

IAEA SAFETY STANDARDS SERIES

Design of Reactor Containment Systems for Nuclear Power Plants

SAFETY GUIDE

No. NS-G-1.10



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DESIGN OF REACTOR CONTAINMENT SYSTEMS FOR NUCLEAR POWER PLANTS

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FOREWORD

by Mohamed ElBaradei
Director General

One of the statutory functions of the IAEA is to establish or adopt standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes, and to provide for the application of these standards to its own operations as well as to assisted operations and, at the request of the parties, to operations under any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of nuclear energy.

The following bodies oversee the development of safety standards: the Commission on Safety Standards (CSS); the Nuclear Safety Standards Committee (NUSSC); the Radiation Safety Standards Committee (RASSC); the Transport Safety Standards Committee (TRANSSC); and the Waste Safety Standards Committee (WASSC). Member States are widely represented on these committees.

In order to ensure the broadest international consensus, safety standards are also submitted to all Member States for comment before approval by the IAEA Board of Governors (for Safety Fundamentals and Safety Requirements) or, on behalf of the Director General, by the Publications Committee (for Safety Guides).

The IAEA's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The standards are binding on the IAEA in relation to its own operations and on States in relation to operations assisted by the IAEA. Any State wishing to enter into an agreement with the IAEA for its assistance in connection with the siting, design, construction, commissioning, operation or decommissioning of a nuclear facility or any other activities will be required to follow those parts of the safety standards that pertain to the activities to be covered by the agreement. However, it should be recalled that the final decisions and legal responsibilities in any licensing procedures rest with the States.

Although the safety standards establish an essential basis for safety, the incorporation of more detailed requirements, in accordance with national practice, may also be necessary. Moreover, there will generally be special aspects that need to be assessed on a case by case basis.

The physical protection of fissile and radioactive materials and of nuclear power plants as a whole is mentioned where appropriate but is not treated in detail; obligations of States in this respect should be addressed on the basis of the relevant instruments and publications developed under the auspices of the IAEA. Non-radiological aspects of industrial safety and environmental protection are also not explicitly considered; it is recognized that States should fulfil their international undertakings and obligations in relation to these.

The requirements and recommendations set forth in the IAEA safety standards might not be fully satisfied by some facilities built to earlier standards. Decisions on the way in which the safety standards are applied to such facilities will be taken by individual States.

The attention of States is drawn to the fact that the safety standards of the IAEA, while not legally binding, are developed with the aim of ensuring that the peaceful uses of nuclear energy and of radioactive materials are undertaken in a manner that enables States to meet their obligations under generally accepted principles of international law and rules such as those relating to environmental protection. According to one such general principle, the territory of a State must not be used in such a way as to cause damage in another State. States thus have an obligation of diligence and standard of care.

Civil nuclear activities conducted within the jurisdiction of States are, as any other activities, subject to obligations to which States may subscribe under international conventions, in addition to generally accepted principles of international law. States are expected to adopt within their national legal systems such legislation (including regulations) and other standards and measures as may be necessary to fulfil all of their international obligations effectively.

EDITORIAL NOTE

An appendix, when included, is considered to form an integral part of the standard and to have the same status as the main text. Annexes, footnotes and bibliographies, if included, are used to provide additional information or practical examples that might be helpful to the user.

The safety standards use the form 'shall' in making statements about requirements, responsibilities and obligations. Use of the form 'should' denotes recommendations of a desired option.

The English version of the text is the authoritative version.

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1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide was prepared under the IAEA programme for safety standards for nuclear power plants. It is a revision of the Safety Guide on Design of the Reactor Containment Systems in Nuclear Power Plants (Safety Series No. 50-SG-D12) issued in 1985 and supplements the Safety Requirements publication on Safety of Nuclear Power Plants: Design [1]. The present Safety Guide was prepared on the basis of a systematic review of the relevant publications, including the Safety of Nuclear Power Plants: Design [1], the Safety Fundamentals publication on The Safety of Nuclear Installations [2], Safety Guides [3–5], INSAG Reports [6, 7], a Technical Report [8] and other publications covering the safety of nuclear power plants.

1.2. The confinement of radioactive material in a nuclear plant, including the control of discharges and the minimization of releases, is a fundamental safety function to be ensured in normal operational modes, for anticipated operational occurrences, in design basis accidents and, to the extent practicable, in selected beyond design basis accidents (see Ref. [1], para. 4.6). In accordance with the concept of defence in depth, this fundamental safety function is achieved by means of several barriers and levels of defence [6]. In most designs, the third and fourth levels of defence are achieved mainly by means of a strong structure enveloping the nuclear reactor. This structure is called the ‘containment structure’ or simply the ‘containment’. This definition also applies to double wall containments.

1.3. The containment structure also protects the reactor against external events and provides radiation shielding in operational states and accident conditions. The containment structure and its associated systems with the functions of isolation, energy management, and control of radionuclides and combustible gases are referred to as the containment systems.

OBJECTIVE

1.4. Requirements for the design of containment systems are established in Section 6 of Ref. [1]. The objective of this Safety Guide is to make recommendations on the implementation and fulfilment of these requirements. It is expected that this publication will be used primarily for land based, stationary

nuclear power plants with water cooled reactors designed for electricity generation or for other heat generating applications (such as for district heating or desalination). It is recognized that for other reactor types, including future plant systems featuring innovative developments, some of the recommendations may not be appropriate or may need some judgement in their interpretation.

1.5. This publication is intended for use by organizations responsible for designing, manufacturing, constructing and operating nuclear power plants, as well as by regulatory bodies.

SCOPE

1.6. This Safety Guide is mainly based on the experience derived from the design and operation of existing reactors, and it applies to the most common types of containment. It also includes some general recommendations for features that would be used in new nuclear power plants for dealing with a severe accident.

1.7. This Safety Guide addresses the functional aspects of the major containment systems for the management of energy, radionuclides and combustible gases. Particular consideration is given to the definition of the design basis for the containment systems, in particular to those aspects affecting the structural design, such as load identification and load combination.

1.8. Recommendations are provided on the tests and inspections that are necessary to ensure that the functional requirements for the containment systems can be met throughout the operating lifetime of the nuclear power plant.

1.9. Design limits and acceptance criteria, together with the system parameters that should be used to verify them, are specific to the design and to the individual State, and are therefore outside the scope of this Safety Guide. However, general recommendations are provided.

STRUCTURE

1.10. Section 2 concerns the safety functions of containment systems and their main features. Section 3 deals with the general design basis for containment systems. Section 4 provides recommendations for the design of containment systems for conditions in operational states and design basis accidents. Section 5 covers tests and inspections, and provides recommendations for commissioning tests and for in-service tests and inspections. Section 6 provides recommendations and guidance on the consideration given in the design phase to severe accidents.

2. CONTAINMENT SYSTEMS AND THEIR SAFETY FUNCTIONS

GENERAL

2.1. The containment systems should be designed to ensure or contribute to the achievement of the following safety functions:

- (a) Confinement of radioactive substances in operational states and in accident conditions,
- (b) Protection of the plant against external natural and human induced events,
- (c) Radiation shielding in operational states and in accident conditions.

2.2. The safety functions of the containment systems should be clearly identified for operational states and accident conditions, and should be used as a basis for the design of the systems and the verification of their performance.

CONFINEMENT OF RADIOACTIVE MATERIAL

2.3. The main functional requirement for the overall containment system derives from its major safety function: to envelop, and thus to isolate from the environment, those structures, systems and components whose failure could lead to an unacceptable release of radionuclides. For this reason, the envelope should include all those components of the reactor coolant pressure boundary,

or those connected to the reactor coolant pressure boundary, that cannot be isolated from the reactor core in the event of an accident.

2.4. The structural integrity of the containment envelope is required to be maintained and the specified maximum leak rate is required not to be exceeded in any condition pertaining to design basis accidents and it should not be exceeded in any condition pertaining to severe accidents considered in the design. This is required to be achieved by means of containment isolation, energy management and structural design (Ref. [1], paras 6.43–6.67). Features for the management of radionuclides should be such as to ensure that the release of radionuclides from the containment envelope is kept below authorized limits.

2.5. In operational states, the containment systems should prevent or limit the release of radioactive substances that are produced in the core, that are produced by neutron or gamma radiation outside the reactor core or that may leak from the systems housed within the containment envelope. Specific systems may be necessary for this purpose, such as the ventilation system, for which requirements are outlined in Ref. [1] (paras 6.93–6.95). Furthermore, the containment systems should enable the reduction of temperature and pressure within the containment when necessary.

2.6. In operational states, most containment systems are in standby mode. During plant shutdown the containment may be intentionally opened (such as via air locks, equipment hatches or spare penetrations) to provide access for maintenance work on systems and components or to provide the necessary servicing space.

2.7. The structural part of the containment envelope is usually a steel or concrete building. The containment is required to be designed to withstand the pressures, thermal and mechanically induced loads, and environmental conditions that result from the events included in the design basis (Ref. [1], para. 6.45).

2.8. Containment isolation features include the valves and other devices that are necessary to seal or isolate the penetrations through the containment envelope, as well as the associated electrical, mechanical and instrumentation and control systems. The design should be such as to ensure that these valves and other devices can be reliably and independently closed when this is necessary to isolate the containment.

2.9. The energy management features¹ should be designed to limit the internal pressures, temperatures and mechanical loading on the containment as well as those within the containment envelope to levels below the design values for the containment systems and for the equipment within the containment envelope. Examples of energy management features are: pressure suppression pools, ice condensers, vacuum chamber systems for pressure relief, structural heat sinks, the free volume of the containment envelope, the capability for the removal of heat through the containment wall, spray systems, air coolers, recirculation water in the sump, and the suppression pool and cooling systems.

2.10. The features for radionuclide management should operate together with the features for the management of energy and combustible gases and the containment isolation system to limit the radiological consequences of postulated accident conditions. Typical features for the management of radionuclides are double containment systems, suppression pools, spray systems and charcoal filters, and high efficiency particulate air (HEPA) filters.

2.11. The features for the control of combustible gases should be designed to eliminate or reduce the concentration of hydrogen, which can be generated by water radiolysis, by metal–water reactions in the reactor core or, in severe accident conditions, by interactions of molten core debris with concrete. Features used in various designs include hydrogen recombiners (i.e. passive recombiners or active igniters), large containment volumes for diluting hydrogen and limiting the hydrogen concentration, features for mixing the containment atmosphere, features for inerting and devices for ensuring that any burning of hydrogen is controlled.

2.12. Energy, combustible gases and features for radionuclide management should be evaluated on the basis of conservative estimates according to their relevance to safety functions.

2.13. Several different designs are used for containment systems. Annex I provides general guidance about the most commonly used containment designs.

¹ Features for the management of energy perform the following functions: pressure suppression, reduction in pressure and temperature of the containment atmosphere, and removal of the containment heat.

2.14. In severe accident conditions, high energetic loading could jeopardize the structural integrity of the containment. Either high energetic loading should be dealt with adequately in the containment design (Ref. [1], Section 6) or features should be incorporated for preventing or limiting such loading (see Section 6 of this Safety Guide for detailed design considerations for severe accidents).

PROTECTION AGAINST EXTERNAL EVENTS

2.15. The containment structures and systems should be so designed that all those components of the reactor coolant pressure boundary that cannot be safely isolated from the reactor core, as well as the safety systems located inside the containment that are necessary to keep the core in a safe state, are protected against the external events included in the design basis.

BIOLOGICAL SHIELDING

2.16. In operational states and in accident conditions, the containment structures contribute to the protection of plant personnel and the public from undue exposure due to direct radiation from radioactive material contained within the containment and containment systems. Dose limits and dose constraints as well as the application of the ‘as low as reasonably achievable’ principle (for the optimization of radiation protection) should be included in the design basis of the structures [1, 9, 10]. The composition and thickness of the concrete, steel and other structural materials should be such as to ensure that the dose limits and dose constraints for operators and the public are not exceeded in operational states or in the accident conditions that are considered in the design.

3. GENERAL DESIGN BASIS OF CONTAINMENT SYSTEMS

DERIVATION OF THE DESIGN BASIS

3.1. The design basis for containment systems should be derived primarily from the results of the analysis of relevant postulated initiating events, which

are defined in Appendix I of Ref. [1]. The postulated initiating events that should be considered include those of internal and external origin that could necessitate the performance by the containment of its intended functions and those that could jeopardize the capability of the containment to perform its intended safety functions.

3.2. Relevant elements of the design basis for normal operation (power operation, refuelling and shutdown) should be derived from the following requirements:

- To confine the radioactive substances produced by neutron or gamma radiation,
- To remove the heat generated,
- To provide for the necessary access and egress of personnel and materials,
- To perform containment pressure tests and leak tests,
- To contribute to biological shielding.

Internal events

3.3. Internal events that should be considered in the design of the containment systems are those events that result from faults occurring within the plant and that may necessitate the performance by the containment of its functions or that may jeopardize the performance of its safety functions. They fall essentially into five categories:

- (1) Breaks in high energy systems located in the containment: The containment should be able to withstand high pressures and temperatures, as well as pipe whips and fluid jet impacts.
- (2) Breaks in systems or components containing radioactive material located in the containment: The containment should be able to confine the radioactive material.
- (3) System transients causing representative limiting loads (e.g. pressure, temperature and dynamic loads) on the containment systems: The containment should be able to withstand these loads.
- (4) Containment bypass events such as loss of coolant accidents (LOCAs) in interfacing systems or steam generator tube ruptures: Appropriate provisions for isolation should be in place.
- (5) Internal hazards: It should be verified that internal hazards will not impair the containment functions.

3.4. Typical internal events that should be considered in the design of containment systems are as follows:

- LOCAs;
- Various failures in the steam system piping;
- Breaks in the feedwater piping;
- Steam generator tube ruptures in a pressurized water reactor;
- Inadvertent opening of a pressurizer safety valve or relief valve in a pressurized water reactor, or of a safety relief valve in a boiling water reactor;
- Condensation oscillations and ‘chugging’ of liquid–gas mixtures during blowdown in a boiling water reactor;
- Breaks in lines connected to the reactor coolant pressure boundary, inside or outside the containment;
- Leakage or failure of a system carrying radioactive liquid or gas within the containment;
- Fuel handling accidents in the containment;
- Internal missiles;
- Internal fires;
- Internal flooding.

External events

3.5. External events that should be considered in the design of containment systems are those events arising from human activities in the vicinity of the plant, as well as natural hazards, that may jeopardize the integrity and the functions of the containment. All the events that are to be addressed in the design should be clearly identified and documented on the basis of historical and physical data or, if such data are unavailable, on the basis of sound engineering judgement.

3.6. All relevant external events should be evaluated to determine their possible effects, to determine the safety systems needed for prevention or mitigation, and to assist in designing the systems to withstand the expected effects.

3.7. Typical external events that should be considered in the design of containment systems are given in Table 1. Additional guidance is provided in Ref. [4].

TABLE 1. TYPICAL EXTERNAL EVENTS TO BE CONSIDERED IN THE DESIGN OF CONTAINMENT SYSTEMS

Human origin hazards	Natural hazards
Aircraft crash	Earthquake
Explosion of a combustible fluid container (e.g. in a shipping accident, an industrial accident, a pipeline accident or a traffic accident)	Hurricane and/or tropical cyclone
	Flood
	Tornado
	Wind
	Impact of an external missile
	Blizzard
	Tsunami (tidal wave)
	Seiche (fluctuation in water level of a lake or body of water)
	Volcanic eruption
	Extreme temperature (high and low)

Design basis accidents

3.8. The results of the analysis of design basis accidents should be used in the determination of the critical design parameters.

3.9. The design basis accidents for the containment systems are the set of possible sequences of events selected for assessing the integrity of the containment and for verifying that the radiological consequences for operators, the public and the environment would remain below the acceptable limits. The design basis accidents relevant for the design of the containment systems should be those accidents having the potential to cause excessive mechanical loads on the containment structure and/or containment systems, or to jeopardize the capability of the containment structure and/or containment systems to limit the dispersion of radioactive substances to the environment.

3.10. All evaluations performed for design basis accidents should be made using an adequately conservative approach. In a conservative approach, the combination of assumptions, computer codes and methods chosen for evaluating the consequences of a postulated initiating event should provide reasonable confidence that there is sufficient margin to bound all possible

results. The assumption of a single failure² in a safety system should be part of the conservative approach, as indicated in Ref. [1], paras 5.34–5.39. Care should be taken when introducing adequate conservatism, since:

- For the same event, an approach considered conservative for designing one specific system could be non-conservative for another;
- Making assumptions that are too conservative could lead to the imposition of constraints on components that could make them unreliable.

3.11. Changes resulting from the ageing of structures, systems and components should be taken into account in the conservative approach.

3.12. All evaluations for design basis accidents should be adequately documented, indicating the parameters that have been evaluated, the assumptions that are relevant for the evaluations of parameters, and the computer codes and acceptance criteria that were used.

3.13. These evaluations should cover, but are not necessarily limited to, the following:

- The mass and energy of releases inside the containment as a function of time;
- The heat transfer to the containment structures and those to and from components;
- The mechanical loading, both static and dynamic, on the containment structure and its subcompartments;
- The releases of radionuclides inside the containment;
- The transfer of radionuclides to the environment;
- The rate of generation of combustible gases.

3.14. The time periods used in these evaluations should be sufficient to demonstrate that the safety limits have been analysed and that the subsequent evolutions of the physical parameters are known and are controllable.

3.15. Design parameters for the containment structures (e.g. design pressure and free volume) that have to be determined early in the design process, before

² A single failure is a failure which results in the loss of capability of a component to perform its intended safety function(s), and any consequential failure(s) which result(s) from it.

detailed safety assessments can be made, should incorporate significant margins.³

3.16. The mechanical resistance of the containment structure should be assessed in relation to the expected range of events and their anticipated probability over the plant lifetime, including the effects of periodic tests.

3.17. Three types of margin should be considered:

- Safety margins, which should accommodate physical uncertainties and unknown effects;
- Design margins, which should account for uncertainties in the design process (e.g. tolerances) and for ageing, including the effects of long term exposure to radiation;
- Operating margins, which are introduced in order to allow the operator to operate the plant flexibly and also to account for operator error.

3.18. Computer codes that are used to carry out evaluations of design basis accidents should be documented, validated and, in the case of new codes, developed according to recognized standards for quality assurance. Users of the codes should be qualified and trained with respect to the operation and limits of the code and with respect to the assumptions made in the design and the safety analysis.

3.19. Computer codes should not be used beyond their identified and documented domain of validation.

3.20. In considering containment systems with double walls, the potential for high energy pipe breaks in the space between the walls should be evaluated. In the event that the possibility of such breaks cannot be eliminated by design features, the internal and external shells, as well as all systems fulfilling safety functions in the annulus between the walls, should be capable of withstanding the related pressures and thermal loads, or else qualified protective features (such as guard pipes) should be installed.

³ Examples of the design margins applied in some States are as follows:

10–25% between the containment design pressure and the peak accident pressure;

15–40% at the design stage for the differential pressure across internal walls (this margin may be reduced in the as-built condition to take account of possible increases in the free area of the openings between compartments).

Severe accidents

3.21. Multiple failures in redundant safety systems could lead to their complete loss, potentially resulting in beyond design basis accident conditions and significant core degradation (severe accidents) and even threatening the integrity of the containment. Although accident sequences exhibiting such characteristics have a very low probability, they should be evaluated to assess whether they need to be considered in the design of the containment. The selection process for such sequences should be based on probabilistic evaluations, engineering judgement or deterministic considerations, as explained in Ref. [1], para. 5.31. The selection process should be well documented and should provide convincing evidence that those sequences that were screened out do not pose undue risks to operators or the public. (See Section 6 for design considerations for severe accidents.)

Design limits

3.22. The performance of containment systems should be assessed against a well defined and accepted set of design limits and acceptance criteria. ‘Well defined and accepted’ generally means either accepted by regulatory bodies in States having advanced nuclear power programmes or proposed by international organizations.

3.23. A set of primary design limits for the containment systems should be established to ensure achievement of the overall safety functions of the containment. These primary design limits are usually expressed in terms of:

- Overall containment leak rate at design pressure;
- Direct bypass leakage (for a double wall containment);
- Limits on radioactive releases, dose limits or dose constraints, specified for operational states, design basis accidents and severe accidents, in relation to the function of confinement of radioactive material;
- Dose limits or dose rate limits and dose constraints for personnel, specified for the biological shielding function.

3.24. Furthermore, design limits should be specified for each containment system as well as for each structure and component within each system. Limits should be applied to operating parameters (e.g. maximum coolant temperature and minimum flow rate for air coolers), performance indicators (e.g. maximum closing time for isolation valves and penetration air leakage) and availability

measures (e.g. maximum outage times and minimum numbers of certain items of equipment that must be available).

Codes and standards

3.25. For the design of the structures and systems of the containment, widely accepted codes and standards are required to be used (Ref. [1], para. 5.21). The selected codes and standards:

- should be applicable to the particular concept of the design;
- should form an integrated and comprehensive set of standards and criteria;
- should normally not use data and knowledge that are unavailable in the host State, unless such data can be analysed and shown to be relevant to the specific design, and the use of such data represents an enhancement of safety for the containment design.

3.26. Codes and standards have been developed by various national and international organizations, covering areas such as:

- Materials,
- Manufacturing (e.g. welding),
- Civil structures,
- Pressure vessels and pipes,
- Instrumentation and control,
- Environmental and seismic qualification,
- Pre-service and in-service inspection and testing,
- Quality assurance,
- Fire protection.

Use of probabilistic safety assessment in design

3.27. A probabilistic safety assessment should be started early in the design process. The probabilistic safety assessment should be used for identification of the core damage frequency (in a Level 1 probabilistic safety assessment) as well as for determination of plant damage states and their frequency (often called a Level 1+ probabilistic safety assessment). These probabilistic safety assessment data are significant in helping to determine the main threats to containment integrity. The probabilistic safety assessment approach is described in Ref. [1], para. 5.73.

3.28. For assessing the design of containment systems, especially with regard to mitigation of the consequences of a severe accident, the probabilistic safety assessment should be extended to Level 2 and a determination should be made of whether sufficient provision has been made to mitigate the consequences of severe accidents. The Level 2 probabilistic safety assessment would address the question of whether the containment is adequately robust and whether the mitigation systems, such as hydrogen control systems and measures for cooling a molten core, provide a sufficient level of protection to prevent a major release of radioactive material to the environment. (See Section 6 for design considerations for severe accidents.)

4. DESIGN OF CONTAINMENT SYSTEMS FOR OPERATIONAL STATES AND FOR DESIGN BASIS ACCIDENTS

GENERAL

Performance of containment systems

4.1. The performance parameters for containment systems should be established in accordance with the functions to be performed in the operational states or design basis accident conditions assumed in the design of the plant. In particular, performance in terms of structural behaviour and leaktightness should be established for the entire period of an accident, including recovery of the plant and establishment of safe shutdown conditions.

4.2. On the basis of the performance parameters, the analyses carried out for each postulated initiating event and each set of plant operating conditions should define a set of design parameters for each containment system. The strictest set of these parameters should become the design basis for each containment system. Examples of these design parameters include heat transfer rates, response times for the actuation of safety features, and the closing and opening times of valves.

4.3. Containment systems should be so designed that their instrumentation and control systems and electrical, structural and mechanical parts are compatible with each other and with other items important to safety.

4.4. Attention should be paid to accidents initiated in shutdown states (e.g. with the containment open and systems disabled for maintenance). In this condition the configuration of the containment systems may be different from their configuration under power, and attention should be paid to the redundancy levels and specific failure modes of systems and equipment. In some cases the containment may lose leaktightness because a hatch or a personnel lock has to remain open for a certain period of time. The time necessary for closure of the hatches or personnel locks should be compatible with the kinetics of the accidents postulated to occur in these conditions.

Layout and configuration of containment systems

4.5. The layout of the containment should be defined with account taken of several factors that are dealt with in this Safety Guide and that are summarized below:

- Optimization of the location of the entire primary system, with particular attention paid to the enhancement of cooling of the core by natural circulation;
- Provision of separation between divisions of safety systems;
- Provision of the necessary space for personnel access and the monitoring, testing, control, maintenance and movement of equipment;
- Placement of the equipment and structures so as to optimize biological shielding;
- Location of penetrations in areas of the containment wall so as to ensure accessibility for inspection and testing;
- Ensuring an adequate single free volume in the upper part of the containment to improve the efficiency of the containment spray (if any);
- Ensuring an adequate free volume and adequate cooling flow paths for passively cooled containments;
- Limitation of the compartmentalization of the containment volume so as to minimize differential pressures in the event of a LOCA and to promote hydrogen mixing, thus preventing the local accumulation of hydrogen.

4.6. The lower part of the containment should be designed to facilitate the collection and identification of liquids leaked, and also the channelling of water to the sump in the event of an accident. The annulus between the primary and secondary containments should form a single volume to the extent possible, in order to maximize the mixing and dilution of any radioactive material released from the primary containment in the event of an accident.

Reliability of containment systems

4.7. Containment systems should be designed to have high functional reliability commensurate with the importance of the safety functions to be performed.

4.8. The functions of containment systems should be available on demand and should remain available in the long term following a postulated initiating event until the specific safety function is no longer needed. Periodic testing of the systems should be performed in order to verify that the assumptions made in the design, including the probabilistic safety assessment if applicable, about the levels of reliability and performance are justified throughout the operating lifetime of the plant.

4.9. The single failure criterion⁴ is required to be applied to each safety group incorporated in the design (Ref. [1], para. 5.34). Containment systems that, in and after design basis accidents, perform safety functions for energy management, radionuclide management, containment isolation and hydrogen control should be designed according to the single failure criterion.

4.10. The containment structure and the passive fluid retaining boundaries of its appurtenances should be of sufficiently high quality (ensured, for example, by means of rigorous design requirements, proper selection of bounding postulated initiating events, conservative design margins, construction to high standards of quality, and comprehensive analysis and testing of performance) that the failure of the containment structure itself and the failure of the passive fluid retaining boundaries of its appurtenances need not be postulated.

4.11. The containment systems should, to the extent possible, be independent of process systems or other safety systems. In particular, the failures of other systems that have caused an accident should not prevent the containment from fulfilling its required safety functions during the accident.

4.12. Consideration should be given to the use of passive systems and intrinsic safety features, which may, in some cases, be more suitable than active systems and components.

⁴ A single failure criterion is a criterion (or requirement) applied to a system such that it must be capable of performing its task in the presence of any single failure. A single failure is a failure which results in the loss of capability of a component to perform its intended safety function(s), and any consequential failure(s) which result from it.

Environmental qualification of containment systems

4.13. The structures, systems and components of the containment systems should be qualified to perform their safety functions in the entire range of environmental conditions that might prevail during and following a design basis accident, or should otherwise be adequately protected from those environmental conditions.

4.14. Components of the containment systems that can be shown to be unaffected by the design basis accident conditions need no environmental qualification.

4.15. The environmental and seismic conditions that may prevail during and following a design basis accident, the ageing of structures, systems and components throughout the lifetime of the plant, synergistic effects, and safety margins should all be taken into consideration in the environmental qualification of the containment systems.

4.16. Environmental qualification should be carried out by means of testing, analysis and the use of expertise, or by a combination of these.

4.17. Environmental qualification should include the consideration of such factors as temperature, pressure, humidity, radiation levels, the local accumulation of radioactive aerosols, vibration, water spray, steam impingement, flooding and contact with chemicals. Margins and synergistic effects (in which the damage due to the superposition or combination of effects may exceed the total damage due to the effects separately) should also be considered. In cases where synergistic effects are possible, materials should be qualified for the most severe effect, or the most severe combination or sequence of effects.

4.18. Non-metallic materials, such as elastomeric seals and concrete, should be qualified for ageing on the basis of sample ageing tests, operating experience in the nuclear or non-nuclear industry, or published test data for the same or similar materials under the same qualification conditions. All ageing mechanisms that are significant and relevant in the expected conditions should be considered in the qualification. Techniques to accelerate the testing for ageing and qualification may be used, provided that there is proper justification. The same applies to the possibility of testing for separate effects rather than the superposition of effects.

4.19. For components subject to the effects of ageing by various mechanisms, a design life and, if necessary, the replacement frequency should be established. In the qualification process for such components, samples should be aged to simulate the end of their design lives before being tested under design basis accident conditions.

4.20. Components that have been used for qualification testing should generally not be used for construction purposes unless it can be shown that the conditions and methods of testing do not themselves lead to an unacceptable degradation of safety performance.

4.21. Qualification data and results should be documented as part of the design documentation.

Maintainability of containment systems and occupational radiation exposure

4.22. In the design and layout of containment systems, sufficient space and shielding should be provided to ensure that maintenance and operations can be carried out without causing undue radiation exposure of personnel. The point of access to the containment should be inside the controlled area and access should be subject to the approval of the radiation protection officer.

4.23. Consideration should be given to the potential exposure to radiation associated with operations that are planned to be conducted after an accident, or with operations that it may be necessary to conduct following the emergency procedures as well as with the recovery actions following an accident. Evaluations should include the consideration of access paths, such as possible open doors and hatches. If the doses due to such exposures exceed the applicable dose limits and dose constraints, additional shielding or even the repositioning of components should be considered.

4.24. Maintenance related factors considered in the containment design should include the provision of adequate working space, shielding, lighting, air for breathing, and working and access platforms; the provision and control of proper environmental conditions; the identification of equipment; the provision of hazard signs; the provision of visual and acoustic alarms; and the provision of communication systems.

Accessibility of the containment

4.25. The accessibility of both the containment and the systems contained within it should be considered for all operational states. The ability to ensure that radiation doses to operators remain within the acceptable dose limits will determine whether access can be allowed to the primary and/or the secondary containment (if applicable) during power operation, or whether plant shutdown is required for permitting such access.

4.26. If entry into the primary or secondary containment during power operation for the purposes of unplanned maintenance or even for routine (planned) maintenance is envisaged, proper provision should be made to ensure the necessary radiological protection and industrial safety of plant staff. This provision should include the application of the principle of keeping exposure as low as reasonably achievable, the provision of the necessary communication systems and alarms, and proper monitoring of the containment atmosphere, especially in the case of inerted containments or containments at subatmospheric pressure. At least two emergency escape routes from the containment should be provided. In addition, security provisions for controlling access to the containment should be considered.

Safety classification

4.27. The process of identification and classification of structures, systems and components that are items important to safety (Ref. [1], paras 5.1–5.3) directs the attention of designers, manufacturers and operators to all the features that are important for ensuring the safety of the plant and to the association of specific design requirements (e.g. the single failure criterion and appropriate codes and standards) with each structure, system and component.

4.28. Several safety classification systems for pressure retaining mechanical equipment use three nuclear safety classes and one non-nuclear safety class. The highest safety class is generally restricted to the components of the reactor coolant pressure boundary.

4.29. The containment pressure boundary, including penetrations and isolation valves, as well as pressure retaining parts of front line systems used for the management of energy and radionuclides in the primary containment during a design basis accident, are generally assigned to the second safety class.

4.30. The pressure retaining parts of systems for the management of energy and radionuclides in the secondary containment during a design basis accident, and of systems for the control of combustible gases during a design basis accident, are often assigned to the third safety class.

4.31. In so far as they are relied upon in design basis accidents, the containment systems are safety systems and should be classified as seismic class 1, the highest level of seismic classification. Electrical equipment of the containment systems, including equipment for emergency power supply, should be assigned to electrical class 1E, the highest level of safety classification for electrical instrumentation and control equipment.

Operator actions

4.32. When the containment system is challenged, there should be no need for any action to be taken by the operator within a certain 'period of grace'⁵. For any necessary manual intervention, the operator should have sufficient time to assess the conditions in the plant before taking any action. The plant design should not prevent the operator from initiating appropriate actions in response to clear and unequivocal information.

Performance of the secondary containment

4.33. The secondary containment should be able to withstand the possible pressurization of the volume between the primary and secondary containments in the event of an accident or a malfunction of the ventilation system, and should be able to withstand external loads either alone or in combination with the primary containment.

4.34. To ensure that the pressure between the primary and secondary containments is maintained below atmospheric pressure, the secondary containment and its air extraction system should be operable in the event of a loss of off-site power.

⁵ Typical periods of grace range from 20 min to 12 h. The period of grace may be achieved by means of the automation of actuations, the adoption of passive systems or the inherent material characteristics (such as the heat capacity of the containment structure), or by any combination of these.

Sharing of parts of the containment system between units

4.35. Safety of Nuclear Power Plants: Design (Ref. [1], para. 5.57) limits the sharing of structures, systems and components in multiunit plants to exceptional cases. For such exceptional cases of the sharing of structures, systems and components between units, all the safety requirements for all the reactors will apply and must be met under all operational and accident conditions.

4.36. External events such as earthquakes that could simultaneously challenge systems serving all units, or events such as the loss of off-site power that could cause the failure of systems common to the units, should be identified and considered in the design.

4.37. Compliance with safety criteria for redundancy, independence and the separation of safety systems should always be considered and any exceptions should be justified.

4.38. In the design of a multiunit plant with a shared or partly shared containment system, appropriate emergency response procedures should be followed for all units in the event that an accident in one unit necessitates the use of the containment function.

Ageing effects

4.39. The containment may be subject to several ageing phenomena such as the corrosion of metallic components, the creep of tendons and the reduction of prestressing (in prestressed containments), the reduction of resilience in elastomeric seals, and the shrinkage and cracking of concrete. The detrimental effects of ageing cannot easily be identified during the plant lifetime. All ageing mechanisms are required to be identified and taken into account in the design. Provision should be made for monitoring the ageing of the containment, for testing and inspection of components where possible, and for periodically replacing items that are susceptible to degradation through ageing (Ref. [1], para. 5.47).

Decommissioning

4.40. As established in Ref. [1], para. 5.68, attention is required to be paid to features that would assist in the final decommissioning of the plant (such as by selecting construction materials so as to reduce radioactivation during operation,

by ensuring access and by providing facilities for waste storage). In general, features intended to facilitate decommissioning will also improve plant operations and maintenance, and they should therefore be carefully assessed at the design stage (Ref. [1], para. 5.68). Guidance on these aspects is given in Ref. [11].

STRUCTURAL DESIGN OF CONTAINMENT SYSTEMS

Design process

4.41. Containment structures and appurtenances (penetrations, isolation systems, doors and hatches) should prevent unacceptable releases of radioactive material in the event of an accident. For this purpose, their structural integrity should be maintained (i.e. the structural functions of protection and support should be ensured), and it should be ensured that the leaktightness criteria are met (Ref. [1], paras 6.43–6.67).

4.42. In steel containments the load bearing and leaktightness functions are generally fulfilled by the steel structure. The metallic structure should be protected against missiles generated inside and outside the containment as a result of internal and external events that affect the plant.

4.43. All loads should be identified, quantified and properly combined in order to define the challenges to structures and components. This process should include the adoption of adequate safety margins (Ref. [1], para. 6.45).

4.44. Acceptance criteria in terms of stresses, deformations and leaktightness should be established for each load combination (Ref. [1], paras 6.48–6.50).

4.45. In choosing the design parameters and determining structural sizing, local stresses should be taken into consideration.

4.46. Design for a specific maximum leak rate is not a straightforward or purely quantitative process. A number of factors should normally be taken into account, including the limitation of stresses in accident conditions, the proper choice of components (e.g. isolation valves), the proper choice of sealing materials, limitation of the number of containment penetrations and control of the construction quality. Extant operational data, experience and practices should be used to the maximum extent practicable.

4.47. Provisions for commissioning tests and for in-service testing and inspection should be included in the design, so as to be able to demonstrate that the containment systems meet design and safety requirements.

Design pressure and design temperature

4.48. The design pressure and the design temperature are the two fundamental parameters used for determining the size of the containment structure (Tables 2 and 3).

4.49. The design pressure should be determined by increasing by at least 10% the peak pressure that would be generated by the design basis accident with the most severe release of mass of material and energy. The calculated peak pressure should be determined on the basis of conservative assumptions in relation to the thermohydraulic characteristics.

4.50. The strength of the containment structure, as tentatively determined on the basis of the design pressure and the design temperature, should be verified for all load combinations and should comply with the corresponding acceptance criteria for the integrity and leaktightness of the containment.

4.51. The design temperature should be specified as the maximum temperature to be anticipated in the structure of the containment, and should be determined by analysing all design basis accidents. The containment structure and systems should be able to maintain their functionality and specified performance when operating below the design temperature.

4.52. All values of pressure and temperature used in the load combinations should be determined with sufficient margins, which should take into account:

- Uncertainties in the amounts of fluids released and in the release rates in terms of both mass and energy, including chemical energy from metal–water reactions;
- Structural tolerances;
- Uncertainties in relation to the residual heat;
- The heat stored in components;
- The heat transferred in heat exchangers;
- Uncertainties in the correlations of heat transfer rates;
- Conservative initial conditions.

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Identification and quantification of loads

4.53. All loads (static and dynamic) that are expected to occur over the plant lifetime or that are associated with postulated design basis accidents should be identified and grouped according to their probability of occurrence, on the basis of operating experience and engineering judgement. Such loads should be specified for each component of the containment structure.

4.54. The metallic liner of the containment (where applicable) should be able to withstand the effects of imposed loads and to accommodate relative movements of the liner and the concrete of the containment without jeopardizing its leaktightness. The liner should not be credited in the structural evaluation for the resistance of the containment.

4.55. The containment structure should be designed to protect the primary pressure boundary and associated components from all the external events that were taken into account in the design.

4.56. The metallic structures, penetrations and isolation valves of the containment should be protected against the jet forces and missiles that could be generated in the course of design basis accidents, preferably by means of protective structures.

4.57. The primary containment together with its support systems should be designed to withstand the following events:

- (a) An inadvertent drop in internal pressure below atmospheric pressure during normal operations and in accident conditions (e.g. due to the inadvertent operation of a spray system); the provision of vacuum breakers would be a means to limit subpressure loads.
- (b) The pressurization of the space between the primary and the secondary containments (where applicable) in the case of a high energy line break inside that space, unless such a break is precluded by the design.

Both concerns are of particular importance for steel containments.

4.58. In Table 2 a typical set of loads on the containment that should normally be considered at the design stage is presented (its applicability to any particular design should be verified).

TABLE 2. MINIMUM SET OF LOADS ON THE CONTAINMENT TO BE CONSIDERED AT THE DESIGN STAGE

Load category	Load	Remarks
Pre-service loads	Dead	Loads associated with the masses of structures or components
	Live	Loads associated for example with component restraints
	Prestressing	Only for prestressed concrete structures
	Loads in construction	Temporary loads due to construction equipment or the storage of major components
	Test pressure	See Section 5, paras 5.15–5.31
	Test temperature	See Section 5, paras 5.15–5.31
Normal or service loads	Actuation of safety relief valve	Boiling water reactors only
	Lifting of relief valve	Boiling water reactors only
	Air cleaning of safety relief valve	Boiling water reactors only
	Operating pressure	In normal operation, including transient conditions and shutdown
	Operating temperature	In normal operation, including transient conditions and shutdown
	Pipe reactions	In normal operation, including transient conditions and shutdown
	Wind	Maximum wind speed assumed to occur over plant operating lifetime (see also Ref. [4])
	Environmental and site related loads	For example, snow load, buoyant forces due to the water table and extremes in atmospheric temperature
	External pressure	Loads resulting from pressure variations both inside and outside the primary containment
Loads due to extreme external events	Extreme wind speeds	Loads generated by extreme wind speeds, i.e. maximum wind speed that may be associated with the site
	Design basis earthquake	See also Ref. [12]

TABLE 2. MINIMUM SET OF LOADS ON THE CONTAINMENT TO BE CONSIDERED AT THE DESIGN STAGE (cont.)

Load category	Load	Remarks
	Loads associated with extreme wind speeds	Associated missiles to be considered
	Aircraft crash	See also Ref. [4]
	External explosion	See also Ref. [4]
	DBA ^a pressure	Calculated peak pressure in an accident
	DBA temperature	Calculated peak temperature in an accident
	DBA pipe reactions	See also Ref. [13]
	Jet impingement and/or pipe whip	See also Ref. [13]
	Local effects consequential to a DBA	See also Ref. [13]
	Dynamic loads associated with a DBA	Loads are design dependent (e.g. for a boiling water reactor design: discharge line clearing loads, pool swell, condensation oscillation and discharge line ‘chugging’)
Loads due to accidents	Actuation of the depressurization system	Depressurization of the primary circuit (where applicable)
	Internal flooding	See also Ref. [13]

^a DBA, design basis accident.

Load combination and acceptance criteria

Load combination

4.59. Identified loads should be combined with account taken of:

- Load type (i.e. static or dynamic, global or local);
- Whether loads are consequential or simultaneous (e.g. LOCA pressure and temperature loads);

- Time history of each load (to avoid the unrealistic superposition of load peaks if they cannot occur coincidentally);
- Probability of occurrence of each load combination.

4.60. In general, load combinations for normal operations and for design basis accidents are taken into account in the relevant design codes. The inclusion of selected severe accidents in the load combination should be considered (para. 6.8).

4.61. At the end of the analysis the number of load combinations may be reduced by grouping them appropriately. The analysis will be performed only for the most demanding cases.

Acceptance criteria

4.62. For each load combination, appropriate acceptance criteria should be determined in terms of allowable stresses, deformations and leaktightness, where applicable. Definitions of allowable stresses and deformations are specific to each design standard and to each type of containment material.

4.63. Codes for the structural design of containment systems provide allowable stress limits for the ‘design’ load combination and test stress limits for the ‘test’ load combination (Table 3). Acceptance criteria for these load combinations should be derived from the structural design code applied.

4.64. For all other load combinations, acceptance limits should be defined according to the expected performance. Design margins should be provided by either:

- Limiting stresses to some fraction of the ultimate limit for that material;
or
- Use of the load factor approach (i.e. increasing the applied loads by a certain factor).

4.65. A limited number of acceptance criteria (levels) should be defined for structural integrity and leaktightness as proposed below. This approach is general and applicable to containments of all types.

4.66. For the structural integrity of the containment, the following levels should be considered:

TABLE 3. LOAD COMBINATIONS AND ACCEPTANCE CRITERIA

Load description	Design	Test	Normal					SL-2 ^a	External pressure	SL-2 plus DBA ^b	DBA	Aircraft crash	External explosion
			Normal operation	Normal operation plus extreme wind speed									
Dead	×	×	×	×	×	×	×	×	×	×	×	×	×
Live	×	×	×	×	×	×	×	×	×	×	×	×	×
Prestressing (if applicable)	×	×	×	×	×	×	×	×	×	×	×	×	×
Test pressure		×											
Test temperature		×											
Design pressure	×												
Design temperature	×												
Operating loads			×	×	×	×	×	×	×			×	×
Operating temperature			×	×	×	×	×	×	×			×	×
Pipe reactions			×	×	×	×	×	×	×			×	×
Extreme wind				×									
External pressure								×					
SL-2 earthquake						×				×			

TABLE 3. LOAD COMBINATIONS AND ACCEPTANCE CRITERIA (cont.)

Load description	Design	Test	Normal				DBA ^b	Aircraft crash	External explosion
			Normal operation	operation plus extreme wind speed	SL-2 ^a pressure	SL-2 plus DBA			
DBA pressure						×	×		
DBA temperature						×	×		
DBA pipe reactions	×					×	×		
Aircraft crash								×	
External explosion									×
Acceptance criteria for structural integrity (limit states)	Design allowable stress	Test stress limits	I	I	II	II	I	II	II
Acceptance criteria for leaktightness (limit states)	Design allowable leaktightness	I	I	I	II	II	I	N/A	N/A

^a SL-2, seismic level 2.

^b DBA, design basis accident.