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Design criteria for the thermal insulation of reactor coolant system main equipments and piping of PWR nuclear power plants

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

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Foreword

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This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 6, *Reactor Technology*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

For PWR nuclear power plants, the function of thermal insulation of reactor coolant system (RCS) equipment and piping is to reduce heat loss, improve ambient condition, reduce thermal stress of RCS equipment and piping and guarantee the normal operation of reactor.

The purpose of this document is to provide internationally uniform design principle and method for thermal insulation of RCS equipment and piping in PWR nuclear power plant, which mainly contains the thermal behaviour, material selection, structural design, and test method requirements.

For thermal insulation which belongs to nuclear safety related class or category, or performing reactor safety related function, the corresponding design requirements are also offered in this document.

Among thermal insulation of various RCS equipment and piping, the following two kinds of thermal insulations would be detailed described on the basis of some common design logic and requirements:

— thermal insulation of reactor pressure vessel (RPV)

— thermal insulation of RCS piping and other equipment

Design criteria for the thermal insulation of reactor coolant system main equipments and piping of PWR nuclear power plants

1 Scope

This document specifies the basic requirements related to the design of thermal insulation of reactor coolant system (RCS) equipment and piping.

This document is valid for two types of thermal insulation.

— metallic thermal insulation

— non-metallic thermal insulation

This document mainly applies to pressure water reactor (PWR) nuclear power plants. For other reactor types, this document can be taken as reference.

2 Normative references

The following standards are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced standards (including any amendments) applies.

ISO 7345, *Thermal performance of buildings and building components — Physical quantities and definitions*

ISO 8302, *Thermal insulation — Determination of steady-state thermal resistance and related properties — Guarded hot plate apparatus*

ISO 8497, *Thermal insulation — Determination of steady-state thermal transmission properties of thermal insulation for circular pipes*

ISO 8990, *Thermal insulation — Determination of steady-state thermal transmission properties — Calibrated and guarded hot box*

ISO 9229, *Thermal insulation — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 7345, ISO 9229 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
metallic thermal insulation
thermal insulation with metallic material as main insulating material

Note 1 to entry: The metallic thermal insulation is composed by amounts of thermal insulation panels. Single thermal insulation panel consists of outer cladding and inner packed metallic reflective foils/sheets. The geometry of inner packed foils/sheets can be embossed or parallel liners.

Note 2 to entry: The detailed description of typical geometry of metallic thermal insulation is shown in Annex A. The geometry mentioned in Annex A can be taken as reference for designer.

3.2
non-metallic thermal insulation
thermal insulation with non-metallic material as main insulating material

Note 1 to entry: Geometry of non-metallic thermal insulation can be divided into three kinds:

— Thermal insulation composed by amounts of thermal insulation panels. Single thermal insulation panel consists of outer cladding and inner packed non-metallic insulating material.

— Thermal insulation strapped layer by layer with non-metallic insulating material.

— Thermal insulation matresses (non-metallic insulation material stuffed in fiber cloth).

Note 2 to entry: The detailed description of typical geometry of non-metallic thermal insulation is shown in Annex B. The geometry mentioned in Annex B can be taken as reference for designer.

3.3
chimney effect
air circulation between inside and outside of thermal insulation derived by heat source

EXAMPLE If any gap was existed between thermal insulation and equipment or piping insulated, meanwhile amounts of heat exchange paths were existed in most part of thermal insulation, thermal pressure or density difference would be formed between the inner and outer side of thermal insulation. Initiated by this difference, the cold air would enter the inside through the lower gaps, move upward and be heated, finally escape to the outside through the top gaps.

3.4
thermal bridge
path with high heat flow, caused by geometry with high thermal conductivity material connecting the inner and outer surface of thermal insulation directly

4 General design procedure

4.1 General requirements

All requirements for thermal insulation function realization shall be comprehensively considered in the design procedure of thermal insulation. The safety class, quality assurance classification and seismic category requirements, which are specified by equipment specification or other corresponding documents, shall be satisfied. The design of thermal insulation can be performed as following subsequence:

— Consideration of requirements about reactor safety

— Material selection

— Thermal behavior design and test

— Mechanical properties design and test, including seismic resistance, vibration resistance, etc.

Besides, other requirements including installation, remove, maintenance, in-service inspection and replacement shall also be considered in the design of thermal insulation.

4.2 Requirements for reactor safety

Design of thermal insulation shall be satisfied with safety requirements about thermal insulation specified in regulations, codes and standards of locality in which the product is to be manufactured and used. Thermal insulation shall be carefully selected and methods for their application shall be specified to ensure the fulfilment of their safety functions and to minimize interference with other

safety functions in the event of deterioration of thermal insulation. Meanwhile, the safety requirements of the RCS component shall also be considered and specified in data sheets for thermal insulation.

As an output of thermal insulation design and an input for safety facilities, the debris source caused by thermal insulation shall not influence the normal operation of emergency core cooling system (ECCS), pit strainer and other safety facilities. Both the quantity and granulometry of debris shall be considered. This requirement is for the whole thermal insulation system but not for a single part.

For thermal insulation parts where workers may contact or be close to, the temperature of thermal insulation outer surface shall be limited to protect the physical security of the workers.

For thermal insulation belonging to nuclear safety related class or category or performing reactor safety related function, the following safety related requirements can be selectively conducted in the design of thermal insulation to meet the functional requirements of NPP safety system. For thermal insulation belonging to non-nuclear safety class or category, the following requirements are not mandatory.

— During normal operation and anticipated incidents, corresponding loads shall be carried, all function of thermal insulation shall be normally performed for the whole design lifetime.

— During seismic conditions, impact of seismic loads on the insulated and adjacent components shall be minimized.

— If any safety function needs to be performed by thermal insulation itself, the function reliability shall be ensured.

4.3 Material selection

4.3.1 General requirements

Materials applied for thermal insulation shall meet the safety requirements of material applied in NPP reactor according to the regulations and codes pertaining to the locality in which the product is to be manufactured and used. Debris source caused by material itself shall be satisfied with requirements in 4.1.

Materials applied in thermal insulation mainly include main insulating material, outer cladding/sealing material, support/fixation material, etc. Material performance degradation due to the totally received radiation dose during whole design lifetime shall be considered in the material selection. The maximum service temperature of all materials shall be higher than the design or operation temperature of equipment and piping insulated and be with appropriate margin.

4.3.2 Main insulating material

The safety requirement, thermal behaviour, mechanical properties and structure of thermal insulation would be directly influenced by the main insulating material. Hence, selection of main insulating material shall be determined firstly. The main insulating material can be classified as the following two types:

— metallic insulating material

— non-metallic insulating material

Based on the two kinds of main insulating material, types of thermal insulation are also classified as metallic thermal insulation and non-metallic thermal insulation.

For metallic insulating material, the thermal insulated function is achieved by radiative heat transfer inhibit effect due to the low surface emissivity of material. Hence, surface bright treatable metallic material with low surface emissivity shall be selected. For instance, austenitic stainless steel, aluminum or galvanized steel can all be recommended.

Chemical composition and physical properties (including mechanical property and corrosion resistant property, etc.) of metallic insulating material shall meet requirements specified in relevant codes and standards, and be with good processing performance.

For non-metallic insulating material, the thermal insulated function is achieved by convective heat transfer inhibit effect due to the interior porous structure of material, such as fibre material, microporous material, etc.

Non-metallic insulating material and their products shall have good resistance to radiation. During the lifetime, phenomenon including obvious embrittlement, pulverization, contraction and obviously increased thermal conductivity shall be avoided. The radiation resistance performance of non-metallic insulating material and their product shall be verified by irradiation test.

Non-metallic insulating material shall be resisted to steam, moisture, fungi, disintegration and fire during whole design lifetime and under its operation condition.

Any noxious or harmful effect (formaldehyde emission, carcinogenicity and other possible harmful factors) of non-metallic material shall be limited as far as practicable and respect the the regulations, codes and standards of locality in which the product is to be manufactured and used. The content of organic binder shall be controlled.

For non-metallic insulating material directly contacted with equipment and piping insulated, the influence of stress corrosion cracking tendency on equipment and piping shall be evaluated and the result shall be available before lot production. For non-metallic insulating material directly contacted with austenitic steel components, the leachable chloride, fluoride, sodium and silicate ions as well as pH value of leached water shall be limited.

4.3.3 Outer cladding/sealing material

The outer cladding/sealing material is used for the cladding shell, sealing panel or other outer protective parts for the main insulating material. During the whole design lifetime, mechanical properties of material shall be enough to sustain loads acting on the cladding or sealing parts.. In order to satisfy sealing requirement under different operation conditions, processes including riveting, fillet welding, intermittent welding, seal welding can be selected to assemble the cladding shell or sealing panel. If the outer cladding/sealing material was different from the main insulating material or the adjacent contacted equipment or piping material, the influence of corrosion or other negative tendency caused by the contact between different types of materials shall be evaluated and the result shall be available before lot production.

4.3.4 Support/fixation material

The support/fixation material is used for support frame, support leg, strap or other supporting and fixation parts of thermal insulation. During the whole design lifetime, mechanical properties of material shall be enough to sustain loads acting on the support or fixation parts. If the support/fixation material was different from the main insulating material or the adjacent contacted equipment or piping material, the influence of corrosion or other negative tendency caused by the contact between different types of materials shall be evaluated and the result shall be available before lot production.

4.4 Thermal behaviourr design and test

4.4.1 Thermal behaviourr design

For thermal behaviour design, the surface temperature or heat productivity value of equipment and piping insulated shall be taken as design input, the heat loss limit of equipment and piping insulated shall be taken as design target. This heat loss limit could be specified by equipment specification or other corresponding documents and mainly described by the following parameters:

— heat flux of thermal insulation outer surface

— temperature of thermal insulation outer surface

— heat loss of thermal insulation

After the above design input and target has been offered or specified, the design thickness of thermal insulation shall be determined by theoretical calculation method. Calculation of the design thickness is based on Equation (1) or Equation (2). Equation (1) is suitable for the calculation under flat wall heat transfer process, Equation (2) is suitable for the calculation under cylinder wall heat transfer process. Besides, Equation (3) can be used to obtain heat flux from heat loss, then the heat flux can be used for the calculation of design thickness. Equation (3) also can be used to verify the heat flux calculation result by comparing with heat loss limit.

The thermal conductivity λ in Equation (1) and Equation (2) can be obtained by querying standards or performing heat transmission test described in Clause 4.3.2. The heat transfer coefficient h should consider both of thermal insulation outer surface heat convection transfer coefficient h_c and heat radiation coefficient h_r, which is shown in Equation (4). For safety, appropriate margin shall be considered for the design thickness.

It shall be noted that the calculated design thickness is the net thickness of main insulating material, not including outer cladding, sealing or any other material without thermal insulate function.

$$q=\Delta T/\left(\frac{\delta}{\lambda}+\frac{1}{h}\right) \tag{1}$$

$$q=\Delta T/\left(\frac{d_0}{2\lambda}\times\ln\frac{d_0}{d_i}+\frac{1}{h}\right) \tag{2}$$

$$Q=q\times A \tag{3}$$

$$h=h_c+h_r \tag{4}$$

where

q is heat flux of thermal insulation

ΔT is temperature difference between inner and outer surface of thermal insulation

λ is thermal conductivity of thermal insulation

δ is design thickness of thermal insulation under flat wall heat transfer process

d_0 is design outer diameter of thermal insulation under cylinder wall heat transfer process

d_i is design inner diameter of thermal insulation under cylinder wall heat transfer process

h is surface coefficient of heat transfer of thermal insulation

h_c is surface coefficient of heat convection transfer of thermal insulation

h_r is surface coefficient of heat radiation transfer thermal insulation

Q is heat loss of thermal insulation

A is thermal transfer area of thermal insulation

In the calculation of the outer surface heat convection transfer coefficient, the shape and direction of thermal insulation, the ambient temperature and the ventilation condition should all be considered. According to the different conditions, different calculation method should be selected for heat