



BSI Standards Publication

Nuclear facilities — Criteria for the design and the operation of containment and ventilation systems for nuclear reactors

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Nuclear facilities — Criteria for the design and the operation of containment and ventilation systems for nuclear reactors

*Installations nucléaires — Critères pour la conception et l'exploitation
des systèmes de confinement et de ventilation des réacteurs nucléaires*



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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 26802 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiological protection*.

Introduction

Containment and ventilation systems of nuclear power plants (NPPs) and research reactors ensure the security of such installations in order to protect the workers, the public and the environment from the dissemination of radioactive contamination originating from the operations of these installations.

This International Standard applies specifically to systems of confinement and ventilation systems for the confinement areas of reactors and their specialized buildings (such as command centres and particular areas for air purging and conditioning). This International Standard is complementary to ISO 17873, which applies mainly to nuclear fuel cycle installations (e.g. reprocessing plants, nuclear fuel fabrication and examination laboratories, plutonium handling facilities) and to radioactive waste storage, research facilities and auxiliary buildings of nuclear reactors.

Nuclear facilities — Criteria for the design and the operation of containment and ventilation systems for nuclear reactors

1 Scope

This International Standard specifies the applicable requirements related to the design and the operation of containment and ventilation systems of nuclear power plants and research reactors, taking into account the following.

For nuclear power plants, this International Standard addresses only reactors that have a secondary confinement system based on International Atomic Energy Agency (IAEA) recommendations (see Reference [10]).

For research reactors, this International Standard applies specifically to reactors for which accidental situations can challenge the integrity or leak-tightness of the containment barrier, i.e. in which a high-pressure or high-temperature transient can occur and for which the isolation of the containment building and the shut-off of the associated ventilation systems of the containment building is required.

For research reactors in which the increase of pressure or temperature during accidental situations will not damage the ventilation systems, the requirements applicable for the design and the use of ventilation systems are given in ISO 17873. However, the requirements of this International Standard can also be applied.

2 Normative references

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

ISO 10648-2, *Containment enclosures — Part 2: Classification according to leak tightness and associated checking methods*

ISO 17873, *Nuclear facilities — Criteria for the design and operation of ventilation systems for nuclear installations other than nuclear reactors*

ICRP 103, *The 2007 Recommendations of the International Commission on Radiological Protection*, ICRP Publication 103, Annals of the ICRP, 37 (2-4), Elsevier

3 Terms and definitions

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

3.1 Accident

3.1.1 design basis accident DBA

accident conditions against which a facility is designed according to established design criteria, and for which the damage to the fuel and the release of radioactive material are kept within authorized limits

3.1.2 beyond-design basis accident BDBA

accident conditions more severe than a design basis accident

3.1.3 severe accident

accident conditions more severe than a design basis accident and involving significant core degradation

3.2 aerosol

solid particles and liquid droplets of all dimensions in suspension in a gaseous fluid

3.3 air exchange rate

ratio between the ventilation air flow rate of a containment enclosure or a compartment, during normal operating conditions, and the volume of this containment enclosure or compartment

3.4 air conditioning

arrangements that allow sustaining a controlled atmosphere (temperature, humidity, pressure, dust levels, gas content, etc.) in a defined volume

3.5 balancing damper control valve

adjustable device inserted in an aerodynamic duct allowing balancing of the fluid flow and/or the pressure of the fluid during plant operation

3.6 barrier

structural element that defines the physical limits of a volume with a particular radiological environment and that prevents or limits releases of radioactive substances from this volume

EXAMPLE Nuclear fuel cladding, primary circuit, containment building of a nuclear reactor, containment walls of auxiliary buildings, filters for some cases.

3.7 cell

shielded enclosure
shielding structure, of fairly large dimensions, possibly leak-tight

See **containment enclosure** (3.10).

NOTE It is often more practicable to limit the spread of a fire by using fire-resistant walls, and to prevent the spread of contamination in the adjacent volumes.

3.8

containment/confinement

arrangement allowing users to maintain separate environments inside and outside an enclosure, blocking the movement between them of process materials and substances resulting from physical and chemical reactions that are potentially harmful to workers, to the public, to the external environment, or for the handled products

3.9

containment compartment

CC

compartment of which the walls are able to contain radioactive substances that would be generated by any plausible fire that breaks out in one of the fire compartments included

NOTE It is often more practicable to limit the spread of a fire by using fire-resistant walls, and to prevent the spread of contamination in the adjacent volumes.

3.10

containment enclosure

enclosure designed to prevent either the leakage of products contained in the pertinent internal environment into the external environment, or the penetration of substances from the external environment into the internal environment, or both simultaneously

See **cell** (3.7).

NOTE This is a generic term used to designate all kinds of enclosures, including glove boxes, leak-tight enclosures and shielded cells equipped with remotely operated devices.

3.11

containment envelope

volume allowing the enclosure, and thus the isolation from the environment, of those structures, systems and components whose failure can lead to an unacceptable release of radionuclides

3.12

containment/confinement system

system constituted of a coherent set of physical barriers and/or dynamic systems intended to confine radioactive substances in order to ensure the safety of the workers and the public and the protection of the environment and to avoid releases of radioactive materials in the environment

NOTE According to IAEA definitions, a containment system concerns the containment structure and the associated systems with the functions of isolation, energy management, and control of radionuclides and combustible gases. This containment system also protects the reactor against external events and provides radiation shielding during operational states and accident conditions. These two last functions are not described in this International Standard, due to the absence of link with the ventilation systems.

3.13

contamination

presence of radioactive substances on or in a material or a human body or any place where they are undesirable or can be harmful

3.14

decontamination factor

measure of the efficiency achieved by a filtration system and corresponding to the ratio of the radiological contents of the inlet and outlet of the filtration system

3.15

discharge stack

duct (usually vertical) at the termination of a system, from which the air is discharged to the atmosphere after control

3.16

dynamic confinement

action allowing, by maintaining a preferential air flow circulation, the limitation of back-flow between two areas or between the inside and outside of an enclosure, in order to prevent radioactive substances being released from a given physical volume

3.17

event

unintended occurrence of a hazard leading to potential safety consequences for the plant and in particular for containment systems

NOTE An event can be internal or external to the plant.

EXAMPLE 1 Internal events:

- human errors;
- loss of coolant accidents (LOCA);
- failures in steam piping systems;
- steam generator tube rupture;
- leakage or failure of a system carrying radioactive fluid;
- fuel handling accident;
- loss of electric power;
- internal missile or explosion;
- fire;
- internal flooding.

EXAMPLE 2 External events:

- aircraft crash;
- external explosion;
- earthquake;
- flood or drought;
- winds and tornados;
- extreme temperature (high and low).

3.18

filter

device intended to trap particles suspended in gases or to trap gases themselves

NOTE A particle filter consists of a filtering medium, generally made of a porous or fibrous material (glass fibre or paper) fixed within a frame or casing. During the manufacturing process, the filter is mounted in a leak-tight manner in this frame, using a lute. Gas or vapour filters are generally found in physical or chemical process units where the primary aim is to trap certain gases. They cover in particular iodine traps (activated charcoal).

3.19

fire area

volume comprising one or more rooms or spaces, surrounded by boundaries (geographical separation) constructed to prevent the spreading of fire to or from the remainder building for a period of time allowing the extinction of the fire

3.20

fire compartment

FC

reference volume delimited by construction elements for which fire resistance has been chosen according to the plausibility that a fire could break out within this volume or penetrate into it

3.21

fire damper

fire blocking valve

device that is designed to prevent, generally by automatic action under specified conditions, the ingress of fire through a duct or through the walls of a room

3.22

fire load

heat energy that can be released in the event of a fire involving the whole combustible contents of a volume, including the surfaces of the walls, partitions, floors and ceilings

3.23

gas cleaning

scrubbing

action that consists of decreasing the content of undesirable constituents in a fluid

EXAMPLE Aerosol filtration, iodine trapping or decay storage of gases.

3.24

iodine trap

scrubbing device, usually based on activated charcoal, intended to remove volatile radioactive components of radioactive iodine from the air or the ventilation gases

3.25

load

physical static or dynamic phenomena that impact the containment systems during plant life or which can be associated with postulated internal or external events, or postulated accidents

3.26

negative pressure

depression

difference in pressure between the pressure of a given volume, which is maintained lower than the pressure in a reference volume or the external ambient pressure

3.27

negative pressure system

regulated ventilation system, which ensures a negative pressure between the ventilated area and an adjoining zone or the external ambient pressure

3.28

off-gas treatment system

system often associated with the primary circuit, that permits a decrease in the gaseous effluent inventory prior to its discharge in the atmosphere

NOTE This system might or might not be associated with the room's ventilation systems.

3.29

prefilter

filter fitted upstream from the main air filters to minimize, by removal of large particles, the dust burden on the latter

3.30

pressure drop

pressure loss in an air stream due to its passing through a section of ductwork or a filter or fittings

3.31

process ventilation system

ventilation system that deals specifically with the active gases and aerosols arising within process equipment (such as reaction vessels, piping networks, evaporators and furnaces)

NOTE The ventilation of the containment enclosures in which such equipment is generally located (e.g. hot cells, glove boxes, fume cupboards or high-radioactivity plant rooms) are not considered part of the process ventilation system.

3.32

safety classification

classification of structures, systems and components, including software instrumentation and control, according to their function and significance with regard to safety

3.33

safety flow rate

flow rate that guarantees air flow through any occasional or accidental opening, sufficient to either limit the back-flow of contamination (radioactive or other) from the working volume, or to avoid the pollution of clean products within the working volume

3.34

ventilation

organization of air flow patterns within an installation

NOTE Two systems are commonly used:

- ventilation in series: ventilation of successive premises by transfer of air from one to the next;
- ventilation in parallel: ventilation by distinct networks or premises or group of premises presenting the same radiological hazard; the term is also used to indicate that the totality of blowing and extraction circuits of each particular volume is directly connected to the general network (in contrast to ventilation in series).

3.35

ventilation duct

envelope generally of rectangular or circular section, allowing air or gas flow to pass through

3.36

ventilation system

totality of network components such as ducts, fans, filter units and other equipment, that ensures ventilation and gas cleaning functions as defined in this International Standard

4 Functions ensured by the ventilation system

4.1 General

The ventilation of nuclear reactors enables the improvement of the safety of the workers, general public and environment and the protection of the safety classified equipment. It plays a role of

- **safety**, by contributing to keeping the work areas and the environment free of contamination in normal situations, to mitigating releases during incidental or accidental situations, and to providing adequate ambient conditions to safety-related components;
- **protection** of the equipment and the handled products (and thus indirectly to safety), by maintaining the internal atmosphere in a state (temperature, humidity, physical and chemical properties) compatible with the proposed operational materials and process conditions.

4.2 Main functions

The ventilation ensures the main following functions, without ranking.

- a) **Confinement**, by acting in a dynamic manner in order to counteract any defects in the leak tightness of the static containment consisting of the physical limits of the relevant enclosures. In this case, the “dynamic” confinement ensured by the ventilation systems has the following two aspects:
- Between equipment, enclosures (or cells) and rooms of the same building (i.e. internal dynamic confinement), the ventilation ensures a hierarchy of pressure in order to impose a circulation of air from volumes with a low potential hazard of radioactive contamination to volumes with a high potential of radioactive contamination hazard. This dynamic confinement is also able to isolate or circumscribe, to process and to control the contamination as closely as possible to its source, at least in the reactor building and, therefore, it complements the other systems provided to protect the workers or the public against the hazards of ionizing radiations [see isolation function b) below].
 - At the interface with the environment (i.e. external dynamic confinement), the ventilation system maintains a significant negative pressure within controlled areas with a high potential radioactive contamination, in order to avoid uncontrolled releases as well as to direct the gaseous effluents towards identified release points, and to enable, if needed, their gas cleaning (purification) and monitoring.
- b) **Isolation**, by closing in a safe and tight way the equipment needed to avoid or limit the spread of the contamination to the other surrounding volumes and the environment. In particular, this function is required to maintain the required leak tightness of the reactor building with regard to the activity released in the reactor building during accidents leading to an increase in mass and energy (increase of pressure, temperature, discharge of vapours and gases) above the design level of the ventilation system's components.
- c) **Purification** (or gas cleaning), by conveying the collected gases including any dust, aerosols and volatile components, towards defined and controlled points for collection, processing and elimination where possible (by using filters, traps, storage for decay, etc.).
- d) **Monitoring** of the installation, by organizing air flows in such a manner as to allow meaningful measurements in order to demonstrate the suppression of the spread of radioactive components or fire. Ventilation systems, with or without surveillance monitoring, can also contribute to the improvement of some radiological protection measures inside rooms by helping to control the background level of natural radioactivity (radon).
- e) **Cleaning** of the atmosphere of the enclosures or rooms, by renewing the volumes of air within it, in order to minimize the hazard levels of the corresponding atmosphere (for example, the elimination of any gas necessary to create the risk of an explosion hazard).
- f) **Conditioning** of the atmosphere of the enclosures or the rooms, to obtain the optimum ambient conditions for the equipment or to improve the safety of some otherwise hazardous operations.
- g) **Comfort** (conditioning of the work place), by ensuring the processing of the air, the regulation of the temperature and the relative humidity of the atmosphere of the rooms, in order to maintain their ambient and hygiene conditions to suit the work that the personnel shall undertake.

According to the results of safety analyses, these functions can be considered important to safety functions. For example, the achievement of comfort is indirectly a safety function, because “human risks”, which can be caused by inadequately regulated ambient conditions, are then substantially reduced.

In any event, the confinement of radioactive materials within a nuclear plant, including the control of discharges and the minimization of releases, is a main safety function that is ensured in normal operational modes, anticipated operational occurrences, design basis accidents and selected beyond-design basis accidents. In this context, according to IAEA principles for nuclear power plants (see Reference [12]), severe accidents should be considered during the design of the confinement function.

According to the concept of in-depth defence, the confinement function is achieved by several barriers and in some cases by accident mitigation systems that can be ensured by the ventilation system.

5 Architecture and description of the different ventilation systems

5.1 Ventilation of the volumes within the primary containment envelope

5.1.1 General

These systems are located mainly inside the reactor building.

The ventilations systems concerned are

- either designed only for normal situations (see 5.1.2), or
- designed for ensuring both safety and protection function in the event of a design basis accident and may be located either inside or outside the reactor building, according to the type of reactor design (see 5.1.3).

5.1.2 Ventilation systems designed for normal operations

5.1.2.1 Ventilation systems located inside the reactor building

In these designs, the ventilation systems usually operate for normal operations and they are not generally able to operate under the conditions of an accident in the reactor building, due to the potentially high pressures and temperatures that can be reached in the reactor building during such accidents.

These systems ensure three main functions:

- conditioning the atmosphere;
- cleaning the atmosphere of the reactor building when people enter in the reactor building;
- purification of the reactor building atmosphere.

As these systems are used only for normal operations, the associated functions described above are similar to those developed in ISO 17873 and the corresponding ISO 17873 requirements shall be met.

5.1.2.2 Ventilation systems located outside the reactor building but ventilating its inner atmosphere

These systems usually operate for normal operations and most of the systems are not designed to operate under the conditions of an accident leading to an increase in mass and energy in the reactor building that initiates the isolation of the fluid systems. They ensure the following functions:

- internal and external dynamic confinement during normal operations or for minor incidents that do not lead to an increase in mass and energy in the reactor building;
- purification or gas cleaning of the reactor building atmosphere for minor incidents that do not lead to an increase in mass and energy in the reactor building;
- monitoring of gases and aerosols in the atmosphere of the reactor building during normal operations or for minor incidents that do not lead to an increase in mass and energy in the reactor building;
- isolation during accidental situations to maintain the integrity of the primary containment envelope and leak tightness.

For the first three functions, the systems shall fulfil the corresponding requirements of ISO 17873.

For isolation function during accidental situations, additional leak-tightness requirements for the isolation valves and ducts shall be fulfilled (see 7.1.4).

5.1.2.3 Ventilation systems used as off-gas treatment systems

These systems are associated with the operation of the components of the primary circuits of the reactor, or are connected to it, where they remove large quantities of gaseous effluents. The systems ensure the following functions:

- purification of the process off-gases prior to their discharge into the environment;
- isolation during accident situations in order to rapidly halt radioactive releases to the environment;
- cleaning and protection by avoiding the mixing of gases in the off-gases systems with those of the room's atmosphere.

The off-gas treatment systems can also be useful during radioactive measurements made at the stack level, in particular associated with routine release measurements.

5.1.3 Ventilation systems designed for accident conditions

5.1.3.1 General

These systems are designed to cope with accidental conditions and can also deal with normal operations.

Two kinds of systems are described in 5.1.3.2 and 5.1.3.3.

5.1.3.2 Ventilation systems ensuring both safety and protection function in the event of a DBA

These systems may be located either inside or outside the containment. It is necessary that they function in the event of a DBA in the containment envelope or support buildings.

These systems, depending on their use, may have the following functions:

- cleaning the atmosphere, consisting mainly to reduce the hydrogen by detection and mitigation (e.g. recombiners, systems for the homogenization or dilution of combustible gases);
- monitoring the atmosphere (pressure, temperature, humidity, hydrogen content, contamination content);
- purification of the atmosphere;
- isolation of radioactive materials contained in the reactor building atmosphere;
- confinement of radioactive products.

In addition to the requirements during normal operations, it is necessary that these ventilation systems fulfil specific requirements, in particular associated with behaviour and leak-tightness requirements (see 7.1.3).

5.1.3.3 Ventilation systems ensuring a mitigation function in the event of a severe accident (mainly for NPPs)

These ventilation systems may be located either inside or outside the containment. They can also be used to clean up the atmosphere following other types of accidents.

They ensure the following functions:

- confinement of radioactive materials;
- isolation of radioactive materials located inside the reactor building;

- purification of the releases;
- cleaning the atmosphere with regard to the management of combustible gases;
- monitoring the atmosphere content in order to be able to manage the severe accident.

These systems function to limit the consequences of a severe accident. It is necessary that these ventilation systems fulfil very specific requirements, in particular associated with integrity, leak-tightness and filtration requirements (see 7.3).

5.2 Ventilation of the volumes located within the secondary confinement

The ventilation systems for the volumes within the secondary confinement usually operate during normal and accidental situations, even during an accident in the reactor building.

The secondary confinement is comprised of all the buildings and rooms that help to collect radioactive materials in order to filter them. Depending on the design types of the reactors, these buildings are either specific to the collection of leaks (for example, the annulus space around the reactor building) or designed to collect leaks in addition to other functions (for example, auxiliary buildings that are designed to collect the leaks). The system shall contribute to limiting non-filtered leaks from the primary containment envelope towards the environment. The system can also lead to a positive or negative pressure inside the dedicated volumes to reach this objective.

With regard to the leaks issued from the primary containment envelope, these ventilation systems shall fulfil the following functions:

- confinement during accidental situations resulting in the leakages released from the primary containment envelope that initiate containment radioactive materials, in particular those emerging in non-filtered areas;
- purification of radioactive leakages in order to minimize the releases into the environment.

Depending on the design, the secondary confinement either provides only additional confinement around the primary containment envelope penetrations and extensions, or completely surrounds the primary containment envelope. In the latter case, it is necessary that specific requirements be fulfilled by the secondary confinement: leak tightness, integrity and protection (e.g. against aircraft crashes, missiles) and dynamic confinement (e.g. ensuring negative pressure in order to cope with severe winds).

Regarding the components or equipment located in these volumes, the ventilation systems shall fulfil the following additional functions:

- monitoring function;
- cleaning function;
- conditioning function.

For these additional functions, the systems shall fulfil the corresponding ISO 17873 requirements.

5.3 Ventilation of the volumes located outside the secondary confinement

This subclause concerns the ventilation systems that ensure a confinement function for rooms or buildings that are not specifically designed to collect and filter leaks from the primary containment envelope, associated with the annex, fuel, waste and effluents treatment buildings. These systems usually operate during normal and accidental situations, even during an accident in the reactor building. As these systems are not designed specifically for the reactor itself, the requirements they shall fulfil are specified in ISO 17873.

5.4 Miscellaneous ventilation systems not connected with containment envelopes

5.4.1 Ventilation systems for control rooms

These systems are designed to operate during normal situations and accidental conditions within the reactor building and auxiliary buildings. According to the design, they are located either within or outside the secondary confinement.

These systems have the following functions:

- conditioning the atmosphere of the control rooms in order to protect both safety systems (e.g. electronic and electrical systems) and workers, by giving them adequate comfort;
- protection function by ensuring a positive pressure inside the control room and purification of the inlet air of the control rooms in order to mitigate and control potential radioactive releases that can enter the control rooms during an accident.

These two functions participate in the “long-term habitability of the control rooms” function.

As they prevent the ingress of contamination (chemicals, radioactive materials, smoke, gases, etc.), rather than providing confinement, these systems shall meet special requirements regarding the protection and the purification function (see 7.2).

Concerning the conditioning function, the requirements given in ISO 17873 shall be fulfilled.

5.4.2 Smoke removal ventilation systems

The smoke removal ventilation systems in contaminated areas shall fulfil the requirements of ISO 17873.

NOTE For smoke removal systems in non-contaminated areas, reference can be made to national or regional standards regarding systems for the evaluation of smoke (for example, the EN 12101 series^[9]).

5.4.3 Ventilation systems ensuring the protection of safety systems

These systems are associated with the operation of the safety systems of the reactor, such as electrical power supply (back-up power and normal), water injection systems, electronic control systems. These systems are designed to operate whatever the situation in the reactor building. They are also classified as safety systems.

The functions ensured by these systems are

- cleaning function;
- conditioning function.

They shall fulfil the corresponding requirements of ISO 17873. Nevertheless, the conditioning function can be highlighted for reactors relative to other types of nuclear facilities due to the fact that they can support the safety systems.

6 Safety aspects for ventilation systems

6.1 General principles

Ventilation systems shall be able to ensure the safety and protection functions defined in the previous clause, in all normal operations and maintenance conditions. Ventilation systems shall also be able to ensure these functions or some of these functions during abnormal operating conditions, exceptional intervention or accidental situations. According to IAEA principles^[10], severe accidents in nuclear power plants should be

considered during the design of containment systems. In this context, the associated requirements are given in 7.3.2.

For new research reactors, it is not possible to take severe accidents into consideration during the design of the containment systems if the probability of the occurrence of such events is extremely low (e.g. $P < 10^{-7}/y$), or if a sufficient number of in-depth defence lines are implemented.

Before beginning any detailed ventilation design, a hazard assessment shall be made so that design safety principles and actual targets can be adequately defined. Subclause 6.2 provides an outline of the hazard assessment process as it relates to ventilation design.

This approach shall be based mainly on the experience derived from the design and operation of existing reactors and it should apply to the most common types of reactor designs. It addresses the functional aspects of the containment systems, such as energy management systems or mitigation systems. It also includes some general recommendations for the features that can be used in new nuclear reactor plants to cope with severe accidents. Particular care is given to the design of the containment systems, in particular those aspects affected by loads identification and loads combination.

General recommendations shall be followed during tests and inspections to ensure that the functional requirements for the ventilation systems can be met throughout the operating life. Design limits and acceptance criteria, together with the system parameters that should be used to verify them, shall be adopted in accordance with the safety authorities.

6.2 Risk assessment procedure — General

6.2.1 Preliminary analysis

The design of an appropriate ventilation system requires a preliminary analysis that takes into account the following.

- a) Radiological hazards arising from the materials and operations that lead to the need for the confinement and purification function of the ventilation systems, with regard to the permitted levels of air and surface contamination within the building and the air monitoring requirements. This can lead to a classification of the area with respect to the contamination hazard, as defined in 7.1.5.1. In the event of radiation exposure hazard (internal and external exposure) for normal operations, a complementary classification of the installation into radiological areas shall be made according to the recommendations proposed by ICRP 103.
- b) Discharge limits from the ventilation system as a whole, and the scrubbing requirements (if any) prior to discharge.
- c) The need to use the ventilation systems to mitigate design basis accidents. If severe accidents are considered, then ventilation systems should be used to mitigate severe accident consequences.
- d) The isolation of some containment penetrations during accidents that involves pressure and temperature conditions in the atmosphere that exceed the design values of these ventilation systems.
- e) The necessity for minimizing the direct leaks from the containment to the atmosphere that are not collected by the dynamic confinement provisions.
- f) Non-radiological internal events (e.g. catastrophic rupture of containment enclosure caused by some mechanical failure, abrupt variation of pressure, explosion, fire, corrosion, condensation, human errors) related to the processes and equipment implemented in the enclosures that shall be ventilated and that can necessitate or jeopardize the confinement functions.
- g) External events (aircraft crash, explosion, fire, flood, earthquake, tornados, wind and extreme temperatures) to which the safety components and the ventilation system itself can be exposed and that can challenge the functions of the ventilation or containment systems (see 4.1).

- h) Possible temporary unavailability of fluids or energy supply (e.g. compressed air or electrical supply) needed for the correct functioning of the ventilation system.
- i) Loads and events combinations that challenge the operation and the design of the ventilation systems. These combinations shall take into account whether loads are consequential or simultaneous (e.g. loss-of-coolant accidents, pressure and temperature loads), the time history of each load (to avoid unrealistic superposition of load peaks if they cannot be simultaneous), the probability of occurrence of each load combination (combinations of unlikely loads should have a reduced probability relative to the probability of each single load).

Other factors which should be taken into account when designing radioactive ventilation systems include the following.

- There is a need to minimize, as far as reasonably possible, the level of radioactivity in the workroom air.
- For protection of the environment, it is necessary to design nuclear process plant systems so as to minimize radioactive waste produced and radioactive releases (liquid and gaseous) as far as practicable. Thus, attention shall be paid to the whole-life considerations of waste streams produced by operational, maintenance and decommissioning activities (consumable seals, filters, swabs; contaminated fluids from lubrication, cleaning, off-gas scrubbing, etc.). It is also “best practice” to ensure that the minimum possible quantities of waste are produced in the higher categories of radioactive waste and the maximum possible fraction in the lowest activity level. In particular, contaminated filters¹⁾, being of low density, are very expensive to store or dispose of as radioactive waste and consideration should be given to the use of self-cleaning or cleanable filters, cyclone filtration, etc., or filter compaction techniques.
- The design of an enclosure, through which air is exhausted via ductwork, filters, fans and a stack to the outside atmosphere, shall take into account the variations of pressure, temperature and humidity that can be tolerated by each component, in an appropriate range of operational and fault conditions.
- Comfortable working conditions shall be provided for operational and maintenance staff.

6.2.2 Risk evaluation

For each element considered, the ventilation systems shall be designed, using a safety risk assessment consistent with that given by IAEA (see References [12] and [13]).

For NPPs, this safety risk assessment includes the combination of the following approaches:

- a deterministic approach, applying safety criteria, such as the single-failure criterion used for the risks linked to the process (circuits connected to the primary circuits, fluid circuits under pressure);
- a probabilistic approach, using a probabilistic safety assessment, in order to identify potential accidental sequences that might not have been identified using the deterministic approach.

For research reactors, this safety risk assessment shall be based on deterministic methods, complemented where appropriate by probabilistic methods and engineering judgement.

It is important not to primarily exclude some combinations of loads when their probability is not residual, in case of effects between loads (e.g. earthquake leading to a fire) or in case of load combinations with a low magnitude load, but with higher probability.

1) The definition of HEPA filters is given in Annex F.

Loads combination rules shall be indicated in the safety documents of the plant. Subclause 4.58 of the IAEA *Safety Standards Series NS-G-1.10-2004* (see Reference [10]) gives minimum load combinations for all the containment systems, including ventilation systems of nuclear power plants.

For DBA, it shall be verified that the design and operation of ventilation systems do not lead to cliff-edge effects²⁾ or to unacceptable consequences to workers, the public or the environment. If one of the functions of the ventilation systems defined in 4.1 is used to limit the consequences of a DBA, then this function shall be designed to cope with this DBA.

For BDBA, an analysis should be carried out in order to establish the margins between ventilation or containment systems design parameters and those needed for coping with these BDBAs (e.g. fire with several in-depth defence lines).

6.2.3 Safety classification

All structures, systems and components of the ventilation or confining systems, including software instrumentation and control, that are items important to safety shall be first identified and then classified on the basis of their function and significance with regard to safety. They shall be designed, constructed and maintained such that their quality and reliability is adapted to this classification. The method for classifying the safety significance of a structure, a system or a component shall primarily be based on deterministic methods, complemented where appropriate by probabilistic methods and engineering judgement taking account of the following:

- the safety function(s) that it is necessary for the item to perform,
- the consequences of failure to perform its function,
- the probability that the item will be called upon to perform the safety function,
- the time following an initiating event at which, or period throughout which, it will be called upon to operate.

Appropriately designed interfaces shall be provided between structures, systems and components of different classes to ensure that any failure in a system classified in a lower class does not propagate to a system classified in a higher class.

All structures, systems and components (SSCs) important to safety shall be clearly identified. This identification is necessary to focus the attention of designers, manufacturers and operators on features that assure the safety of the plant and are associated with the application of specific design requirements (e.g. single failure criterion) or of more conservative codes and standards.

SSCs important to safety may be further sub-classified according to a number of criteria. Different safety classification systems are used worldwide for the purpose of assigning structures, SSCs important to safety to the different classes and controlling the application of codes and standards, as well as of quality assurance procedures.

Examples of safety classification systems are given in Annex C.

6.3 Risk assessment procedure for severe accidents

Concerning more specifically the severe accidents, IAEA indicates (see Reference [10]), for nuclear power plants, that “consideration shall be given to severe accident sequences, using a combination of engineering judgement and probabilistic methods, to determine those sequences for which reasonably practicable preventive or mitigation measures can be identified”.

2) As defined by IAEA in Reference [10].

A severe accident corresponds to a significant core degradation resulting from the multiple failures in redundant safety systems that can lead to their complete loss and even threaten the containment integrity or the ventilation systems used to cope with this type of accident. Though sequences exhibiting such characteristics have a very low probability, IAEA (see Reference [10]) indicates that they should be evaluated to assess whether it is necessary that they be addressed in the containment systems design. The occurrence of accidents with severe environmental consequences should be made extremely unlikely by means of preventive and mitigation measures.

Severe accidents should be evaluated by means of the best estimate approach, i.e. without excessively conservative margins.

As severe accidents are difficult to take into account for existing plants, IAEA (see Reference [10]) distinguishes two types of recommendations.

- a) For *existing* plants, the phenomena relating to potentially severe accidents and their consequences should be carefully analysed in order to identify design margins and accident management measures that can be carried out to prevent or mitigate their effects. These accident management measures should make full use of all available equipment, including the use of alternate or diverse equipment, as well as of external equipment for the temporary replacement of design basis components. Furthermore, the introduction of complementary equipment should be considered in order to improve the preventive and mitigation capabilities of the containment systems. Then, an analysis should be carried out in order to establish the margins between ventilation or containment systems design parameters and the severe accident conditions, in particular with regard to temperature, pressure, irradiation and contamination conditions. If not qualified for severe accident conditions, modifications should be considered on these systems.
- b) For *new* plants, severe accidents should be taken into consideration at the design stage of the containment systems. Consideration of severe accidents should be aimed at practically eliminating the following:
 - severe accident conditions that can damage the containment in an early or late phase;
 - severe accident conditions with an open containment, namely during shutdown states;
 - severe accident conditions with containment bypass.

In this context, severe conditions are considered practically eliminated if they are physically impossible or when it can be considered with a high degree of confidence that they are extremely unlikely to arise. For severe accidents that cannot be practically eliminated, the containment systems should contribute to reducing their releases to such a level that the extent in area and time of off-site emergency measures is small. Therefore, ventilation systems should be designed to cope with the severe accident conditions, in particular with regard to temperature, pressure, irradiation and contamination conditions.

Concerning research reactors, considerations of severe accidents shall be used carefully. These severe accidents can be considered in the same way as for NPPs, except when it is demonstrated that by adequate and strong prevention provisions their occurrence is extremely low.

7 Requirements for the design of ventilation systems

According to Clauses 4 and 5, the ventilation systems ensure several functions that shall fulfil several general requirements^{3), 4)}. In 7.2 and 7.3, the requirements for application to the ventilation systems for each function are considered, and in 7.4 the specific requirements associated with specific functions that exist in various nuclear reactors are considered.

3) Most of the ISO 17873 requirements for the ventilation systems are completely applicable to nuclear power reactors. However, some possible exceptions are related to the definitions of the barriers, the confinement requirements for the containment, and the different safety approach for nuclear power plants.

4) For research reactors, the safety approach is very similar to the ISO 17873 approach.

7.1 Confinement of radioactive material

7.1.1 General

In nuclear reactors, the confinement of radioactive material is one fundamental safety function, together with

- the safe shutdown of the reactor and maintenance in the safe shutdown condition, and
- the removal of heat from the core and maintenance of the water inventory.

To ensure the safety of a nuclear reactor, these safety functions shall be achieved during operational states, during and following a design basis accident, and to the extent practical during and following the considered plant conditions beyond the design basis accident conditions.

The function of the confinement of radioactive materials also includes the control of normal operational discharges, as well as the limitation of accidental releases.

7.1.2 Source term

Ventilation systems are used to strongly reduce radionuclide releases under normal circumstances, incident situations and to mitigate the consequences of accidents⁵⁾. In order to quantify the performances of such systems, an evaluation of the nuclides inventory and source term that shall be dealt with by ventilation systems is necessary.

For light, heavy-water or gas-cooled (VVER, PHWR, PWR, BWR, PBMR)⁶⁾ and research reactors, radioactive inventory in the circuits usually contains

- noble gases such as fission products (^{133}Xe , ^{85}Kr , etc.);
- gaseous activated products with structure or coolant, such as tritium and carbon 14;
- iodine products (^{131}I , ^{132}I , ^{133}I , ^{134}I , ^{135}I , traces of ^{129}I , etc.);
- aerosols such as fission products (^{137}Cs , ^{134}Cs , ^{106}Ru , etc.) or activation products (^{60}Co , ^{58}Co , etc.);
- alpha emitters from the fuel.

For sodium-cooled reactors, radioactive inventory contains sodium nuclides (^{22}Na , ^{24}Na , etc.) in addition to the nuclides for water-cooled reactors.

Annex A summarizes typical products associated with different types of reactors in the reactor core, and in the gaseous releases in normal and accident conditions. The possible releases into the environment depend on the fuel inventory and quality of confinement and ventilation systems in addition to containment requirements.

5) For new nuclear power plants, design stages shall also include the identification and the evaluation of the source term for accident situations, including severe accidents.

6) VVER: water-water energetic reactor
PHWR: pressurized heavy water reactor
PWR: pressurized water reactor
BWR: boiling water reactor
PBMR: pebble bed modular reactor

7.1.3 Containment barriers and systems

7.1.3.1 General requirements concerning the confinement function

The basic principle with regard to the prevention of the spread of the radioactive material is

- a) in normal situations, to limit the release of radioactive material outside the facility (with regard to the regulatory authorization), but also to maintain a level of contamination as low as reasonably achievable inside the facility;
- b) in incidental or accidental situations, to limit to acceptable levels the radiological consequences for the environment, for the operators and for the general public.

The application of this principle leads to the provision of different containment barriers between the environment and the radioactive substances. Each containment/confinement system and the associated devices are designed to suit the risks that they are intended to control. The potential use of dynamic systems during an accident requires the functionality of at least one stage of effective filtration between the contaminated areas and the environment.

In nuclear reactors, several containment/confinement systems and barriers are distinguished. Each system can be made of

- one or several static containment barriers;
- complemented, if necessary, by means of dynamic systems, consisting of a specific ventilation system and appropriate air-cleaning devices.

The design should be based on the possible compromise between a static containment and the different types of dynamic confinement systems presented in Clause 5. Generally, this best compromise for the radiological consequences is based on the operation of a ventilation system ensuring a negative pressure with the lowest possible flow rate.

Figure 1 shows the principle of the confinement for nuclear reactors. Annex B gives several schematic diagrams of typical NNP designs.

7.1.3.2 First barrier

The first barrier is the fuel cladding. Its purpose is to be as tight as possible during normal operations or accidental situations in order to prevent the release of radioactive substances into the primary circuit.

However, operational feedback has shown that it cannot be assumed that this barrier is absolutely tight for normal operations or accidental transients. Therefore, the design of the other barriers shall take into account failure of the first barrier.

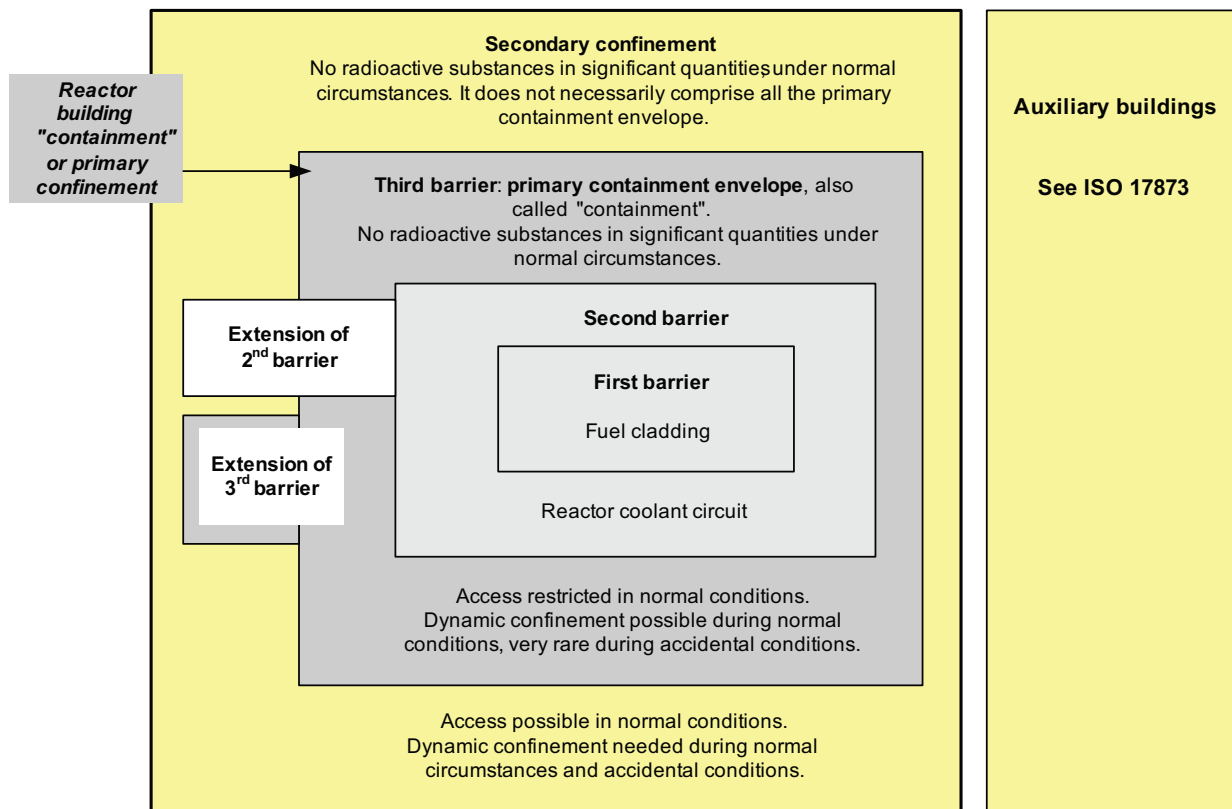


Figure 1 — Schematic diagram of reactor confinement systems

7.1.3.3 Second barrier

The second barrier consists of the primary circuit(s). The goal of the second barrier is to limit the releases of radioactive contamination from the primary circuit into the containment building in normal situations, as well as in accidental situations.

For nuclear power plants, the second barrier also comprises the internal tubes of the steam generator with the goal of minimizing leaks. It could also include the circuits, connected to the primary circuit, which are used in normal conditions to help to operate the reactor (e.g. water purification system, chemical treatment system, etc.) and considered as extensions of the second barrier.

Nevertheless, despite the very high quality of the primary circuit, many postulated accidents take into account the failure of this barrier as an initiating event, which leads to an increase of mass, energy and radioactive products in the containment building. It is necessary to consider the ambient and radiological conditions issuing from these postulated accidents during the design of the containment systems and, in particular, the ventilation systems.

7.1.3.4 Third barrier: primary containment envelope

7.1.3.4.1 Structural parts of the primary containment envelope

The first two barriers cannot be considered as totally efficient barriers against the spread of radioactive material during accidents, due to the fact that fuel cladding cannot ensure its leak tightness during accidents, and that primary-circuit-pipe failures are considered as initiating events for design basis accidents.

Therefore, the goal of the third barrier is to prevent the release of radioactive contamination outside the whole building in case of failure of the first two barriers and to provide for the protection of the general public, the environment and the workers located in annex buildings. The third barrier is, therefore, the primary containment envelope, also called "containment" and is generally composed of the inner walls of the reactor

building and also the circuit penetrations passing through these walls and the associated isolation valves. The ventilation and air conditioning system boundaries associated with the primary containment envelope are, in some designs, parts of the primary containment envelope, e.g. if they are located outside this envelope.

All the ventilation systems that constitute parts of the primary confinement shall withstand the same accident conditions as the structural parts themselves. If they cannot cope with accident conditions, these systems are considered as lost during accidents and, therefore, are isolated if they are located outside the primary containment.

It shall be noted that depending on the design of the reactor, the primary containment can be an area non-accessible to workers during normal operations. Nevertheless, in some designs, in particular research reactors or boiling water reactors, there is a possibility for these workers to access it. The design of ventilation systems shall take into account the possible access or not of workers inside the primary containment.

Primary containment should satisfy the requirements of the static containment leak-tightness in order to be able to mitigate accident consequences.

7.1.3.4.2 Extensions of the third barrier

Some circuits located outside the primary containment envelope constitute extensions of the third barrier when

- these circuits are open voluntarily or incidentally to the primary containment atmosphere during accidents;
- they are closed to the containment atmosphere, but can carry, voluntarily or incidentally, primary circuit radioactive products during accidents.

The ventilation systems can constitute an extension of the primary containment envelope.

Leaks from components belonging to the extension of the third barrier can lead to a containment bypass. The releases arising from a containment bypass, i.e. arising with a sequence of faults that allows primary coolant and any accompanying fission products to escape to the outside atmosphere without having been discharged into and mixed with the air in the containment, shall be minimized as much as possible.

One example of containment bypass involves the use of the safety injection system located outside the primary containment envelope during accidents.

The components of this extension shall satisfy the requirements for a high degree of leak tightness and integrity. Strong safety provisions (e.g. passive or an active single-failure criterion) should be given to these components. The rooms in which these components are located should be considered as part of the secondary confinement (see 7.1.3.5).

7.1.3.5 Secondary confinement

The goal of the secondary confinement is to ensure the recovery of leaks from the containment in order to protect the general public and the environment and, thus, to limit non-filtered or non-controlled releases, in particular in the case of the severe accidents considered in the design, if any.

The secondary confinement may include

- the outer wall of the double wall containment and the ventilation systems of the internal space between the two walls;
- the structure of the rooms enclosing the primary containment volumes and their associated ventilation systems: rooms, ducts of the associated ventilation networks, filters installed on these ducts, etc.;
- the volumes in which leaks from the penetrations through the primary containment envelope are collected and the associated ventilation systems.

It is not necessarily comprised of the entire primary containment envelope.

The design of the secondary confinement shall take into account the maximum quantity of radioactive substances that is present in a dispersible form inside the primary containment, the quality of the containment barrier(s) and the possible consequences of the hazards introduced by the industrial process(es) being implemented.

Ventilation systems can be used to collect leaks from pipes used as an extension of the primary containment envelope.

The requirements applicable to the static containment of auxiliary buildings are given in ISO 17873.

It should be noted that the secondary confinement constitutes the last barrier in the event of a severe accident, in particular when leaks are collected through these buildings and when the ventilation systems are not designed to cope with the events that are at the origin of the severe accident (e.g. the total loss of electrical supply). In most designs, auxiliary buildings are included in the secondary confinement.

Table 1 summarizes the constitution of the different containment/confinement systems.

Table 1 — Typical examples of containment/confinement systems

	Barrier	NPP	Research reactors
	First barrier	Fuel cladding	Fuel cladding (or primary circuits for research reactors aiming to study limited core melting)
	Second barrier and extensions	Primary circuit (vessel, pipes, etc.) and connected circuits	Process circuits, pool boundaries ^a
Primary containment/confinement	Third barrier, also called "containment"	Reactor building, building ventilation network, mechanical and electrical penetrations, containment hatch, etc.	Reactor building, building ventilation network, mechanical and electrical penetrations, containment hatch.
	Extension of third barrier	Parts of connected circuits located outside the third barrier and opened during normal or accidental situations (safety injection system, heat exchangers of heat removal system, etc.) Parts of circuits located outside the third barrier and open to the containment atmosphere and used during normal or accidental situations (ventilation systems, hydrogen removal system, etc.)	
Secondary containment/confinement		Outer wall of a double wall containment system, NPP auxiliary buildings, volumes in which leaks from the penetrations through the primary containment envelope are collected and the associated ventilation systems	

^a Pool boundaries, often used in research reactors, cannot be considered as efficient barriers (no warranty of presence during all types of accidents and bad retention factors for gases), although they have retention capabilities.

7.1.4 Isolation function (static containment)

This isolation function is useful for volumes (mainly containment building) during a DBA and for which confinement strategy is based on a tight isolation of this volume, on leak tightness of the structure and on the collection of leaks by a secondary confinement.

For isolation function during accidental situations, it is necessary that additional requirements be fulfilled for the systems located outside of, and requiring some penetrations through, the containment building. These systems

- a) might not be needed for accident conditions or not qualified for accident conditions (they are considered as lost); these systems shall fulfil an isolation function when located outside the containment;

- b) might not be needed for short-term accidental conditions (i.e. the systems are not designed to cope with the peak pressure and the temperature resulting from accidental conditions, but designed to lower pressure and temperature conditions); they are located outside the containment and require an isolation function;
- c) can be required for accident situations and designed for the accident ambient condition; whether or not they require an isolation function depends on whether they are located inside or outside the accident zone.

This function can also be required when an accident occurs in buildings other than the reactor containment building. In addition, this function makes some specific demands related to

- the leak tightness of structures, penetrations, valves, etc.;
- the safe and quick actuation of valves or circuits.

To ensure the reliability of the isolation, the isolation valves should be redundant, hermitically sealed in the event of a loss of fluid (electrical supply, compressed air), be seismically resistant and be backed up by diesel generators and a permanent electrical supply, when necessary. They shall satisfy the same requirements as the containment structure itself.

For safety reasons or protection purposes, exceptions can, nevertheless, be accepted for the isolation valves of circuits that are required during an accident (e.g. systems belonging to the extension of the third barrier and for which redundancy on isolation valves can reduce the reliability of the function ensured by the valves). Then the leak tightness criteria shall be associated with the pipes and ducts of the circuits.

The leak tightness of buildings and structures varies according to the type of reactor design. Typical examples of leak tightness rates for NPP primary-containment envelopes for the peak pressure and temperature ambient conditions are

- double containment without liner: $\leq 1 \text{ %/day}$;
- double containment with an internal liner: $\leq 0,3 \text{ %/day}$;
- single containment with an internal liner: $\leq 0,3 \text{ %/day}$.

The ventilation design should minimize the discharge of unfiltered gas leaking from the primary containment envelope to work areas or to the environment, consistent with the safety analysis.

The average values of leak tightness of other specific isolation components, established for the peak accident conditions, should not affect the global leak rate of the primary containment envelope. Typical examples of leak rate are given in Annex H.

The secondary confinement envelope is affected by the leaks as a result of the pressure and temperature effects induced by the accident in the primary containment envelope and by the wind effects on the structure. To minimize these wind effects, one solution can be to adopt a very low leak rate for the secondary confinement envelope (e.g. $< 1 \text{ %/day}$ for the pressure induced by the most severe winds).

For the auxiliary buildings included in the secondary containment envelope, appropriate leak-tightness requirements (e.g. $< 0,1 \text{ vol/h}$ during DBAs, 1 vol/h during seismic conditions) shall be satisfied.

Time closure of valves shall be consistent with the accident kinetics. Examples of time closure are between 3 s and 5 s, depending on the diameter of the valves.

Finally, NPP ventilation systems with confinement function located outside the containment shall satisfy additional requirements related to their leak tightness and safe closure in order to limit external leaks. These circuits shall be located in confined rooms.