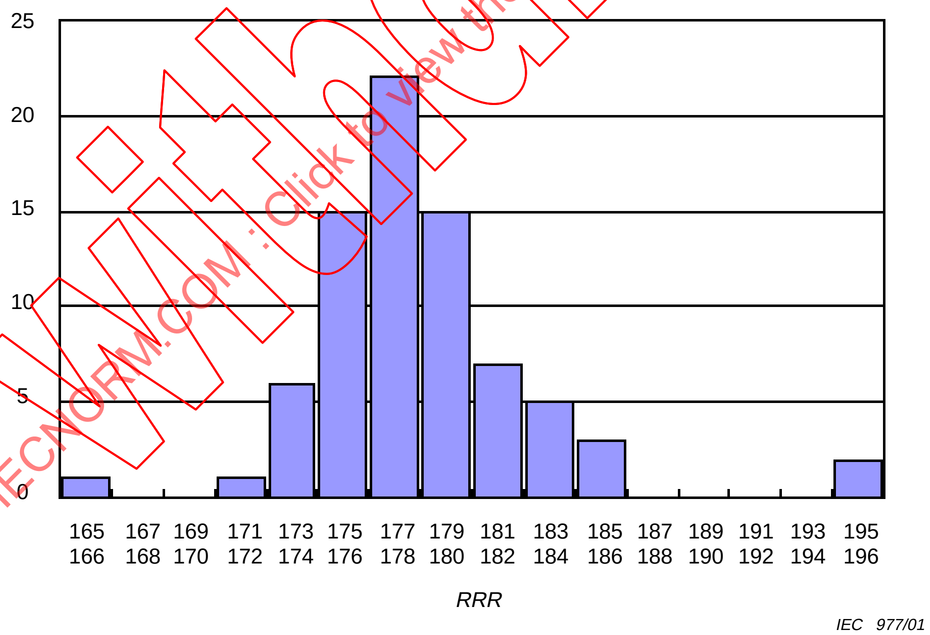

Figure A.6 – Distribution of observed *RRR* of Cu/Nb-Ti composite superconductor