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Nuclear power plants — Instrumentation important to safety — Thermocouples: characteristics and test methods

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National foreword

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NUCLEAR POWER PLANTS – INSTRUMENTATION IMPORTANT TO SAFETY – THERMOCOUPLES: CHARACTERISTICS AND TEST METHODS

FOREWORD

International Standard IEC 62651 has been prepared by subcommittee 45A: Instrumentation and control of nuclear facilities, of IEC technical committee 45: Nuclear instrumentation.

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

FDIS	Report on voting
45A/904/FDIS	45A/920/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 2.

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- withdrawn,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.

INTRODUCTION

a) Technical background, main issues and organisation of the Standard

This IEC standard specifically focuses on thermocouple characteristics and test methods.It is intended that the Standard be used by operators of NPPs (utilities), systems evaluators, designers and by licensors.

b) Situation of the current Standard in the structure of the IEC SC 45A standard series

IEC 62651 is the third level SC 45A document tackling the generic issue of design and qualification of thermocouples. It provides the technical background to the nature and use of thermocouples. It provides information on the choice of thermocouple type in relation to the nuclear power applications of concern. It describes the method of use of thermocouples in nuclear reactors. It gives detailed type test and manufacturing test requirements.

IEC 62651 is to be read in association with IEC 60737 which is the appropriate IEC SC 45A document which provides guidance on temperature sensors for reactor applications in general, and with IEC 60780 for equipment qualification. Other IEC standards of general application to thermocouples are given in the normative references of clause 2, and IAEA documents and background information are referenced in the bibliography.

For more details on the structure of the IEC SC 45A standard series, see item d) of this introduction.

c) Recommendations and limitations regarding the application of the Standard

It is important to note that this Standard establishes no additional functional requirements for safety systems.

Aspects for which special recommendations have been provided in this Standard are:

- the types of thermocouple suitable for nuclear reactor applications;
- the normal mounting arrangements;
- the use of hot or cold reference junctions and of compensating cable;
- the mechanical and metallurgical aspects to be considered;
- the use and types of cold-end seals;
- installation;
- testing.

To ensure that the Standard will continue to be relevant in future years, the emphasis has been placed on issues of principle, rather than specific technologies.

d) Description of the structure of the IEC SC 45A standard series and relationships with other IEC documents and other bodies documents (IAEA, ISO)

The top-level document of the IEC SC 45A standard series is IEC 61513. It provides general requirements for I&C systems and equipment that are used to perform functions important to safety in NPPs. IEC 61513 structures the IEC SC 45A standard series.

IEC 61513 refers directly to other IEC SC 45A standards for general topics related to categorization of functions and classification of systems, qualification, separation of systems, defence against common cause failure, software aspects of computer-based systems, hardware aspects of computer-based systems, and control room design. The standards referenced directly at this second level should be considered together with IEC 61513 as a consistent document set.

At a third level, IEC SC 45A standards not directly referenced by IEC 61513 are standards related to specific equipment, technical methods, or specific activities. Usually these documents, which make reference to second-level documents for general topics, can be used on their own.

A fourth level extending the IEC SC 45A standard series, corresponds to the Technical Reports which are not normative.

IEC 61513 has adopted a presentation format similar to the basic safety publication IEC 61508 with an overall safety life-cycle framework and a system life-cycle framework. Regarding nuclear safety, it provides the interpretation of the general requirements of IEC 61508-1, IEC 61508-2 and IEC 61508-4, for the nuclear application sector, regarding nuclear safety. In this framework IEC 60880 and IEC 62138 correspond to IEC 61508-3 for the nuclear application sector. IEC 61513 refers to ISO as well as to IAEA GS-R-3 and IAEA GS-G-3.1 for topics related to quality assurance (QA).

The IEC SC 45A standards series consistently implements and details the principles and basic safety aspects provided in the IAEA code on the safety of NPPs and in the IAEA safety series, in particular the IAEA Safety Standard SSR 2/1, establishing safety requirements related to the design of Nuclear Power Plants, and the Safety Guide NS-G-1.3 dealing with instrumentation and control systems important to safety in Nuclear Power Plants. The terminology and definitions used by SC 45A standards are consistent with those used by the IAEA.

NOTE It is assumed that for the design of I&C systems in NPPs that implement conventional safety functions (e.g. to address worker safety, asset protection, chemical hazards, process energy hazards) international or national standards would be applied, that are based on the requirements of a Standard such as IEC 61508.

NUCLEAR POWER PLANTS – INSTRUMENTATION IMPORTANT TO SAFETY – THERMOCOUPLES: CHARACTERISTICS AND TEST METHODS

1 Scope

This International Standard describes the requirements for thermocouples suitable for nuclear power plant (NPP) applications. Thermocouples are widely used in NPPs with other temperature measurement devices such as Resistance Temperature Detectors (RTDs). They are simple and robust and have some specific characteristics (range of measurement and maximum temperature) which make them uniquely suitable for some measurements.

The requirements given in this standard for thermocouples include design, materials, manufacturing, testing, calibration, procurement, and inspection.

The scope of this standard does not cover the design, material selection, and construction of the thermowell, the guide tube, the extension cable, and the temperature transmitter or bridge which may be associated with the thermocouple.

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 60584-1:1995, *Thermocouples – Part 1: Reference tables*

IEC 60584-2:1982, *Thermocouples – Part 2: Tolerances*
Amendment 1:1989

IEC 60584-3:2007, *Thermocouples – Part 3: Extension and compensating cables – Tolerances and identification system*

IEC 60737:2010, *Nuclear power plants – Instrumentation important to safety – Temperature sensors (in-core and primary coolant circuit) – Characteristics and test methods*

IEC 60780, *Nuclear power plants – Electrical equipment of the safety system – Qualification*

IEC 60980, *Recommended practices for seismic qualification of electrical equipment of the safety system for nuclear generating stations*

IEC 61513, *Nuclear power plants – Instrumentation and control important to safety – General requirements for systems*

IEC 61515:1995, *Mineral insulated thermocouple cables and thermocouples*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
accuracy of measurement
closeness of the agreement between the result of a measurement and the conventionally true value of the measurand

Note 1 to entry: "Accuracy" is a qualitative concept.

Note 2 to entry: The term precision should not be used for "accuracy".

[SOURCE: IEC 60050-394:2007, 394-40-35]

3.2
calibration
set of operations that establish, under specified conditions, the relationship between values of quantities indicated by measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards

[SOURCE: IEC 60050-394:2007, 394-40-43]

3.3
reference junction
junction of the thermocouple which is at a known (reference) temperature to which the measuring temperature is compared

Note 1 to entry: The reference junction is also called the cold junction.

[SOURCE: IEC 60584-1:1995, definition 2.4]

3.4
drift
variation in sensor or instrument channel output that may occur between calibrations that cannot be related to changes in the process variable or environmental conditions

[SOURCE: IEC 62385:2007, definition 3.7]

3.5
measurement junction
the metal-to-metal junction of the thermocouple located where the temperature is measured. The second junction is located at a reference temperature

Note 1 to entry: The measurement junction is also called the hot junction.

3.6
performance monitoring
process of demonstrating that an installed instrument channel continues to perform its intended function of monitoring the process variable with the expected accuracy, response time, and stability

[SOURCE: IEC 62385:2007, definition 3.13]

3.7
response time
the period of time necessary for a component to achieve a specified output state from the time that it receives a signal requiring it to assume that output state

[SOURCE: IAEA Safety Glossary, edition 2007]

3.8
extension and compensating cables
cables used for the electrical connection between the open ends of a thermocouple and the reference junction in those installations where the conductors of the thermocouple are not directly connected to the reference junction. The thermoelectric properties of extension and compensating cables must be close to the properties of the corresponding thermocouple

[SOURCE: IEC 60584-3:2007, definition 3.1]

3.9
extension cables
cables manufactured from conductors having the same nominal composition as those of the corresponding thermocouple. They are designated by the letter "X" following the designation of the thermocouple, for example "JX"

[SOURCE: IEC 60584-3:2007, definition 3.1.1]

3.10
compensating cables
cables manufactured from conductors having a composition different from the corresponding thermocouple. They are designated by the letter "C" following the designation of the thermocouple, for example "KC". In some cases different tolerances apply for the same thermocouple type over different temperature ranges. These are distinguished by additional letters such as, for example, KCA and KCB

[SOURCE: IEC 60584-3:2007, definition 3.1.2]

3.11
thermocouple
pair of conductors of dissimilar materials joined at one end and forming part of an arrangement using the thermoelectric effect for temperature measurement

[SOURCE: IEC 60584-2:1982, definition 2.2]

3.12
thermocouple assembly
an assembly used for temperature measurement, comprising a double set of junctions (hot and cold junctions), cables, connections and an electronic system measuring very low voltages

3.13
thermowell
protective jacket for RTDs, thermocouples and other temperature sensors. The thermowell is also used to facilitate replacement of the temperature sensor

[SOURCE: IEC 62385:2007, definition 3.19]

3.14
time constant
in the case of a first order system, the time required for the output signal of a system to reach 63,2 % of its final variation after a step change of its input signal. If the system is not a first order system, the term "time constant" is not appropriate. For a system of a higher order, the term "response time" should be used

[SOURCE: IEC 62385:2007, definition 3.20]

3.15
thermoelectric (Seebeck) effect
the thermoelectric effect is the production of an electromotive force EMF due to the difference of temperature between two junctions of different metals or alloys forming part of the same circuit

[SOURCE: IEC 60584-2, definition 2.1]

4 List of abbreviations

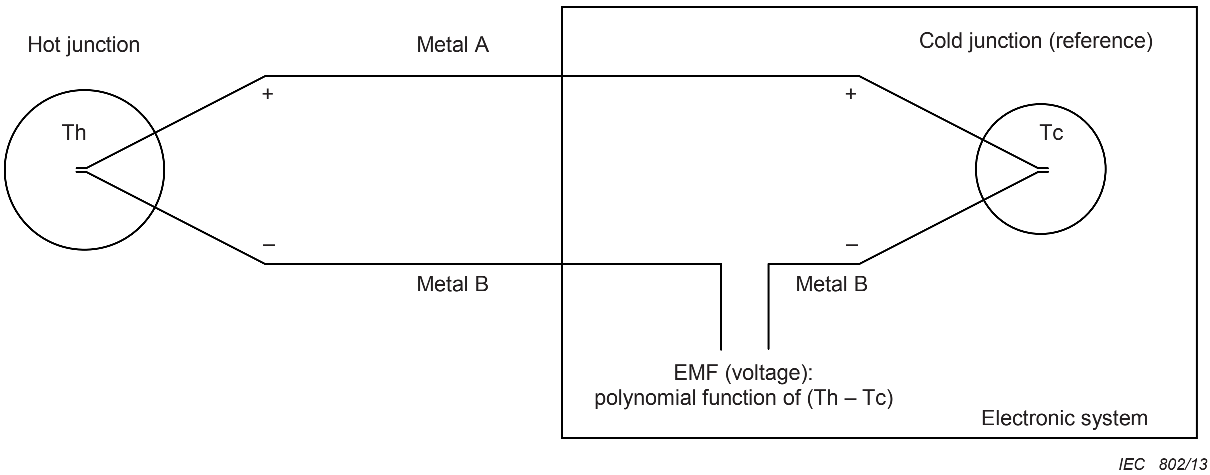
EMF	Electromotive Force
HELB	High Energy Line Break
LOCA	Lost Of Coolant Accident
NPP	Nuclear Power Plant
QA	Quality Assurance
RTD	Resistance Temperature Detector

5 Principle of a thermocouple

5.1 General

When two wires made from dissimilar metals are joined together (by welding or at terminals) at both ends, a small voltage appears on the loop depending on the temperature difference between the two ends as shown on Figure 1. This phenomenon is known as the Seebeck effect. It is the basic principle of a thermocouple used for temperature measurement.

The metal forming one wire is electrically positive compared to the other.



Key

Th temperature of hot junction

Tc temperature of cold junction

Figure 1 – Schematic diagram of a thermocouple

The measuring end is called the hot junction and the other end at a reference temperature is called the cold junction. An electronic system measures the voltage and converts it to give the temperature by comparison with the reference temperature measured by another principle. The relationship between the thermocouple EMF signal and the process temperature is a polynomial combination whose coefficients are given by Table 1 of IEC 60584-1:1995. The typical voltage generated by type K thermocouple is about 40 µV/°C from a source with the impedance of the loop resistance of the metals.

The EMF, and therefore the sensitivity and the range of measurement, depend on the nature of the metals. Although many combinations of metals are possible, only specific ones are selected, defining a limited range of types of thermocouple. Each type of thermocouple is defined according to three tolerance classes: Class 1, 2 or 3. Each class corresponds to a tolerance and an associated range where the tolerance is valid.

IEC 60584-2 gives detailed requirements about the classes of tolerance.

IEC 61515 gives general requirements regarding mineral insulated thermocouples and cables.

The environmental conditions in an NPP imply that only some types of thermocouples are recommended.

Table 1 gives the most common thermocouple types. The given temperature range corresponds to the superposition of the three classes of tolerances as described in IEC 60584-2.

Table 1 – List of thermocouples and their use in an NPP

Type	Positive Metal/Alloy	Negative Metal/Alloy	Typical temperature range °C	Example of application
K	Nickel – Chromium	Nickel – Aluminium	–200 to +1 150	Primary circuit PWR
T	Copper	Copper – Nickel	–200 to +350	Not in neutron flux
J	Iron	Copper – Nickel	–40 to +750	Not in neutron flux
N	Nickel – Chromium- Silicon	Nickel – Silicon	–200 to +1 200	Fuel temperature
E	Nickel – Chromium	Copper – Nickel	–200 to +750	Not in neutron flux
C	Tungsten – Rhenium (5 %)	Tungsten – Rhenium (26 %)	0 to +2 300	Not in neutron flux
R	Platinum – Rhodium (13 %)	Platinum	0 to +1 700	Not in neutron flux
S	Platinum – Rhodium (10 %)	Platinum	0 to +1 700	Not in neutron flux
B	Platinum – Rhodium (30 %)	Platinum Rhodium (6 %)	+600 to +1 820	Not in neutron flux

Some other types of thermocouples based on Molybdenum – Niobium (MoNb) or their alloys may be considered for high performance applications.

The categories (T, J, E, C, R, S, B) are described in 5.2 for information only.

Only K, N and E types are generally used for nuclear applications, in accordance with the limitations on exposure to neutron flux of Table 1.

5.2 Types of thermocouples for nuclear applications

5.2.1 General

For nuclear applications, and specifically for measurement on and in the primary coolant circuit of reactors, thermocouples with a robust design and a high quality shall be used. They are protected within a metal sheath and insulated with a mineral material.

Thermocouples are used on water reactors for measurement of fuel channel outlet temperature, which is particularly important in beyond design basis conditions. They may be used in travelling fuel channel probes on water-cooled reactors, often for calibration purposes. They are used on gas cooled reactors for measurements of fuel temperature, and fuel channel outlet temperature, which are needed for reactor protection and for control, and are also used for measurement of moderator and core support structural temperature.

More details are given in IEC 60737.

5.2.2 Type K

Type K thermocouple is the most widely used thermocouple. Its voltage output signal curve is virtually linear against the temperature and has a good sensitivity. Type K thermocouples can be used in temperatures up to 1 150 °C and, for short periods, up to 1 250 °C depending on sheath material and diameter.

5.2.3 Type T

This thermocouple is not very commonly used. Its temperature range is limited to –200 °C up to +350 °C. It is used in moist or negative temperature conditions because of its resistance to corrosion and the greater homogeneity of the component wires that reduce errors due to temperature gradients.

5.2.4 Type J

Type J Thermocouple has a limited temperature range: –40 °C to +750 °C. Its sensitivity increases up to 55 μV/°C and its output signal can be changed by the contamination of the iron. It is not recommended for nuclear applications.

5.2.5 Type N

This thermocouple has a good thermoelectric stability. It has an excellent oxidation resistance at high temperature. It is well adapted for accurate measurements in air, up to 1 200 °C. In vacuum or controlled atmosphere, it can withstand 1 300 °C depending on sheath materials and diameter

N thermocouples are more stable than noble metal thermocouples (S or B) under radiation conditions, but they are less stable at high temperature without radiation. Their drift depends on the sheath material and the temperature. Under certains conditions Type K are more stable than type N.

5.2.6 Type E

Thanks to its high sensitivity, the type E thermocouple is mainly used for cryogenic measurements. As it is non-magnetic, it can be preferred for some specific applications.

5.2.7 Type C

The type C thermocouple is mainly used for high temperature measurements, specifically for nuclear applications not subject to neutron flux.

5.2.8 Noble metal thermocouples (Type S,R,B)

The noble metal thermocouples are dedicated to high temperature measurements (over 1 500 °C). Pure platinum and platinum/rhodium alloys develop smaller voltages than junctions with common metal. These thermocouple become active and are not recommended for nuclear applications.

6 Technology of thermocouple assemblies

6.1 Thermocouple assembly

6.1.1 General

A thermocouple is a sensitive element which delivers a small electric signal in direct relation with the temperature. It can be used in association with mechanical and electrical components (thermowell, cables, junction box), to position, protect and connect it to an electronic device for signal processing. The set of these components is the thermocouple assembly. This standard refers to the thermocouple assemblies and their use in an NPP.

The basic structure of a thermocouple used in NPP is a mineral insulated cable with the thermocouple junction at the end of the cable. Two structures are possible:

- Insulated or ungrounded structure when the thermocouple is not electrically connected to the sheath.
- Grounded structure when the thermocouple is in direct contact with the envelope of the sheath.

Figure 2 shows the two possible structures of a thermocouple

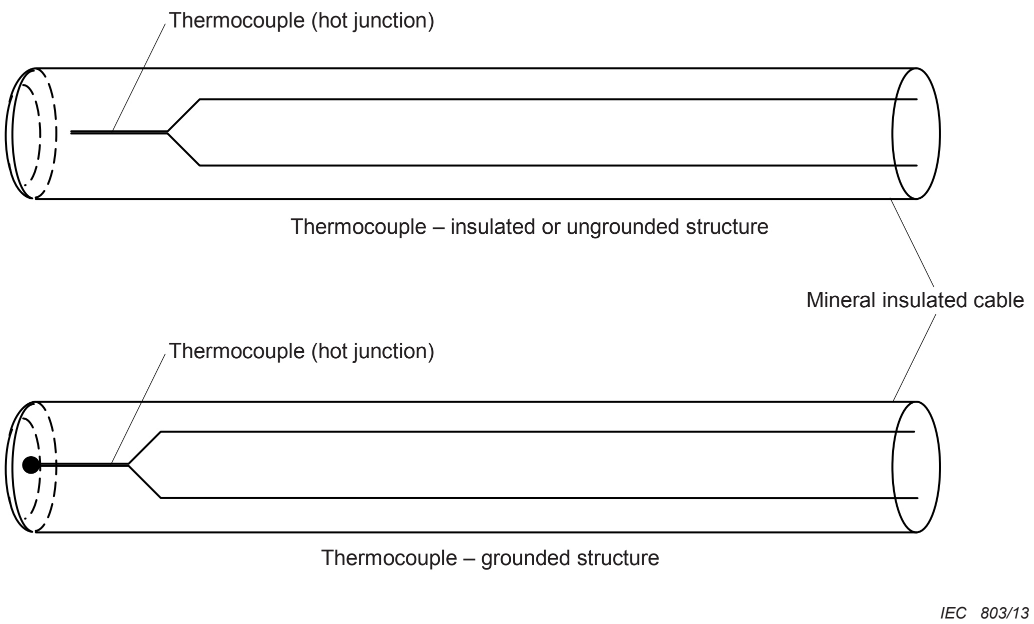


Figure 2 – Electrical structures of a thermocouple

Depending on the nature of the substance whose temperature is measured (gas, liquid, solid) and the conditions of measurement (fixed, flow rate, electrical conditions), the mechanical arrangement of the thermocouple will differ according to:

- direct contact with the component;

- direct immersion;
- protected in a metallic support (thermowell) .

6.1.2 Direct contact

The end of the thermocouple is welded or fixed on the metallic surface of the component. This is for example the typical arrangement for the incore thermocouple for the measurement of in-core temperature on the surface of the fuel element.

6.1.3 Direct immersion

The thermocouple is in direct contact with the fluid of which the temperature is measured.

6.1.4 Thermowell mounted

In the case of the measurement of the temperature of a fluid in a circuit, the thermocouple is generally inserted in a protective support called the thermowell.

The use of a thermowell makes any replacement of the thermocouple easier.

The mechanical contact of the end of the thermocouple with the envelope of the thermowell is important regarding the accuracy and the response time.

6.2 Performance

6.2.1 Accuracy

The accuracy of a thermocouple depends on the characteristics of the materials themselves and the accuracy of the cold junction temperature measurement. IEC 60584-2 specifies the amount by which the measurements may deviate from ideal behaviour for each type of thermocouple. Three classes of tolerance are defined in Table 1 of IEC 60584-2:1982. The class of tolerance of a thermocouple depends on the manufacturing process.

6.2.2 Range of measurement

The range of measurement is given by the type of the thermocouple as indicated above. The range differs according to the class of tolerance as indicated in IEC 60584-2.

6.2.3 Response time

The response time of a thermocouple assembly depends on its structure including the thermowell.

The response time of a thermocouple depends on the diameter of the wires, the mass of materials around the junction and its efficiency in transferring heat from its outer surfaces to the wire sensing element. A thermocouple can be shaped in order to reduce the thermal inertia and to shorten the response time.

For NPP applications, the response time requirement shall be specified according to the functions to be performed.

6.2.4 Reliability

The reliability requirement of thermocouples used for safety functions are defined from reliability requirements of the safety system. Experience of carefully manufactured thermocouples provided with high Quality Assurance and Quality Control requirements for NPP applications is that their reliability is high. Thermocouples operated in safety systems should have their design lives defined. For thermocouples whose design life is less than the design life of the NPP or the safety system, then arrangement shall be made for these thermocouples to be replaced or re-assessed before their design life is reached.

6.3 Design and construction requirements

6.3.1 General

The thermocouple and its associated devices shall meet the requirements described in this standard and in IEC 60737. Safety or other requirements for the application shall be determined according to national and international requirements and practice, including IEC 61513.

6.3.2 Reference junctions

A thermocouple is a differential device giving an electric signal related to the difference of temperature between the hot junction (to be measured) and the cold junction (reference). The cold junction is typically not kept at a known temperature but rather the temperature is measured at the cold junction and this measurement is used to perform the cold junction temperature compensation to obtain the actual process temperature at the measurement junction.

6.3.3 Construction principles

Thermocouples can be supplied in different internal constructions, which depend on the manufacture, qualification requirements, and applications. For thermocouples being used in an NPP, the design and structure of the thermocouple should consider the environmental conditions in which the sensor is being used under normal operating and under design basis accident conditions, as well as the qualification tests specified by the user. The use of a flexible mineral-insulated cable between the thermocouple and the connector is commonly adopted, and the user may also adopt any other construction. A variation of this design may include a rigid exterior sheath over the mineral-insulated cable between the thermocouple and the connector, this sheath being welded to the connector.

Thermocouples can be manufactured with various forms depending on the conditions of the measurement.

Three types of thermocouple are commonly used:

- Simple thermocouple: The wires are not protected and separate from each other, the hot junction is directly fastened or soldered onto the surface of the component. This type is not normally used in NPPs.
- Thermocouple with a grounded hot junction: The wires are isolated from each other (except at the junction itself) and inserted in a metallic protective sheath. The hot junction is electrically connected to the protective sheath.
- Thermocouple with an isolated hot junction (i.e. ungrounded): The wires are isolated from each other (except at the junction itself) and inserted in a protective sheath. The hot junction is electrically isolated from the protective sheath.

The methods of manufacture of the measuring junction are:

- exposed junction – the thermocouple is made with the junction extended beyond the end of the sheath and insulant and remaining unprotected, such arrangements are not normally used;
- grounded junction – the conductors are welded to the end cap, which is welded to the sheath to form the closure;
- ungrounded or isolated junction – the thermocouple is formed and the hot junction located at a controlled position from the sheath closure end cap.

Protecting the measuring junction with a sheath has the following advantages:

- The conductors are protected from the environmental conditions.
- The insulant is protected from moisture.
- The conductors are not subject to mechanical damage.

The ungrounded or insulated junction also has the following advantages:

- Differential expansion between conductors and sheath will not cause stress on the conductors.
- The thermocouple is protected from earth faults.
- The signal interference problems of earthed thermocouples can be eliminated.

6.3.4 Materials

6.3.4.1 Thermocouple wires

The wires used for thermocouples shall be carefully identified and documented. The size of conductor is a compromise. It should balance:

- mechanical strength;
- an allowance for oxidation;
- minimum loop resistance;
- reduction of thermal conduction from the hot junction;
- reduction of radiation;
- the time taken to reach thermal equilibrium.

6.3.4.2 Cable construction

Matched thermocouple conductors are surrounded by a mineral insulation, held in a metal tube. This is then reduced by drawing, swageing, or rolling, which also compacts the insulant and removes voids.

Depending on the type of the measurement needed, the design of the cable can differ significantly.

The method of construction and the quality checks employed shall be sufficient to ensure that the geometry of the thermocouple is adequately controlled. This includes wire spacing, symmetry, position of the junction, and the absence of voids in the insulant.

The characteristics of the cable include:

- quality of the insulant of the highest grade of magnesia;
- standard outside diameters of cables;
- capacity of passing a specific pressure test;
- sheath materials like chromium-nickel alloy where fuel temperature is measured, of the same composition as the fuel element sheath.

6.3.4.3 Seals and adhesives

Sheathed thermocouples (see 6.3.3) shall be hermetically sealed. The connector may or may not be an integral part of the thermocouple assembly. Thermocouples used in a harsh environment, such as in high-temperature and/or radiation areas, shall be designed without organic material. The use of mineral material is recommended. The leak tightness of the insulating termination shall be tested according to an adequate and proven procedure. Commonly suggested seals of the connector are glass-to-metal or ceramic-to-metal, which should have less than 10^{-8} cm^3/s leak rate when tested with helium at an atmospheric differential pressure.

All cements, adhesives, or seals used internally in the device shall be capable of withstanding the service conditions without functional deterioration and without emitting gases. All non-metallic materials, when used for seals, protective finishes, and so forth, shall be moisture and flame-resistant. These non-metallic materials shall not support fungus growth and shall not be adversely affected by the ambient environments specified in the performance requirements of this standard.

6.3.4.4 Sheath closure

The sheath closure at the measuring junction should be an end cap of the same material, welded onto the sheath, using argon-arc methods. This also allows filling the end void with insulant before the sheath is closed. For sizes below 1,5 mm, plasma-arc welding may be used, with no end cap fitted and closure done by heating the sheath metal with the measuring junction pointing downwards so that it can flow to form a cast end.

6.3.4.5 Reference (cold end) seal

To prevent ingress of moisture, a seal is needed at the cold end of the thermocouple, by a seal pot fixed to the sheath by brazing, welding or crimping. Before attaching the seal pot to the sheath, flexible wires fitted with insulating sleeves are brazed to the thermocouple conductors. The joints should be arranged about halfway along within the seal pot. This is filled with a sealing compound suitable for sealing up to 105 °C. The seals shall be tested for effectiveness after completion.

6.3.5 Insulation resistance (ungrounded thermocouple)

The insulation resistance is a parameter that gives information regarding the tightness of the sheath.

The insulation resistance of an ungrounded thermocouple depends on the diameter of the cable sheath, the temperature, the quality and purity and moisture content of the insulant.

The insulation resistance and the voltage to use for the resistance measurement shall be given by the manufacturer at ambient temperature and operation temperature. The insulation resistance should be in the range of at least 100 MΩ to 1 000 MΩ and the voltage for the measurement in the range 50 V to 500 V, depending on the diameter of the sheath.

Typically, the insulation resistance decreases by two orders of magnitude between the ambient temperature and 200 °C, and this needs to be considered in design.

6.3.6 Interchangeability – Replacement

Every sensor produced under the same specification shall be interchangeable with any other of the same type, within the tolerances.

The handling of thermocouples when removed from the reactor circuit and any radiation hazards that may be involved should be considered in any design.

6.4 Installation of thermocouple assembly

6.4.1 Installation requirements

Errors can be introduced because of installation conditions. The following precautions should be observed:

- any action that might cause cold working should be avoided;
- installation should note the manufacturer’s specified minimum bending radius for the cable;
- severe bending or flexing of the wires should be avoided;

- conductors should be connected correctly;
- the number of connections in the measuring circuit should be kept to a minimum;
- the thermocouple reference junctions should be accessible and not in a hostile environment;
- the thermocouple should be located so that the measured temperature is representative of the object or medium being observed;
- for fluid temperature measurement, the thermocouple depth of immersion should be such that the effects of heat transfer from the measuring junction or laminar flow conditions are minimised.

6.4.2 Installation in a thermowell

In a thermowell, the thermocouple shall be held by spring pressure (see Figure 3). The user shall ensure that the thermocouple is compatible with the design of the thermowell, the connection head, the extension guide tube, and the end fittings.

The connector assembly shall prevent moisture intrusion that may result in a leakage current, thus degrading the signal and producing a false temperature indication. The cable connector assembly shall also provide mechanical protection for the connections, thus preventing mechanical stresses from rendering the circuit susceptible to the effects of moisture intrusion, or breaking off the connections completely.

If fastening devices, such as screws, pins, bolts and similar, are used, these parts shall be installed with a means for preventing loss of tightness. These parts, when subject to removal or adjustment, shall not be swaged, peened, stacked, or otherwise permanently deformed.

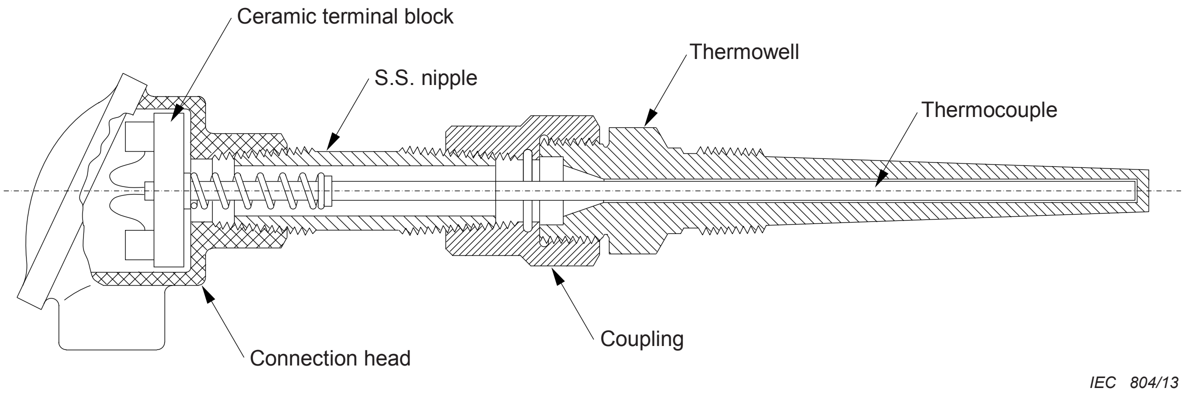


Figure 3 – Installation of a thermocouple in a thermowell

6.4.3 Connections

6.4.3.1 Cables

6.4.3.1.1 General

In an NPP, the connection of the thermocouple to the electronic system requires the use of a cable. This cable needs very specific characteristics to avoid parasitic signals due to the gradient of temperature all along the cable route. Two solutions are possible to select the cable:

- extension cable;
- compensating cable.

Extension cables or compensating cables shall have characteristics matching the EMF/temperature curves for the thermocouple itself over a limited temperature range.

Requirements from IEC 60584-3 for the identification and colour coding of the compensating and extension wires, the tolerances applicable, and their electrical properties shall be considered in the design.

6.4.3.1.2 Extension cables

An extension cable should have conductors of the same nature as the thermocouple elements, extending it to the reference junction and having the same thermoelectric properties as those of the thermocouple within the whole range of utilisation of the table.

6.4.3.1.3 Compensating cable

Compensating cable should be used from the positions of the primary junction boxes where the thermocouple cables themselves are brought out from the reactor (or other measurement location), for connection to the measurement system. The compensating cable should have the same characteristics as the thermocouple itself at the general environmental conditions of the cable ways and routes taken from the primary junction boxes to the measurement system.

Where compensating cable is used, the junction with the thermocouple wires shall be in a suitable termination box which should be hermetically sealed. The thermocouple cable shall be sealed against moisture ingress to the insulant material. An insulation testing criteria shall be defined for such thermocouples, (typical figures are for several megohms, see also IEC 60737). The seal and extension cable may be specified as part of the application or recommended by the temperature-sensor manufacturer.

6.4.3.2 Connectors

As a connector is, by definition, an extra junction, the choice of a connector for a thermocouple has great importance. Only a specific and appropriately matching connector can be used for a given thermocouple. The nature and polarity of each contact shall be selected carefully against the type of thermocouple and its cables.

The temperature rating of the thermowell connector shall equal or exceed the maximum possible temperature or the accident temperature specified by the user.

Unless otherwise specified, the manufacturer shall supply the mating connector half with the thermocouple.

6.5 Operational features of thermocouples

6.5.1 General considerations on the use of thermocouples

In nuclear application, both “direct-immersion” and “thermowell-mounted” thermocouple designs are commonly used; however, this standard does not exclude any other design of thermocouple which may be required for certain special applications in various types of reactors.

A thermocouple by principle has a very small sensitive element, characterized by some specific features:

- It can measure the temperature at a small location.
- The response time of a thermocouple is faster than the response time of a RTD, due to its small dimensions and thermal inertia.
- It can be in direct contact (by soldering, welding or suitable fixtures) with the surface of the component whose temperature is measured.

- It can measure high temperatures, therefore it is the preferred solution for in-core applications, when the temperature can be higher than 1 000 °C.
- It can withstand a very high radiation dose rate, due to its metallic and mineral structure.

6.5.2 Ambient conditions (normal and accident operations)

The environmental conditions for operation of each thermocouple assembly shall be specified:

- Range and maximum temperature for the sensitive element.
- Plant design life.
- Radiation exposure rate (normal operation and accident operation).
- Air / steam environments (temperature, humidity, contaminants, steam pressure).

6.5.3 Metallurgical inhomogeneities

An ideal thermocouple has homogeneous conductors with uniform EMF characteristics. Then the thermal EMF is a function only of the temperature difference between the junctions, and only depends on the characteristics of the individual thermocouple elements. However, chemical, physical and metallurgical inhomogeneities are produced in manufacture and in subsequent use of the thermocouple.

Therefore the thermal EMF of a practical thermocouple is also a function of the temperature distribution along individual thermo elements. The thermocouple characteristics therefore have a component caused by the interaction of the inhomogeneous regions of the thermocouple and the temperature gradient. This component is superimposed on the ideal EMF output characteristic.

Inhomogeneities from the manufacturing process can be kept small and constant. Inhomogeneities from usage of the thermocouple give greater concern. All thermocouples have spurious thermal EMFs due to inhomogeneities which are developed at elevated temperatures in subsequent use.

6.5.4 Corrosion

Oxidized or severely corroded thermocouples can have an erroneous signal. Changes in wire composition can result from corrosion and contamination by other elements. Oxide scale, brazing alloys and fluxes constitute possible source of drift away from initial calibration. Periodic checks are recommended to verify the calibration of a thermocouple.

6.5.5 Thermocouple stability

The stability and EMF of thermocouples are affected by:

- Contaminants in the thermocouple alloys (sulphur, oils and greases).
- The nickel-base alloys of Type K thermocouples are subject to attack in conditions of limited oxygen availability;
- Inhomogeneities of composition as reactive solute elements such as chromium, manganese and aluminium, which are depleted by internal oxidation.
- Cold working causing small changes in characteristics, which can be removed by heat treatment. The alloys NiCr, CuNi and NiAl can recover by heating to 450 °C for a period of several hours.

By changing the alloys from the disordered state to the ordered condition, the output of the thermocouples can change by at least ± 1 %. The conditions in nuclear reactor application can also affect accuracy and stability as follows:

- Thermal and fast neutron flux affect thermocouple alloys, producing material composition and structural changes.

- Nickel is particularly stable so nickel-based thermocouples are recommended for use within the core of a nuclear reactor, although long-term exposure to in-core flux levels can cause changes in thermocouple output of several degrees.
- Magnetic field effects can cause transformations perturbing the thermal EMFs of the Type K negative conductor.

6.5.6 Cold working phenomena

Repeated stressing or bending, commonly called “cold working” of a thermocouple wire can generate stress and distortion of the material crystalline structure, resulting in significant potential for measurement error. This produces unintended junctions in the wire. When these junctions are located in a temperature gradient, a voltage is generated that results in a temperature measurement error

Installation shall be prepared carefully with specific extension or compensating cable to limit this phenomenon.

7 Tests

7.1 General

Tests shall be carried out to prove that thermocouples comply with the requirements of this standard. It is not intended or recommended that all tests shall be performed on every thermocouple being supplied.

Three kinds of tests are therefore described as follows:

- Performance tests
- Qualification tests (type tests)
- Routine production tests

Qualification tests (type tests) shall be carried out on samples of each particular design and range of thermocouple. Where the function of the thermocouple is important to safety, equipment qualification requirements shall be determined and carried out in accordance with IEC 60780 and IEC 60980.

Routine production tests shall be carried out on every thermocouple after manufacturing.

The manufacturer shall conduct all routine tests and carry out all inspections necessary to ensure that the material, workmanship, and operation are of the degree of excellence required by this standard and to demonstrate that the equipment supplied is calibrated and functionally performs as specified herein.

All inspection and test procedures, calibration equipment, and calibration equipment certificates shall be available to the user for acceptance prior to the commencement of manufacture.

7.2 Performance tests and pre-production testing

7.2.1 General

These tests are performed to validate the design of a thermocouple. Each thermocouple shall meet the performance requirements of this subclause.

7.2.2 Calibration

Calibration is the operation that allows the measurement of the functional response of the thermocouple at fixed and stable temperature. Two methods are generally considered to calibrate thermocouples:

- The fixed point method: The method consists of placing the sensor in a chamber whose constant uniform temperature is defined by the thermodynamic equilibrium between different phases of a pure substance.
- Comparison method to a reference sensor. The method consists of placing the sensor in a chamber whose constant uniform temperature has been measured using a standard sensor which is taken as a reference.

The temperature measurement consists of converting an accurate voltage measurement into a temperature by using a polynomial function given in normative Annex A of IEC 60584-1.

The typical calibration procedure is a combination of the fixed point method (0 °C) and the comparison method at higher temperature, with a reference junction held at an accurately known temperature such as 0 °C.

a) At 0 °C: fixed point method

   The sensor comes to equilibrium in a well-stirred ice bath maintained at 0 °C ± 0,2 °C.

   The EMF generated by the thermocouple shall be measured with a high resolution DC voltmeter (typically better than ±0,05 %).

b) At 100 °C or at operating temperature as specified by the user: comparison method.

   The sensor is immersed in a bath of silicone oil, or other appropriate fluid, adjacent to a secondary standard, which is directly traceable to an approved temperature standard. The sensor shall be immersed deeply enough to render the stem conduction error negligible.

   The bath temperature shall be within ±1 °C of the desired calibration temperature when the EMF reading is taken. The bath temperature stability and temperature uncertainty shall be established and the effect of any non-uniformity or residual temperature stability of the bath shall be accounted for in calculating the overall accuracy of the thermocouple calibration process.

7.2.3 Response time

A typical test method for determining response time is to quickly plunge the detector at 20 °C into water flowing at a specified speed and temperature (typically = 1 m/s ± 0,15 m/s and at 75 °C ± 2,5 °C). Alternatively, the sensor can be heated in air and then plunged into room temperature water flowing at 1 m/s. Unless otherwise specified, the time to reach 63,2 % of the step change in temperature shall not exceed 20 s for a thermocouple in a thermowell or 3 s for a thermocouple alone (ungrounded structure).

7.2.4 Electrical insulation resistance tests

Electrical insulation tests are performed only on thermocouples with a junction insulated from the sheath (ungrounded structure). The measurement is performed with a megohmmeter at a voltage specified by the manufacturer. The thermocouple with insulated junction shall successfully meet acceptance criteria for the electrical insulation resistance test as specified in 6.3.5.

7.3 Qualification tests (type tests)

7.3.1 General

To demonstrate that the thermocouple is suitable for the service stipulated above, 10 % of the same production batch or no less than three sensors chosen at random, produced by normal methods and processes, shall be subjected to a qualification test. This test shall qualify all models of a common design.

The qualification tests are performed on thermocouple after the production tests.

These qualification tests shall be specified according to the operational environmental conditions. For example they consist of the following tests:

- repeatability;
- vibration test;
- steam test;
- thermal cycle, and
- final calibration and accuracy.

When thermocouples are used for applications important to safety and under design basis accident environmental conditions, the qualification test shall include the following special tests:

- accident simulation test, based on the most onerous conditions to be withstood;
- seismic test; and
- irradiation test.

Environmental qualification for a plant accident scenario, such as a LOCA or a high-energy line break, shall be specified in the individual thermocouple specification sheets. Qualification shall be carried out in accordance with the technical specification defined by the user. In the absence of any specific instruction from the user, the qualification tests shall be performed in accordance with the methods and procedures provided in IEC 60780 and in IEC 60980.

For the laboratory to perform the qualification tests, the user shall define

- the normal operating environments of these thermocouples;
- the thermocouple mounting arrangement;
- the harsh environments as a result of the postulated accidents or design basis accidents;
- the normal and accident safety functions;
- the thermocouple performance requirements;
- the mission times of the measurements; and
- the floor response spectrum for seismic qualification.

7.3.2 Repeatability (thermal shock)

The thermocouples shall successfully meet the acceptance criteria stated in the repeatability (thermal shock) test specified below.

Minimum and maximum temperatures (Tmin and Tmax) shall be specified. The thermocouple EMF is monitored during the test with a high resolution DC voltmeter (typically better than ±0,05 %).

The sensor shall be transferred between baths at Tmin to Tmax and back to Tmin for 25 cycles. Each transfer shall be achieved in less than 5 s and the sensor shall remain immersed in the bath for a minimum of 60 s between transfers. The sensor may be mounted in the thermowell to be used for this test but shall be allowed to stabilize at each temperature for a minimum period of 1 min.

The number of cycles and the procedure may be specified jointly by the user and the manufacturer.

7.3.3 Vibration

The thermocouple shall successfully meet acceptance criteria for a mechanical endurance test (vibrations). The conditions of the test (frequency range, duration of one sweep cycle, type of frequency sweep, vibration level, and test duration) and the acceptance criteria should be defined according to the conditions and the application of the temperature measurement.

An example of a typical test procedure is given as follows:

The sensor is mounted in a fashion similar to the installation (in particular, the spring tension shall be identical to the installation) and heated at a specified temperature for the duration of the test. The sensor is then subjected to vibration in two planes in two separate runs: one perpendicular and one parallel to the sensor's longitudinal axis. An example of vibration conditions to be used for each run is given in Table 2.

Table 2 – Example of vibration test requirements

Frequency range	10 Hz - 5 000 Hz
Duration of one sweep cycle	10 Hz - 5 000 Hz - 10 Hz cycle in 1 h
Type of frequency sweep	Logarithmic
Vibration level	0,762 mm max. peak to peak, subject to 5 g max. peak
Test duration	2 h in each plane

The thermocouple EMF shall be continuously monitored on an oscilloscope for continuity and short circuits over the test run.

The sensor shall be disqualified unless all the following conditions are met:

a) no short or open circuit is indicated;

b) calibration at ice-point has shifted by no more than ±0,2 °C

c) calibration at 100 °C has shifted by no more than ±0,5 °C, and

d) the sensor meets the insulation resistance requirements (for insulated junction type thermocouple).

This vibration test is not intended to replace any seismic qualification test which may be called for by the user. If the thermocouple is required to perform any temperature measurement during and after a seismic event, see IEC 60980.

7.3.4 Steam test or high pressure hydraulic test

7.3.4.1 Steam test

This test concerns specific thermocouple assemblies which have to withstand such environmental conditions. It applies to the whole thermocouple assembly.

The thermocouple shall be tested to demonstrate that the measurements capability is kept after applying the test conditions. The assembly is exposed to saturated steam at 101 kPa ± 2,0 kPa for a period of 2 h. At the end of this period, the connector pins shall be dried.

The insulation resistance of insulated thermocouples shall be checked. The value shall be higher than 100 MΩ at 100 V.

7.3.4.2 High pressure hydraulic test

A high pressure hydraulic test may be performed in lieu of a steam test. The thermocouple is exposed for 2 h to a high hydraulic pressure in a test chamber. The pressure is fixed according to the operating conditions.

The insulation resistance of insulated thermocouples shall be checked. The value shall be higher than 100 MΩ.

7.3.5 Thermal cycling

The thermocouple shall be cycled between two stable temperatures for a specified number of complete cycles. The temperature range and number of cycles shall be agreeable to both the user and the manufacturer. Typical temperature range and number of cycles are between ambient temperature and Tmax for 100 complete cycles.

The cycle speed may be chosen for convenience, the only requirement being that the sensor is allowed to stabilize at each temperature. Calibration at 0 °C shall be checked before and after the test. The calibration shall not shift more than 0,2 °C at 0 °C and 0,3 °C at 100 °C.

The insulation resistance of insulated thermocouples shall be checked. The value shall be higher than 100 MΩ.

7.3.6 Harsh environmental conditions qualification

Environment qualification for a plant accident scenario, such as a loss of coolant accident (LOCA) or a high-energy line break (HELB), shall be specified in the individual thermocouple specification sheets. Qualification shall be done in accordance with the technical specification as defined by the user. In the absence of any specific instruction from the user, the qualification tests shall be performed in accordance with the methods and procedures provided in IEC 60780.

Certain thermocouples with their cable connector assemblies may be used in nuclear safety I&C systems; they are required to perform their temperature measurement safety functions continuously throughout the defined mission time. If such a requirement is specified, the thermocouple with the complete assembly shall be subjected to a range of qualification tests. This is to demonstrate and to ensure that the thermocouple and its assembly is capable of performing its required functions under various operating and design basis accident conditions that may occur during the life of the plant.

For the laboratory to perform the qualification tests, the user shall define the normal operating environments of these thermocouples, harsh environments as a result of the postulated accidents or design basis accidents, normal and accident safety functions, the thermocouple performance, their mission times, and floor-response spectrum for seismic qualification, see IEC 60980.

The thermocouples specific for in-core measurements shall be qualified to their operating conditions (normal and accidental). That includes tests in reactor and tests in a test loop at the maximum temperature condition

7.4 Production tests

7.4.1 Manufacturing factors

Each thermocouple produced shall be subject to a sequence of tests to verify the quality of the manufacturing as defined in IEC 60737.

The following factors shall be considered in specifying a production program and a schedule of production tests:

a) Manufacturing materials shall be approved. In particular, the surface of components shall be free from contamination by nuclear poisons such as boron, cadmium and gadolinium, by materials that may become a source of corrosion and by chemically reactive materials such as chlorine. Unacceptable lubricants and other injurious materials shall be excluded.

   The materials used for the manufacture of cable and sensor sheaths shall be in accordance with the specification and shall be free from harmful defects which might shorten the sensor's useful life. The insulating materials shall have a composition designed to ensure high-insulation resistance, freedom from corrosion and acceptable irradiation performance throughout the sensor life.

b) Cables shall be correctly processed and tested. This should include tests or evidence of conformity of materials to show

   - heat treatment to ensure correct annealing and grain size;
   - tests to ensure conductor geometry;
   - sheath integrity tests to ensure freedom from holes;
   - sheath and conductor ductility tests;
   - tests to ensure correct conductor resistance and insulant insulation resistance;
   - tests for susceptibility to corrosion;
   - tests to ensure that the sheath has adequately uniform thickness and is free from sources of potential failures.

   The method of the insulation resistance measurement shall be specified.

c) Before assembly is started, an approved process shall be used to clean all sensors and cable sheaths. After cleaning, they shall be inspected for surface finish and leak tested to ensure integrity.

d) Every completed sensor shall be calibrated and a test certificate supplied.

e) The quality of the junction depends on the manufacturing process. The process should be validated by a metallograhic examination of the junction on a sample.

f) Every completed sensor and cable shall be labeled with its type, a serial number, the length of its cable and the name of the cable manufacturer. It shall be supplied in an approved container which will protect it during transport, storage and handling at the reactor site.

g) Documentation, such as certificates of witnessed tests, etc., shall be agreed between the manufacturer and the purchaser. This documentation should make it possible to ensure compliance with this standard and other applicable or agreed standards which relate to materials and their purity.

h) It is possible to damage mineral insulated cables by the application of excessive test voltages. The maximum test voltages to be used during insulation resistance measurements shall be specified.

i) Thermocouples shall be made from approved cables. Conductor materials shall conform to appropriate thermocouple standards and the manufacturer should certify to the purchaser compliance with these requirements. Checks to verify the thermoelectric EMF of the conductors should be carried out.

j) The welding of junctions and the closure of cable sheaths shall be carried out by approved processes. These should address the need to minimize exposure of the insulant to ambient moisture levels. Electrical insulation (if applicable), conductor loop resistance and radiographic tests including radiographs of the hot junction should be carried out on all units. Tests for metallurgical conditions such as metallographic examination or ductility and corrosion tests shall be carried out on a small sample basis.

k) Both ends of the thermocouple shall be sealed before shipment.

7.4.2 Examination

The sensor shall be examined to comply with the criteria below:

a) Workmanship – the sensor shall exhibit high-quality workmanship.
b) Finish – pits, scratches or other defects outside the agreed tolerances shall be cause for rejection.
c) Dimensions – all parts of the sensor shall be measured to ensure conformance to the approved drawing dimensions.
d) Identification – the sensor shall be checked to ensure that all identification data required by this standard is present.

7.4.3 Identification

Each device shall be identified with the following information:

- manufacturer's name or identity;
- manufacturer's model and/or serial number;
- user's identification number(s).

The identification shall be made by electro-etching on a non-critical surface according to the acceptable quality assurance procedure. Also, when specified, each device shall show the code identity of the user, attached to the instrument in the form of a metal tag, wired securely to the device. The tag shall be brass or stainless steel.

8 Technical information required

The technical information required should include drawings of the thermocouple, clearly showing dimensions, internal wiring diagrams, materials used and internal construction, as well as information regarding dimensions of supports, mounting arrangements, and electrical connections.

The thermocouple manual shall consist of, as a minimum, the following information:

- descriptive data on the equipment;
- applicable drawings;
- internal wiring diagrams;
- specifications;
- production test results;
- qualification test results, as applicable; and
- a detailed parts list.

The NPP shall maintain up-to-date manuals for the duration of the station life or for the operating life of the thermocouple, as appropriate.

A performance specification for the thermocouple may include the following:

- type and range of measurement;
- nominal calibration curve and accuracy;
- depth of immersion;
- thermal response time with thermowell;
- insulation resistance in case of insulated thermocouple;
- qualified service conditions;
- environmental and seismic qualification, as applicable;
- any other pertinent data, such as electrical characteristics.

A description of the quality assurance program and an outline plan for quality control of the thermocouple production may be filed together with the performance specification.

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