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Design of Reactor Containment Systems for Nuclear Power Plants

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DESIGN OF REACTOR CONTAINMENT SYSTEMS FOR NUCLEAR POWER PLANTS

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SAFETY GUIDE

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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.

CONTENTS

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 features[1] 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 failure[2] 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.

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[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 criterion[4] 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.

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[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.

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[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.

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
	Extreme wind speeds	Loads generated by extreme wind speeds, i.e. maximum wind speed that may be associated with the site
Loads due to extreme external events	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 coincidently);
— 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 operation	Normal operation plus extreme wind speed	SL-2[a]	External pressure	SL-2 plus DBA[b]	DBA	Aircraft crash	External explosion
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 operation	Normal operation plus extreme wind speed	SL-2[a]	External pressure	SL-2 plus DBA	DBA[b]	Aircraft crash	External explosion
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	II	I	II	II
Acceptance criteria for leaktightness (limit states)	Design allowable leaktightness	I	I	I	II	II	N/A	I	N/A	N/A

[a] SL-2, seismic level 2.
[b] DBA, design basis accident.

— Level I: elastic range. No permanent deformation of, or damage to, the containment structure occurs. Structural integrity is ensured with large margins.
— Level II: small permanent deformations. Local permanent deformations are possible. Structural integrity is ensured, although with margins smaller than those for Level I.
— Level III: large permanent deformations. Significant permanent deformations are possible, and some local damage is also expected. Normally this level is not considered in analysing design basis accidents (see paras 6.8–6.11 for consideration of severe accidents).

4.67. For leaktightness, the following levels should be considered:

— Level I: leaktight structure. Leakages from the containment are below the design value and can be correlated with the internal pressure.
— Level II: possible limited increase of leak rate. The leak rate may exceed the design value, but the leaktightness can be adequately estimated and considered in the design.
— Level III: large or very large increase of leak rate. Leaktightness cannot be ensured owing to large deformations of the containment structure. Structural integrity may still be ensured.

4.68. Acceptance levels for structural integrity and leaktightness should be indicated for each load combination included in the design basis. The acceptance levels should be selected according to the expected performance determined by safety considerations.

Correlation of load combination and acceptance criteria

4.69. Table 3 presents a minimum set of recommended load combinations for a typical pressurized water reactor. Their applicability should be checked and the list modified or new lists created for specific applications, with account taken of the actual features of the design. For example, design specific load tables may be needed for penetrations, air locks or hatches. Load combinations for selected severe accidents are not included in the table (for a discussion of severe accidents, see Section 6). Table 3 also shows the recommended acceptance criteria for each load combination.

4.70. Loads resulting from an SL-2[6] earthquake [14] and design basis accidents should be combined, although one cannot realistically be a consequence of the other since the pressure boundary is designed to withstand an SL-2 earthquake.[7]

Local stresses and fatigue

4.71. Localized stress distributions, including those at welding sites, and their effects on the mechanical performance of structures, including leak rates, should be evaluated.

4.72. For prestressed concrete containments, particular attention should be paid to identifying areas of low prestressing (such as areas surrounding large penetrations and transition zones between cylinder and basemat), so that measures can be taken to avoid fractures and leakage due to concrete creep and shrinkage. In these critical areas, if the containment has no internal liner, leaktightness should be ensured by means of a local coating, local injection of sealing products or other appropriate methods.

4.73. For containments provided with a metallic liner, the zones of anchorage of the liner to the concrete and the connections of the liner to other metallic structures such as penetrations are also critical areas. Local effects of stress in these zones should be analysed and taken into account.

4.74. The assessment of the susceptibility of structures to fatigue should be made on the basis of a complete evaluation of the stresses and cycling, including pressure cycling for testing, temperature cycling and pipe reactions.

Ultimate capability and failure mode

4.75. An analysis should be performed to identify the ultimate capability of the containment. The bulk behaviour of the containment structure under static (pressure, temperature and actions of pipes) and dynamic (seismic) loads

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[6] A seismic level 2 (SL-2) earthquake corresponds directly to ultimate safety requirements. The level of ground motion associated with such an earthquake is required to have a very low probability of being exceeded over the plant lifetime. It represents the maximum level of ground motion to be assumed for design purposes.

[7] In some States this combination is not required; in other States, leaktightness of the containment is required to be ensured for the maximum DBA pressure combined with one half of the earthquake loads.

should be considered, and proper attention should be paid to local effects such as penetrations and structural singularities.

4.76. Failure modes such as liner tearing, penetration failures and tendon failures should be analysed. To the extent possible, a failure should not be catastrophic and should not cause additional damage to systems and components for retaining radioactive material.

4.77. It should be demonstrated in the analysis that the acceptance criteria for structural integrity and leaktightness of the containment are met with an adequate margin so as to avoid ‘cliff edge’ effects[8].

Design of structures within the containment

4.78. Consideration should be given to the possibility of large releases of mass and energy, and the need for the internal structures to withstand the pressure differentials that could arise between different compartments so as to prevent any collapse. For each compartment, the most unfavourable location for a break should be considered. Openings between compartments should be considered by means of a conservative approach at the design stage and should be verified to be free of unintended obstructions after construction has been completed.

4.79. Consideration should be given to the need for the internal structures to withstand the loadings associated with design basis accidents, and so to withstand the hydrodynamic loads that are caused by water flowing from the discharge line of the safety valves and the relief valves into the suppression pool, the swelling of the pool water, the oscillation of condensate water, chugging and any other relevant hydraulic phenomena.

Design of the secondary containment (if applicable)

4.80. Reinforced concrete structures are generally used for the outer wall of double wall containments. The leak rate for the outer wall should be low enough to ensure that there is an underpressure in the annulus for the purposes of leak collection. The maximum leak rate should be defined with account

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[8] A ‘cliff edge’ effect is an instance of severely abnormal plant behaviour caused by an abrupt transition from one plant status to another following a small deviation in a plant parameter, and so a discontinuity in the first derivative of the response to a small variation in an input.

taken of the most severe loads in the annulus associated with design basis accidents and of external environmental parameters (especially extreme wind speeds). The secondary containment structure should be designed to prevent the direct impact of external missiles onto the primary containment, or at least to limit the associated loads.

Structural design of containment systems

4.81. For containment systems, a set of representative loads and load combinations, as well as a set of adequate acceptance criteria, should be established by a similar procedure as for the containment structures, with account taken of the relevant design basis accidents.

ENERGY MANAGEMENT

General

4.82. Energy management is a term used to describe the management of those design features of the containment that affect the energy balance within the containment and thereby play a part in maintaining pressure and temperature within acceptable limits. The elements for energy management used in water cooled reactors of extant and new designs are as follows:

(a) Inherent energy management features (e.g. the free volume of the containment and structural heat sinks),
(b) Spray systems,
(c) Air cooler systems,
(d) Suppression pool systems,
(e) Ice condenser systems,
(f) Vacuum pressure reduction systems,
(g) External recirculation cooling systems,
(h) Passive containment cooling systems.

4.83. Active components of the systems for energy management that are normally in the standby mode during normal operation should be testable.

Control of pressure and temperature during plant operation

4.84. During normal plant operation, a ventilation system should be operated to maintain the pressure, temperature and humidity in the containment atmosphere within the limits specified in the design on the basis of the assumptions and results of the safety analysis. These limits should be in compliance with the equipment qualification parameters. Appropriate monitoring of the activity of the exhausted air and appropriate filtering should be provided.

4.85. In some designs the need may arise for a periodic purging of air because of the buildup of pressure caused by leaks from instruments and service air systems. In this case, appropriate monitoring of the content of radioactive material of the exhausted air and appropriate filtering should be provided.

Control of pressure and temperature in design basis accidents

4.86. Various types of energy management system are used for different types of containment (Annex I). The design performance of the systems for energy management should be established so as to be able in the event of an accident to reach a stable state, with the containment depressurized, within a reasonable period of time (typically a few days) after its onset.

4.87. The containment design should not depend on venting as a means of maintaining structural integrity in any design basis accident condition.

Inherent energy management features

4.88. The free volume of the space within the containment envelope is the primary physical parameter determining peak pressures after postulated pipe rupture events. It can thus be used as an inherently safe and reliable design feature. If the volume of the containment is subdivided into compartments that are provided with collapsing panels or louvres that open in the event of LOCAs, these collapsing panels or louvres should be designed to open quickly at the predetermined pressure so as to achieve fast equalization of the pressures in the various compartments and to utilize the full free volume of the containment.

4.89. The containment structure and its internal structures, as well as the water stored within the containment, act as a passive heat sink. In the postulated conditions of a pipe rupture accident, the rate of transfer of heat to structures is an important parameter in determining pressures and temperatures. The primary mechanism for heat transfer is the condensation of steam on exposed surfaces, and the thermal conductivity of the structure plays an important part in determining the rate of heat transfer. All conditions that could affect the transfer of heat to the structures, such as the effects of coatings or gaps, should be considered in a conservative manner in the design, and adequate margins should be applied.

Containment spray systems

4.90. The energy management function of the spray system is to remove thermal energy from the containment atmosphere in order to limit both the maximum values and the time durations of the high pressures and temperatures within the containment envelope following a design basis accident.

4.91. Containment spray systems should be designed so that a major fraction of the free volume of the containment envelope into which the steam may escape in an accident can be sprayed with water after a LOCA. For ice condenser containments, consideration should be given to installing spray systems in both the upper and the lower compartments (para. 4.110).

4.92. The spray headers and nozzles should be designed to provide an even distribution of water droplets, which should be small enough to reach thermal equilibrium with the containment atmosphere quickly during their fall.

4.93. The initial source of water for the containment spray system after a pipe rupture is usually a large storage tank. Later the spray system may operate in a recirculation mode and take water from appropriate collection points in the containment sump or the suppression pool. In determining the necessary capacity of these collection points, the need to protect equipment important to safety by preventing its submergence or by ensuring its operability despite its submergence should be taken into account in the design. Where this is not feasible the equipment should be relocated.

4.94. When the spray system is designed to operate in a recirculation mode, the spray nozzles should be designed against clogging by the largest postulated pieces of debris that can reach them through the intake screens. In the same way, the spray pumps should be designed to cope with cavitation or failure due to debris in the pump suction lines.

4.95. The pressure limiting effect of spray systems may depend on the time necessary for spray to be delivered after a LOCA. The delay time for spray delivery should therefore be determined for use in analyses of containment pressure and temperature transients. The actuation times of components and the time necessary to fill the spray piping, headers and nozzles should be taken into account in the analyses.

Air cooler systems

4.96. In LOCA conditions, containment air cooling systems may operate largely in the condensing heat transfer mode. Appropriate analytical correlations of heat transfer rates with temperatures, pressures and steam content should therefore be used in the design and for the testing.

4.97. The evolution of the atmospheric density during a design basis accident should be taken into account in the design of the air cooler fans. The heat removal capacity of the cooling water supplied to the air coolers should be such as to preclude boiling on the coolant side. In addition, the cooling water system for the air coolers should be designed to allow the resumption of cooling water flow following a temporary interruption to that flow.

Pressure suppression pool systems

Bubble condenser suppression pool systems

4.98. Containments of a design with a suppression pool system are divided into two separate compartments called the dry well (which contains the reactor) and the wet well (which contains the suppression pool). The two compartments are normally isolated from one another. When the pressure in the dry well is sufficiently higher than the pressure in the wet well, steam and gases flow from the dry well to the wet well and the steam condenses into the pool of water. In some designs, communication between the dry well and the wet well can also occur if the pressure in the wet well is higher than the pressure in the dry well. In the containments of some designs the suppression pools are also used to collect the steam discharged from the safety valves or the relief valves, or to provide water for recirculation in the emergency core cooling system. Complex hydraulic and pressure transients occur when steam and gases are vented into the suppression pool water. The design of the dry and wet wells should be such that the hydraulic responses and the dynamic loads can be reliably determined by analysis and tests.

4.99. The hydraulic response and the loading function associated with various likely combinations of normal operating events and anticipated operational occurrences should be determined.

4.100. The structural design of the pressure suppression pool system should be such as to ensure that the pool, as well as the containment system as a whole and other safety systems, remains functional in all operational states and/or all postulated accident conditions.

4.101. The pressure suppression pool system should be designed in such a way that the pathway for steam and gases from the dry well to enter the wet well following a postulated LOCA is through submerged vents in the wet well water pool.

4.102. The leakage between the dry well and the wet well that bypasses the submerged venting lines should be minimized and should be taken into account in the design.

4.103. The use of the pressure suppression pool system for other functions should not impair the performance of its main function of providing a means of control in LOCAs.

4.104. The dry well should be designed to withstand, or should be protected from (e.g. by automatic vacuum breaker valves), excessive underpressure caused by operation of the spray system either inadvertently or following a LOCA.

Jet condenser suppression pool systems

4.105. Jet condensers are pressure suppression devices installed to cope with LOCAs. Condensation of steam released from the reactor cooling circuits is achieved by direct contact with and/or mixing with cold water in a mixing chamber of the condenser. The condenser is often located in a water pool that is also used for other purposes, for example as an emergency water tank. Construction of the condenser should be such as to ensure that the mixing and condensation processes take place in the upper part of the condenser, and that warm condensate is released to the top of the water pool while the cold water necessary for condensation is drawn from the bottom of the pool.

4.106. Jet condensers should have the following characteristics:

— The design should be such as to enable the containment structure to withstand thermal loads and pressure loads throughout a design basis accident, including those during the very first few seconds.

— Mixing and condensation should be localized in the condenser, without affecting the walls and equipment in the large water pool.
— The entire volume of water available for pressure suppression should be used effectively.
— The condenser should work efficiently over the wide range of mass flow rates of steam to be condensed.
— Condensation of steam should be stable, without large oscillations, as a result of needing only a low pressure differential for maintaining the flow through the condenser.
— The formation and rapid condensation of large steam bubbles, which could cause pressure waves in the water pool, should be avoided.
— The carryover of water from the water pool into the venting line should be minimized.

Ice condenser systems

4.107. The ice condenser containment is divided into three main compartments: a lower section, an upper section and the ice condenser chambers. After a high energy pipe rupture, a flow path from the lower compartment to the upper compartment through the ice condenser is established. When the high pressure steam–air mixture flows between the columns of borated ice, the steam condenses on the surface ice. If the flow of steam continues for an extended period of time, a complete meltdown of the ice will occur. Long term energy management should then be performed by some other means, for example by containment spray systems.

4.108. The design of the ice condenser system should be such as to ensure that:

— The rate of heat transfer from the steam to the ice columns is sufficient in all postulated accident conditions (i.e. that the ice loading is sufficient).
— The structures of the ice condensers maintain their geometry under any accident loading.
— The vent doors open reliably.

4.109. The heat transfer correlations used in the calculations for the ice condenser system should be based on representative tests.

4.110. The ice condenser should be designed to permit periodic maintenance, inspection and testing. The important features of the ice condenser that should be maintained during operation are the ice temperature, the total amount of ice, the uniformity of distribution of the ice, the adequacy of the flow passages between the ice columns and the operability of the vent doors. The long term behaviour of the containment systems should be considered in the design. In the course of an accident, air and non-condensable gases will flow into the upper compartment while the lower compartment becomes filled with steam. Thus the containment spray, if injected into the upper compartment only, will not reduce the pressure below a certain limit, which will depend on the ratio of the volumes of the compartments. If equipment is installed for direct energy management for the lower compartment, a vacuum relief system of an appropriate design to eliminate pressure differentials between the two compartments should be included.

Vacuum pressure reduction systems

4.111. For designs in which the pressure of the containment is lower than atmospheric pressure, a pressure relief system, a vacuum building and associated vacuum equipment provide the front end energy management, to relieve the pressure generated in the reactor building by a LOCA. The pressure relief valves isolating the vacuum building respond to an increase of pressure by opening to connect the reactor building to the vacuum building via ducts; the steam–air mixture resulting from a LOCA is thus drawn into the vacuum building. In some designs, panels are provided to isolate each reactor building from the common duct in normal operation and to open if the pressure in the reactor building rises. The panels should open reliably and should have an adequate flow area. The vacuum system should be capable of maintaining the vacuum at the design value. The design of the pressure relief valves should be such as to ensure that:

— The vacuum building is isolated from the pressure relief duct in normal operation;
— In the event of any pipe break in the reactor coolant system, a sufficient flow area is opened to prevent pressurization of the reactor buildings and the relief duct beyond their design pressure;
— The overpressure can be relieved fast enough to keep radioactive releases from the containment below specified limits;
— A sufficient filtered vent flow of a controllable nature is provided to return the containment promptly to operation at subatmospheric pressure.

External recirculation cooling

4.112. Some energy management systems use the external recirculation of sump water or wet well water through heat exchangers to remove the residual heat from the containment over the medium term (after about one hour). These external recirculation loops are part of the containment envelope. They should be subject to specifications for structural integrity and leaktightness comparable with those of the containment structure itself.

4.113. The specification of the volume of water to be stored in the sump and the design of the suction points should be such that an adequate net pump suction head will be available to the recirculation pumps at any time. The possibility of water boiling in the sump should be considered in the design of the recirculation system if relevant.

4.114. The recirculation loops and their support systems should be redundant so as to satisfy the single failure criterion, and they should be spatially separated so as to reduce the potential for common cause failure. The devices at which suction takes place should be designed to minimize cavitation and to prevent the ingress of foreign material (such as thermal insulation), which could block or damage the recirculation system.

4.115. To avoid the clogging of screens and filters, special care should be taken in the design of piping, component insulation and the intake screens and filters themselves, and consideration should be given to the behaviour under accident conditions of organic paints and coating materials.

4.116. The recirculation loops should be equipped with leakage detection and isolation devices outside the containment and close to the containment penetrations so as to be able to isolate any leaks in the external recirculation loops and therefore to maintain a sufficient water inventory for cooling. Any leakage between the containment penetration and the isolation valve should be prevented by design, for example (a) by means of the provision of a guard pipe or by locating the isolation valve close to the penetrations; (b) by means of quality control in the production of devices to prevent leaks. Strict inspections, maintenance and test controls should be instituted.

4.117. An intermediate cooling system should be provided for heat transport to the ultimate heat sink. This cooling system should be equipped with features to detect and isolate leaks within the recirculation loop heat exchangers. This system should be classified as a safety system.

4.118. Some containment designs do not make use of containment atmosphere cooling systems such as spray or air cooler systems. In the event of a LOCA, they rely on passive heat dissipation and on the release of steam from the reactor coolant systems to the containment atmosphere, limited in time by means of safety injection systems (especially hot leg injection) of appropriate designs. In such cases, it should be demonstrated that energy management for the containment in the medium term and long term can be provided by means of sump recirculation cooling performed by the safety injection system.

4.119. The design of the safety injection system should be such that the release of steam from a broken pipe is sufficiently limited in time, with account taken of the available passive heat sinks provided by the containment and its internal structures.

Passive containment cooling systems

4.120. In some containments with a steel shell, heat released in the containment under accident conditions can be removed passively through the containment walls. The secondary containment is designed to remove the heat by providing a natural circulation path for air (the chimney effect) and a means for passive spraying of the outside of the primary containment. Other containments introduce passive cooling condensers that transfer the heat by means of natural convection to a water pool. If such passive containment cooling is adopted, the following aspects should be considered:

(a) The area of the cooling surface should be sufficient to transfer the heat generated in the containment and to cool down the atmosphere and the structures inside the containment. The heat transfer coefficient should be conservatively determined for all operational states.
(b) The necessary natural circulation within the containment and that to the outside heat sink should be ensured for all relevant design basis accidents.
(c) The entire system should be well validated by means of tests and analyses. A thorough search should be conducted for possible harmful effects and failure modes, in order to achieve a high degree of confidence that the safety functions will be fulfilled in all design basis accidents.

Containment source term

4.121. To assess the overall containment performance and in particular the measures for radionuclide management, the amount and isotopic composition of the radionuclides postulated to be released from the containment (the source term) should be assessed for the various accidents to be considered. For design basis accidents, this should be done by means of a conservative analysis of the expected behaviour of the core and of the safety systems. Consideration should be given to the most pessimistic initial conditions for the relevant parameters (e.g. for the inventory of radionuclides in systems and for leak rates) within the framework of the allowable limits specified in the technical specifications for the plant.

4.122. The anticipated evolution of the physicochemical forms of the radionuclides in the containment should be assessed, with account taken of the latest knowledge (e.g. it is known that certain paints enhance the production of organic iodine).

4.123. Once iodine is trapped in water pools inside the containment, it may revolatilize in the medium to long term if appropriate pH conditions are not maintained. It is therefore necessary to assess all conditions that could change the pH of the water pools during an accident and, if necessary, provide the necessary means to keep the water pools alkaline.

Leaktightness of the containment

4.124. An effective way to restrict radioactive releases to the environment is to maintain the leak rate below conservative specified limits throughout the plant's operating lifetime[9]. As a minimum, leak rates should be small enough to ensure that the relevant dose limits are not exceeded during normal operations or in accident conditions.

4.125. At the design stage, a target leak rate should be set that is well below the safety limit leak rate, i.e. well below the leak rate assumed in the assessment

[9] Examples of such limits that are applied in Member States are: 0.25–0.5% overall leakage of the contained mass of free gas and steam per day at design pressure for steel containments or concrete containments with a steel liner; 1.0–1.5% per day overall leakage for prestressed concrete containments without a steel liner.

of possible radioactive releases arising from accidents. This margin is useful to reduce the likelihood that unforeseen modifications made at the stage of design or construction cause an actual leak rate to approach the safety limit leak rate.

4.126. To limit the number of leak paths, the number of penetrations should be kept as low as possible. The external extensions of the penetrations should be installed in a confined building, at least until the first isolation valve, in order to collect and filter any leaks before a radioactive release occurs.

4.127. Leak rates of isolation devices, air locks and penetrations should be specified with account taken of their importance to safety and the integral leaktightness of the containment.

4.128. A reliable actuation system for containment isolation should be incorporated, as described in paras 4.169–4.183 and 4.225–4.230, to ensure the leaktightness of the containment in the event of an accident.

4.129. Additional measures to eliminate possible leakage paths should be considered if necessary. For example, some designs use a pressurization system that injects a fluid (water or nitrogen) between isolation valves in series (in which case at least three valves are necessary to cope with a single failure).

Reduction in airborne radionuclides

General

4.130. As an application of the defence in depth concept, and in addition to the measures taken to ensure the leaktightness of the containment, measures should be taken to reduce the inventory of radionuclides in the containment atmosphere.

4.131. In general, a single system is not sufficient for reducing the concentrations of radionuclides, and multiple systems are usually employed. Methods used for the reduction of airborne radionuclides in water cooled reactors of extant and new designs are:

(a) Deposition on surfaces,
(b) Spray systems,
(c) Pressure suppression pools,
(d) Ventilation systems.

4.132. As long as active systems for the reduction of the concentrations of airborne radionuclides are in the standby mode in normal operation, they should be testable.

Deposition on surfaces

4.133. The containment structure and its internals provide the first mechanisms for the removal of airborne radioactive material, since they present a large surface area for deposition. The plate-out and desorption factors ascribed to the containment structure should be conservatively based on the best available knowledge of deposition of radionuclides on surfaces. The surfaces of the containment and its internal structures should be decontaminable to the greatest extent possible.

Containment spray system

4.134. The radionuclide management function of the containment spray system is intended to reduce amounts of airborne radioactive substances by removing them from the containment atmosphere and retaining them in the water of the containment sump or the suppression pool. This serves to limit any radiological consequences resulting from leakage of radioactive material from the containment to the atmosphere in postulated accident conditions.

4.135. Important parameters and factors that should be considered in the design of the containment spray system include spray coverage, spray drop size, drop residence time and the chemical composition of the spray medium. Chemicals should typically be added to the spray water to enhance the removal of radionuclides from the atmosphere. Radioiodine is of particular importance, because of its potential consequences in terms of high specific doses. The chemical additive system should be designed to maximize the dissolution of radioiodine and to maintain the sump chemistry or the suppression pool chemistry such that radioiodine will not be released from solution in the long term following an accident.

4.136. Any chemicals added should be non-corrosive for the materials present in the containment, both in the short term and in the long term after an accident. Corrosion might not only reduce the strength of vital structural components and impair the operation of safety systems but might also generate combustible gases and other undesirable compounds.

4.137. The design of the containment spray systems should be such as to ensure that the probability of spurious actuation is low.

Pressure suppression pool

4.138. Water pools or tanks through which the containment atmosphere is bubbled for steam condensation should be considered a valuable means for the removal of radioactive products. However, care should be taken in evaluating the efficiency of such a process, since it is dependent on the thermodynamic conditions of water and steam. For example, the degree of subcooling of the water and the consequent efficiency of steam condensation have a significant effect on the scrubbing efficiency of a suppression pool.

Ventilation and venting systems

4.139. Where ventilation systems are used for cleaning exhaust air to mitigate the consequences of an accident, filters should be so designed and maintained as to preclude any loading of the filters with pollutants beyond authorized limits prior to their use in relation to an accident.

4.140. The ventilation system should, if necessary, be provided with equipment (such as moisture separators and preheaters before the filters) to prevent the temperature from dropping below the dew point at the air filter inlet.

4.141. The efficiency of the sorption material in iodine filters should be demonstrated in laboratory tests under simulated accident conditions as deemed appropriate. Provisions should be made to test periodically the filter system in situ.

4.142. Ventilation systems are often used to collect, filter and discharge air from the interspace of double containment systems or from a secondary confinement, which may become contaminated with airborne radionuclides in accident conditions as a result of leakage from the containment. For such cases the recommendations in paras 4.139–4.141 apply.

4.143. Where containment venting systems are installed, the discharge should be filtered to control the release of radionuclides to the environment [15]. Typical filter systems include sand, multi-venturi scrubber systems, HEPA or charcoal filters, or a combination of these. HEPA, sand or charcoal filters may not be necessary if the air is scrubbed in a water pool.

4.144. Noble gases cannot be filtered out, but consideration should be given to the use of systems to delay their release until further radioactive decay has occurred.

Containment bypass

4.145. Containment bypass events arise when a fault sequence allows primary coolant and any accompanying fission products to escape to the outside atmosphere without being processed by containment systems for the management of energy, radionuclides and combustible gases. In interfacing system LOCAs, valves isolating the low pressure piping fail and the piping connected to the reactor coolant system fails outside the containment. Possible paths for interfacing system LOCAs should be eliminated as far as possible, either by relocating the system in the containment or by increasing the design pressure of the low pressure system above the pressure of the reactor coolant system. For any remaining possible paths for interfacing system LOCAs, the provisions for isolation between the high pressure system and the low pressure system should be as reliable as is practicable.

4.146. In pressurized water reactors, a steam generator tube rupture is a containment bypass event that could lead to significant releases of radioactive material. Preventive design features should be installed in steam generators to reduce the frequency of such events to a very low value. The design of the plant should allow isolation of the containment bypass due to the damaged steam generator to be achieved before the authorized limits on radioactive discharges to the environment are reached [15].

Double wall containments

4.147. A double wall containment is an arrangement with the primary containment completely enclosed in a secondary containment. The purpose of the secondary containment is not to take over the functions of the primary containment should it fail but to allow for the collection of leaks in the space between the two structures and for a filtered release via the vent stack. This function is termed secondary confinement.

4.148. The systems associated with secondary confinement should be designed to collect, filter and discharge gases and liquids containing radionuclides that have leaked from the containment in accident conditions, or to pump leaked liquids back into the containment. This is a way of reducing accidental radioactive releases (by filtering) and their impacts (by means of stack release of gases instead of releases at ground level). The merits of a complete or partial secondary confinement should be considered for new plants. A partial secondary confinement (i.e. one which does not completely enclose the primary containment) should enclose the more leakage prone areas of the primary containment (such as the penetration areas). If no secondary confinement is provided, a thorough justification for this should be made on the basis of anticipated radioactive releases or dose calculations for all relevant design basis accidents and for severe accident conditions.

4.149. To maximize the efficiency of the secondary confinement, a filtered ventilation system should be provided. This should quickly reduce the pressure in the volume between the primary and the secondary containment (the confinement volume) to a negative gauge pressure after a postulated initiating event involving a loss of coolant and should maintain it even under the assumed worst wind conditions. If a negative gauge pressure cannot be achieved and maintained in the confinement volume, account should be taken in the calculations of the radiological consequences of the unfiltered leakage to the environment that will result. The confinement volume should be kept at subatmospheric pressure in normal operation, to enable the leaktightness of the secondary containment to be monitored.

4.150. When a secondary confinement is provided, direct leaks (i.e. leak paths from the containment directly to the outside without transiting the confinement volume) should be prevented to the extent possible. Criteria should be set for the control of direct leaks and for the leaktightness of the secondary confinement envelope. It should be verified periodically by means of testing that these criteria are being met.

4.151. The following features should be incorporated into the design to limit the number of direct leaks:

— Systems that have to penetrate the primary containment should be located in the confinement volume, either entirely (if possible) or up to the isolation valves.
— Recirculation systems (e.g. safety injection systems and spray systems) should be located entirely in the confinement volume.
— Large penetrations (e.g. the containment ventilation system) should be equipped with three isolation valves (one in the containment, one in the confinement volume and one outside the containment). The space between the second and third isolation valves should be connected to the confinement volume by a small line equipped with two isolation valves in

parallel that are open when the large valves are closed; this ensures that, even with a single failure of the isolation valves, leaks from the containment are collected in the confinement volume.
— Doors of the air locks penetrating both containment walls should be equipped with a double seal; the space between the seals should be connected to the confinement volume rather than to the air lock volume when the door is closed.

Control of leakage from recirculation lines

4.152. Many containment designs include systems to recirculate water from collection points inside the containment envelope, either through heat exchangers or directly, for reinjection into the reactor vessel or into the containment spray system in an accident. Parts of these recirculation systems may be located outside the containment envelope, giving rise to a potential for leakage of radionuclides from pumps, valves or heat exchangers outside the containment envelope. Where a design of this type is used, provisions should be made to minimize the uncontrolled release of radionuclides to the environment resulting from such leakage, to test the leak rate periodically, and to detect and isolate accidental leaks by qualified means.

Control of leakage in buildings outside the containment

4.153. In buildings outside the containment, sources of radioactive material arising from leaks from the containment in accident conditions or from radioactive material stored in the buildings should also be confined.

4.154. In establishing the design basis for these buildings, consideration should be given to all possible events of both internal and external origin that could cause the release of radioactive material to the environment.

4.155. Design measures such as subdividing the buildings into compartments and ensuring adequate leaktightness should be adopted to minimize the dispersion of radioactive material inside the buildings. A filtered ventilation system should be provided to limit and control the release of radioactive material to the environment.

MANAGEMENT OF COMBUSTIBLE GASES

Generation of hydrogen

4.156. Hydrogen and oxygen are generated during normal operation of a plant as a result of the radiolysis of water in the core. After a LOCA, a mixture of hydrogen and air might be formed in the containment atmosphere as a consequence of:

- Radiolysis of the water in the core,
- Radiolysis of the water in the sump or the suppression pool,
- Metal–water reactions in the core,
- Chemical reactions with materials in the containment,
- Degassing of hydrogen dissolved in the primary coolant,
- Releases from the hydrogen tanks used for control of the primary coolant chemistry.

All these contributions to the generation of hydrogen should be evaluated.

4.157. The amount of hydrogen generated should be calculated for normal operation and for LOCA conditions. The uncertainties in the various possible mechanisms for hydrogen generation should be taken into account by the use of adequate margins.

Systems for hydrogen monitoring or sampling

4.158. A hydrogen monitoring or sampling system should be provided within the containment for determining the hydrogen concentrations at representative points over time in accident conditions, especially those caused by a LOCA. If mixing of the containment atmosphere cannot be guaranteed, proper location is essential for the monitoring or sampling devices to be representative of the areas and locations where hydrogen might accumulate.

4.159. If the systems for hydrogen monitoring or sampling could transport radionuclides outside the containment, they should be considered extensions of the containment and should be designed to meet the same criteria as the containment itself.

Measures for the prevention of uncontrolled hydrogen ignition

4.160. Systems for hydrogen removal, deliberate ignition, homogenization or inerting should be provided so as to avoid reaching the hydrogen ignition limit globally or locally inside the containment at any time during or after a postulated LOCA.

4.161. If hydrogen control systems could transport radionuclides outside the containment, they should be considered extensions of the containment and should be designed to meet the same criteria as the containment itself.

Removal

4.162. Passive means such as passive autocatalytic recombiners and/or active means such as igniters should be provided for removing hydrogen.

4.163. If it is determined by means of analysis that the hydrogen concentration would increase slowly over a long period of time, the actuation of active means of hydrogen removal may be by manual means. In this case, it may be assumed that off-site power is available for active means. If analysis shows with sufficient certainty that the accumulation of hydrogen under LOCA conditions is slow, a mobile control system for combustible gases (i.e. a mobile recombiner) may be used. In this case, appropriate provisions should be made in the design and in the procedures for the use of such a system. The provisions for shielding should be such as to permit connection of the mobile system without causing any undue exposure of operators to radiation.

4.164. A single failure during the use of active hydrogen control systems need not be postulated provided that:

— Repair or means of substitution can be shown to be practicable.
— The generation of hydrogen is slow enough that hydrogen concentration limits will not be exceeded, either during the predicted repair time or during the time necessary to introduce substitute means (such as by putting a mobile recombiner into operation).

Homogenization

4.165. The containment design either should incorporate active means (such as sprays and mixing fans qualified for operation in a combustible gas mixture) or should facilitate the action of mechanisms (such as large volume dispersion or natural circulation) to enhance the uniform mixing of the containment atmosphere within and between compartments. This is to ensure that localized hydrogen concentrations do not reach combustion limits following an accident. Alternatively, it should be shown by analysis either that uncontrolled local ignition will not occur or else that safety systems and components can survive local ignition.

Inerting

4.166. One possible way to avoid hydrogen combustion is to inert the containment atmosphere during reactor operation (usually with nitrogen). This is mainly applicable to small containments such as those of boiling water reactors.

MECHANICAL FEATURES OF THE CONTAINMENT

4.167. The mechanical features of the containment comprise the mechanical components of the outermost barrier and the mechanical parts of the extensions of this barrier (i.e. piping, valves, ducts and penetrations). Together with the containment structure, these features comprise the containment envelope.

4.168. The leaktightness criteria for mechanical features of the containment and its extensions should be consistent with the assumptions used in the radiological analyses for design basis accidents.

Provisions for containment isolation of piping and ducting systems

4.169. To ensure containment isolation, piping and ducting systems that penetrate the containment envelope should have appropriate provisions for isolation (i.e. valves and dampers). Requirements for containment isolation are established in Ref. [1], paras 6.55–6.57.

4.170. In the provisions for containment isolation, two barriers should be provided for each penetration. Annex II elaborates on means of isolation for piping and ducting systems.

4.171. Each line penetrating the containment that is not part of a closed loop[10] and that either (a) directly communicates with the reactor coolant during normal operation or in accident conditions or (b) directly communicates with the containment atmosphere during normal operation or in accident conditions should be provided with two isolation valves in series. Each valve either should be normally closed or should have provisions to close automatically. Where the line communicates directly with the reactor coolant or the containment atmosphere, one valve should be provided inside the containment and one valve outside. If two valves either inside or outside the containment structure can provide an equivalent barrier (i.e. can meet all the design requirements) in certain applications, then this may also be an acceptable arrangement. Each valve should be reliably and independently actuated. Isolation valves should be located as close as practicable to the structural boundary of the containment.

4.172. Loops that are closed either inside or outside the containment should have at least one isolation valve outside the containment at each penetration. This valve should be an automatic valve, a normally closed valve or a remotely operated valve[11]. Where the failure of a closed loop is assumed as a postulated initiating event or as a consequence of a postulated initiating event, the recommendations in the previous paragraph will apply to each line of the closed loop.

4.173. Loops that are closed both inside and outside the containment envelope should have at least one isolation valve, an automatic valve, a normally closed valve or a remotely operated valve outside the containment envelope at each penetration.

4.174. Exceptions to the above recommendations are permitted for small dead-ended instrumentation lines that penetrate the containment. For these

[10] A closed loop is a piping or ducting system that penetrates the containment envelope and that is designed to form a closed circuit either inside or outside, or inside and outside the containment in operational states and in accident conditions.

[11] An automatic valve is a valve or damper that can be actuated either by the protection system signals or by other instrumentation and control circuits without action by the operator or by the process medium itself. For example, certain types of check valves are considered automatic valves. A normally closed valve is a valve that is closed under active administrative control (such as being locked closed or continuously monitored to show that the valve is in the closed position) except for intermittent opening for specific purposes such as monitoring, testing or sampling. A remotely operated valve is a valve or damper that can be actuated by an operator from the control room and in some cases also from the supplementary control points.

lines a single manually operated valve outside the containment is sufficient. Instrumentation lines that are closed (i.e. not in communication with the atmosphere) both inside and outside the containment are acceptable without isolation valves provided that they are designed to withstand design basis accidents for the containment. The rooms where these lines emerge should be equipped with a filtration–ventilation system to maintain subatmospheric pressure. Such rooms and the equipment within them should be designed to withstand increased levels of temperature and humidity due to possible leakage from these lines.

4.175. The need for isolation of the containment in accident conditions and the need for operation of the safety systems that penetrate the containment envelope may result in contradictory design requirements. In such cases, consideration of the isolation provisions should be balanced against the need for the availability of safety systems and the need to avoid escalation of the accident conditions. Check valves may be used for the inner isolation barrier to resolve this issue, but the use of two check valves in series should not be considered an acceptable method of isolation.

4.176. Overpressure protection should be provided for closed systems that penetrate the containment and for isolated parts of piping that might be overpressurized by the raised temperature of the containment atmosphere during design basis accidents.

4.177. The extensions of the containment envelope should be designed and constructed to levels of performance that are at least equivalent to those for the containment barrier itself.

4.178. For the systems or piping that are normally closed to the containment atmosphere, but which might be opened in some reactor shutdown states (i.e. opening of the steam generator envelope in shutdown states or of the fuel transfer tube when the spent fuel pool is located outside the containment), and for which isolation can be provided by only one means,

— The leaktightness of the existing means of isolation should be demonstrated.
— A qualified mobile device should be used as a means of isolation.
— The system concerned should be opened only when the risk to safety is sufficiently low.

4.179. Particular consideration should be given to the containment isolation features of the following systems:

— Those systems, such as safety injection lines and emergency cooling lines, that are connected with the primary circuit and that can transport radionuclides outside the containment in design basis accidents;
— Those systems that can transport airborne radionuclides from the containment atmosphere to outside the containment in design basis accidents (i.e. systems used in some designs to mix the atmosphere inside the containment in order to prevent the ignition of hydrogen);
— Those systems that support systems important to safety (inside the containment) for which, in the event of leakage, fluids with a high activity might be released outside the containment (i.e. in some designs the component cooling water system, the containment sump purge system or the sampling systems).

4.180. Systems connected to the primary circuit in normal operations (i.e. primary circuit filtration systems or in some designs the chemical and volume control system) and systems connected to the containment atmosphere should be automatically isolated in accident conditions when they are not necessary for safety.

4.181. If valves used for normal operations are also used for containment isolation, they should meet the same design requirements as the containment isolation system.

Isolation valves

4.182. To achieve the objective of limiting any radioactive release outside the containment, the isolation devices should be designed with a specified leaktightness and closure time. In specifying the leaktightness and closure time, the amounts of potential radioactive releases should be taken into account. In making the choice between motorized and pneumatic valve operators, the requirement for the valve to reach a safe position in the event of loss of its motive force and the required closure time of the valve should be taken into account. It may be necessary to limit the closing speed of valves or dampers, particularly for larger penetrations, to ensure their proper functioning and tight sealing.

4.183. Design provisions for leakage tests (such as nozzles and instrumentation test lines) should be made such that each isolation valve may be tested. Any possible exceptions should be fully justified.

Penetrations

4.184. Containment penetrations should be designed for the same loads and load combinations as the containment structure, and for the forces stemming from pipe movements or accidental loads (Ref. [1], paras 6.51–6.54).

Piping penetrations

4.185. In the mechanical design of piping penetrations, including isolation valves, the loads originating from the piping system as well as loads originating from the containment should be taken into account. Special attention should be paid to complex features like metallic bellows. For these solutions, means such as nozzles or double seals should be used to test the leaktightness of piping penetrations individually.

4.186. Piping penetrations should be accessible so that leaks from individual penetrations can be detected in the leaktightness tests.

Electrical penetrations

4.187. Penetrations through the containment for electrical power cables and instrument cables should be leaktight. Means for ensuring the leaktightness of these penetrations may be based on the following:

(a) *Pressure glass penetrations.* The pressure glass design consists of studs embedded in a pressurized disc of glass flanged to the containment. Cables are connected to the studs, which extend on both sides of the glass disc and provide continuity for the electric power. The glass ensures electrical isolation between the studs and acts as a sealant. The design should include double seals on the flange to ensure the leaktightness of the assembly. These penetrations should be removable and individually testable for leaktightness at the design pressure.
(b) *Pressurized and continuously pressure monitored penetrations.* For pressurized penetrations, the pressurization should normally be higher than the internal pressure in the containment for design basis accidents, so that leaktightness can be tested continuously. In any case, the pressure should not be lower than the pressure used in the containment leak rate test. The effects of increase in temperature on the design pressure of the fluid inside the penetrations should be assessed and taken into account in the design of the penetrations.

(c) *Injected sealant penetrations*. Penetrations of this type should be leak testable in integrated leak tests.

4.188. Preference should be given to designs of electrical penetrations that allow each penetration to be tested individually.

4.189. Heat produced by the electrical cables should be taken into account in selecting the materials for electrical penetrations. The materials used should be heat resistant and non-flammable. Penetrations using sealant injection should be at least flame retardant.

Air locks, doors and hatches

4.190. Penetrations (containment air locks) for access by personnel or equipment to the containment are required to have air locks equipped with doors that are interlocked to ensure that at least one of the doors is closed during reactor operations and in design basis accidents (Ref. [1], para. 6.58). In addition, they are required to be designed to prevent any undue exposure of operators to radiation in operational states of the plant.

4.191. The two air lock doors should be designed to withstand the same plant conditions as the containment. Local transient effects, such as exposure to open flames caused by hydrogen burning, need not be considered for the outer door.

4.192. The chamber between the two air lock doors should be so sized as to allow the passage of necessary maintenance equipment and a sufficient number of personnel, so as to avoid having to open the air lock too frequently during plant shutdown and maintenance.

4.193. The inner door of the air locks should be of a pressure sealing type. Double seals should be provided on each door and there should be provisions for testing the leaktightness of the doors and the inter-seal space. Low pressure alarms should be provided if inflatable seals are used.

4.194. Equipment hatches are large openings in the containment structure that are normally closed. They are usually designed with a bolted flange, whose leaktightness is ensured by means of soft elastomeric seals. Leak testable double seals should normally be provided. Loads and deformations due to temperature effects should be taken into account in the design of equipment hatches. In order to transport large components, the need may arise to open equipment hatches in certain reactor states other than full shutdown and for which the risk is sufficiently low. The containment should only be opened for such conditions if provision can be made for the rapid closure of equipment hatches, consistent with the possible kinetics of the accidents considered in the design basis for the reactor state concerned.

4.195. Containment openings (i.e. penetrations, air locks and hatches) should normally be closed in order to minimize the active measures required for containment isolation in the event of an accident. Exceptions are allowed if they are necessary for operational reasons and provided that the openings can be closed quickly and reliably to comply with established acceptance criteria that apply for the accident. Provisions for indicating the state of the containment openings should be put in place.

MATERIALS

Concrete

4.196. Concrete should have characteristics of quality and performance (strength, porosity and tightness) consistent with its use. The quality of the concrete used for containment structures should be correspondingly high, consistent with the safety function of the containment. Design considerations will depend on the containment concept: a concrete containment with stressed cables usually ensures both strength and leaktightness, whereas a reinforced concrete containment structure usually ensures only strength while its steel liner ensures leaktightness.

4.197. Consideration should be given to the design capacity of the concrete to cope with the loads (pressure loads and thermal loads) and environmental conditions (of heat, moisture and radiation) generated by design basis accidents. This should lead to strict specifications for the concrete in terms of strength and leaktightness.

4.198. Concrete with appropriate rigidity, thermal expansion and resistance to compression should be used for all electrical penetrations, large penetrations such as equipment hatches and the joint with the basemat.

4.199. In prestressed containments, the concrete should remain in a prestressed condition even in accident conditions. Concrete materials that would limit creep or shrinkage over the years and with low porosity should be used. The possible loss of prestress of the containment tendons over the operating lifetime of the plant should be evaluated and considered in the design.

4.200. Sleeve–concrete interfaces should be designed to minimize leaks by avoiding direct paths through the interface.

4.201. Design and construction processes should be such as to prevent the development of cracks or high leak zones.

4.202. Ageing effects are required to be evaluated in the selection and design of types of concrete (para. 4.39 and Ref. [1], para. 5.47).

Metallic materials

4.203. Metallic materials used for containment systems, including welds, should be of high quality; qualified and certified materials that meet national safety standards should be used.

4.204. In the selection of metallic materials, the following considerations should be taken into account:

— Thermal and mechanical loads;
— Chemical interactions, including those with chemicals used in containment spray systems;
— Resistance to brittle fracture;
— Resistance to corrosion.

4.205. Metallic materials such as zinc and aluminium that have the potential to generate hydrogen on contact with water or steam should not be used inside the containment. If such materials are essential to the design, their use should be limited and the effects of hydrogen generation should be analysed.

Soft sealing materials

4.206. Soft sealing materials are commonly used in multiple containment applications, such as in the sealing of ventilation valves or the inflatable sealing of air locks. Although these materials contribute to a very high leaktightness of the containment under normal conditions, their behaviour in design basis accidents should be properly demonstrated. Potentially damaging effects for soft sealing materials include embrittlement and cracking due to high temperatures and irradiation, dissolution due to moisture and steam, and swelling or shrinkage due to temperature fluctuations. Specific consideration should be given to the protection of these materials from the direct effects of hydrogen burning and/or the accumulation of radioactive aerosols. In extreme conditions such materials may degrade to the extent that their mechanical properties are altered.

4.207. The anticipated lifetimes of soft sealing materials and the ageing mechanisms that affect their performance should be assessed, and appropriate replacement intervals should be established (para. 4.39). Sealing components should be designed to be easily inspectable and replaceable.

Materials for thermal insulation

4.208. Thermal insulation materials should not compromise any safety functions in the event of their deterioration. They should be installed and affixed to prevent loosening and the possible clogging of sieves and valves as a consequence.

4.209. In particular, materials used to insulate pipes and tanks inside the containment should be selected and designed to achieve the following:

(a) To minimize the production of debris that can accumulate on containment floors and clog sumps or damage recirculation pumps,
(b) To ensure easy decontamination if the need arises,
(c) To avoid giving rise to fire hazards,
(d) To minimize the release of toxic gases during their heating at startup.

4.210. Ageing mechanisms that affect thermal insulation materials should be assessed and appropriate replacement intervals should be established (para. 4.39).

Materials for coverings and coatings

4.211. Materials for coverings and coatings (such as paint, sealant and epoxy resin) should be selected to ensure that they do not interfere with any normal operations or safety functions, for example by deteriorating and causing clogging of the filters of sumps, or as a result of the formation of organic iodine. Appropriate paints and coatings should be used to facilitate decontamination of the walls.

4.212. If organic liners are applied to increase the leaktightness of the containment structure, they should be selected to withstand the thermal loads and pressure loads, as well as the environmental conditions in the containment, without losing their safety function. Provision for managing the ageing of these organic liners should be made, including provision for maintenance and surveillance.

4.213. Painting and coating materials should be selected so as not to pose a fire hazard.

4.214. In the selection of painting and coating materials, consideration should be given to the effect of the dissolution of their solvents in the sump on the volatility of iodine.

INSTRUMENTATION AND CONTROL SYSTEMS

4.215. To provide defence in depth and to enhance the general reliability of the containment systems, instrumentation should be provided for the purposes of:

(a) Detecting deviations from normal operation,
(b) Monitoring the stability of the containment structure,
(c) Leakage testing and integrity testing,
(d) Monitoring the availability of the containment systems,
(e) Providing actuation signals for containment systems,
(f) Post-accident monitoring.

Detection of deviations from normal operation

4.216. Specific design recommendations regarding instrumentation for monitoring the containment for the early detection of deviations from normal operation are provided in Appendix I. See also Section 6 on instrumentation for the detection and monitoring of severe accident conditions.

Control of the containment structure

4.217. Appropriate instrumentation should be incorporated inside the containment in order to monitor closely any deformation (radial, vertical or circumferential) or movement of the containment structures or the containment walls.

4.218. For prestressed concrete walls, means to detect loss of the prestressing should be provided. The concrete compression and rigidity parameters (such as Young's modulus) should be defined, and they should be verified by such means as acoustic measurements. The temperature in concrete singularities should also be measured to aid the interpretation of the results of pressure proofing tests.

4.219. Appropriate instrumentation for measurements relating to earthquakes should be provided on the basemat of the containment or on a suitable floor.

Instrumentation for leak testing

4.220. Appropriate instrumentation should be incorporated inside the containment for conducting the periodic leak tests. This should include instrumentation for monitoring pressures, temperatures, humidity and flow rates. For steel containments, the temperature of the steel should also be measured. The number and the locations of instruments should be specified by the designer in accordance with the environmental conditions to be expected. Guidance on leak rate testing is given in Section 5.

4.221. Means for monitoring major leaks (e.g. by assessing the mass of the containment atmosphere by the use of devices for measuring pressure and temperature) should be incorporated to detect any major openings in the containment boundary caused by equipment failure or operator error. Guidance on monitoring for major leaks is given in para. 5.21.

4.222. Any containment leaks that are not collected in a building equipped with filtration devices, so-called direct leaks, should be carefully monitored to ensure that any leakage directly to the atmosphere would be detected.

Monitoring of the availability of containment systems

4.223. Appropriate instrumentation should be used to monitor the availability of the containment systems used for energy management or for the management of radionuclides.

4.224. The availability of the containment systems should be verified by means of the following:

— By continuous monitoring and display in the main control room of the main parameters important to safety (a single integrated monitor for critical safety parameters is used in many reactor designs);
— For the systems for energy management, by monitoring the positions of valves, the status of components in operational states and flow rates;
— For the systems for radionuclide management, by monitoring the positions of isolation valves and doors, the pressure of inflatable airlock seals and water levels in spray water tanks;
— By testing, for example, the flow rates of some systems, the leaktightness of containment systems and the efficiency of aerosol filters or iodine filters.

Actuation and functioning of containment systems

4.225. In the event of a significant release of radioactive material into the containment (such as in a LOCA), signals for the actuation of containment systems (such as the systems for energy management, radionuclide management and the management of combustible gases) should be derived, depending on the design, from the values of parameters such as:

— High pressure and/or high radiation levels in the containment,
— Low pressure in the reactor coolant system,
— A small subcooling margin in the reactor coolant system,
— A low water level in the reactor pressure vessel.

4.226. Many of these signals are typically used in the reactor protection system to initiate automatic containment isolation or to actuate systems important to safety (such as spray systems, ventilation systems and active igniters).

4.227. Signals for the following conditions should also be used to initiate automatic isolation or for initiating isolation by operator action in the control room:

— High levels of radiation or contamination in the containment atmosphere,
— High levels of radiation in the sump water.

4.228. The lines that penetrate the containment and that are necessary for the operation of safety systems in accident conditions should not be isolated upon the automatic isolation of the containment. Other means should be used to ensure that any release of radioactive material through the containment envelope does not exceed the limits set for plant operational states and design basis accidents.

4.229. In addition to those events for which isolation of the containment is required, there are other events for which only the individual isolation of the affected lines is necessary to limit the release of radioactive material from the containment to the environment. This is the case for a break outside the containment in a pipeline for radioactive material that penetrates the containment, or for the failure of an interface between two associated systems (such as the rupture of a heat exchanger on a water line of a component cooling system) that leads to a release of radioactive material from a system inside the containment to a system outside. The actuation of the isolation devices should be derived from the values of appropriate parameters, such as:

— Levels of radiation or of airborne contamination,
— Pressure changes,
— Temperature changes.

4.230. For all lines not associated with the operation of safety systems, the following criteria should be met:

(a) Lines that penetrate the containment envelope should be automatically isolated when process parameters indicate LOCA conditions.
(b) Lines that communicate with the containment atmosphere should be automatically isolated when a specified level of radiation in the containment atmosphere is exceeded.
(c) Lines that communicate with the containment sump and penetrate the containment should be isolated when a specified level of radiation in the sump water is exceeded.
(d) Lines that are connected to the reactor coolant system via a heat exchanger (such as the main steam lines in a pressurized water reactor) should be isolated when specified radiation levels in the lines are exceeded.

Post-accident monitoring and sampling

4.231. Instrumentation should be provided for the reliable monitoring of environmental conditions (such as pressures, temperatures, sump water levels and radiation levels) inside the containment envelope during and following an accident. This instrumentation should be qualified for the environmental conditions to be expected. Guidance on the monitoring of hydrogen concentrations is given in paras 4.158, 4.159, 6.29 and 6.30.

4.232. Appropriate instrumentation should be installed to provide the information necessary to enable operators to assess the status of the containment.

4.233. Information from post-accident monitoring and information on the positions of isolation valves should be displayed in the main control room.

4.234. Provisions should be made in the design for sampling of the containment atmosphere and the sump water at suitable locations. The sampling devices used should be qualified for the expected containment conditions and should be installed so as to avoid a containment bypass in the event of their rupture. They should be designed to ensure that occupational radiation dose limits are not exceeded for the personnel who operate them.

SUPPORT SYSTEMS

Power supply

4.235. The containment systems should be designed to continue fulfilling their functions following a loss of off-site power with a single failure taken into account. Electrical isolation valves that would have to be closed using electric power in a design basis accident should be provided with non-interruptible power supplies.

Compressed air systems

4.236. Containment isolation valves with a clear safe position should be designed to move to their safe positions in the event of a loss of pneumatic pressure.

4.237. If the operation of pneumatic valves is necessary during a design basis accident, the autonomy of the compressed air system (such as by means of having reserve air tanks) should be demonstrated. Otherwise, installation of a backup compressed air system should be considered. Where reserve air supply tanks are installed inside the containment, the increased internal pressures caused by the high temperatures in the containment during design basis accidents should be taken into account in their design.

4.238. The compressed air systems should be designed in such a way as to avoid a containment bypass or pressurization of the containment. Safety systems that are needed in the long term after a design basis accident should therefore not depend on compressed air systems for fulfilling their safety functions. To avoid gradual pressurization of the containment due to the leakage of compressed air systems, consideration should be given to the installation of a dedicated post-accident compressed air system to supply instruments inside the containment with air exhausted from the containment.

5. TESTS AND INSPECTIONS

5.1. In order to demonstrate that the containment systems meet design and safety requirements, commissioning and in-service tests and inspections should be conducted as outlined in the following.

COMMISSIONING TESTS

5.2. Commissioning tests for the containment should be carried out prior to the first criticality of the reactor to demonstrate the containment's structural integrity, to determine the leak rate of the containment envelope and to confirm the functioning of related equipment.

Structural integrity test

5.3. A pressure test should be conducted to demonstrate the structural integrity of all parts of the containment envelope (including extensions and penetrations) and of the containment systems. If the containment structure comprises two containment walls that are both subject to pressure loads, both walls should be tested.

5.4. The pressure test should be conducted at a specified pressure for which account is taken of the applicable codes for the material used, and which is at least the design pressure. The value of the test temperature should not be close to the ductile–brittle transition temperature for the metallic material.

Integrated leak tests

5.5. A leak test should be conducted following the structural integrity test to demonstrate that the leak rate of the containment envelope does not exceed the specified maximum leak rate. The test should be conducted with the components of the containment in a state representative of the conditions that would prevail following an accident, to demonstrate that the specified leak rate would not be exceeded under such conditions.

5.6. To establish a point of reference for future in-service leak tests, the leak test performed during commissioning should be conducted at a test pressure or pressures consistent with the pressure selected for in-service leak tests:

(a) At values of pressures between the pressure selected for in-service leak testing and the positive design pressure, if the in-service tests are to be conducted at a pressure lower than the design pressure; or
(b) At the design pressure of the containment, if the in-service tests are to be conducted at this pressure.

5.7. The need to validate the leak rate assumed in the safety analysis reliably over the entire plant operating lifetime for the entire range of pressures calculated should be taken into consideration in the choice of test pressure(s).

5.8. The need for initial and periodic testing should be considered in the design, and all the components that might be damaged during testing should be identified. The necessary means to pressurize and depressurize the containment and appropriate instrumentation for testing should be included in the design.

5.9. One way of determining leak rates is the absolute pressure method, in which the leakage flow is determined by measuring the decrease in pressure as a function of time. In this method, the temperature and pressure of the containment atmosphere, the external atmospheric temperature and pressure, and the humidity of the containment atmosphere should be measured continuously and factored into the evaluation. Means should be provided to ensure that the temperature and humidity of the containment atmosphere are uniform.

5.10. Appropriate instrumentation should be provided in the containment, appropriately positioned and installed either permanently or as needed, to determine representative atmospheric conditions in the different zones of the containment.

5.11. For double wall containments, one way to determine the direct leak rate from the containment to the environment (i.e. if the leaked water or gas does not collect in the annular space between the inner and the outer containment walls) is by calculation. This calculation should determine the difference between (a) the total leak rate from the inner containment as determined by the leak test for the inner containment (this consists of both flow from the inner containment into the annulus and flow from the inner containment to the atmosphere) and (b) the leak rate from the inner containment wall to the annulus, obtained after ventilation of the annulus has been stopped (this is typically calculated by subtracting the normal flow out of the annulus vent from the flow out of the annulus vent during the leak test).

Local leak tests of isolation devices, air locks and penetrations

5.12. Leak tests should be performed to establish a baseline leakage measurement for each isolation device, air lock and penetration. The following components are the most sensitive parts of the containment envelope, and special attention should be paid to them:

(a) Isolation devices in systems open to the containment atmosphere;
(b) Isolation devices in fluid system lines penetrating the containment;
(c) Penetrations that have resilient or inflatable seals and expansion bellows, such as:
   - personnel air locks,
   - equipment air locks,
   - equipment hatches,
   - spare penetrations with bolted closures,
   - cable penetrations with resilient seals,
   - pipe penetrations with flexible expansion bellows in the connections to the containment.

Functional tests of equipment and wiring in the containment

5.13. Tests should be carried out to verify that the equipment in all containment systems is functional. Exceptions may be made if it is impracticable to demonstrate some operational characteristics under non-accident conditions or if such tests would have a detrimental effect on safety.

5.14. Tests should be carried out on all electrical wiring associated with the containment systems to demonstrate that there are no deviations from the design and that all connections are in accordance with the design.

IN-SERVICE TESTS AND INSPECTIONS

5.15. Periodic in-service tests and inspections should be performed to demonstrate that the containment systems continue to meet the requirements for design and safety throughout the operating lifetime of the plant.

5.16. The test methods and intervals for in-service tests should be specified so as to reflect the importance to safety of the items concerned. In devising test methods and determining the frequency of testing, consideration should be given to the necessary levels of performance and reliability of the containment systems individually and as a whole.

5.17. Appropriate features should be provided for performing commissioning and in-service testing for containment pressure and leaktightness, and the correlated loads should be considered for the purposes of structural design.

5.18. General guidance on in-service inspection is provided in Ref. [16]. The remainder of Section 5 provides additional guidance specific to containment systems.

Structural integrity tests

5.19. Periodic structural tests should be conducted to demonstrate that the containment structure continues to perform as intended in the design. The test pressure should be the same as in the pre-operational test and as required by the applicable design codes. In the design, attention should be paid to the additional stresses imposed by the tests, and margins should be included to prevent the tests from causing any degradation of the containment structure. A leak test should be performed during any structural integrity test. Additional guidance is provided in Ref. [5].[12]

[12] In some States, structural integrity tests are conducted at intervals of once every 10 years.

Integrated leak tests

5.20. The design should provide the capability for periodic in-service testing of the leak rate to prove that the leak rate assumed in the safety analysis is maintained throughout the operating lifetime of the plant. The in-service leak rate tests may be made at either:

(a) A pressure that permits a sufficiently accurate extrapolation of the measured leak rate to the leak rates at the accident pressures considered in the safety analysis; or
(b) The containment design pressure.

5.21. There are also methods available to provide a continuous estimate of the overall containment leak rate during plant operation and to derive rough indications of containment leak rates in accident conditions. Such approaches are generally based on variations in the containment pressure or the mass balance during normal operation of the plant. In some cases, the use of these methods together with extensive local leak rate tests during shutdown for refuelling may justify a reduction in the frequency of the global tests.

5.22. The design should permit leak tests of isolation devices, air locks, penetrations and containment extensions (para. 5.12).

5.23. The design should facilitate local testing by providing access to penetrations and incorporating necessary connections and isolation valves.

5.24. To permit greater precision in measuring the leak rate and to improve the detection of leaking valves, a capability for testing individual valves should be provided. This may require the provision of additional isolation valves.

5.25. Design provisions should be made to permit testing of the secondary confinement envelope (the secondary containment and the surrounding building). Local leak tests of isolation devices, air locks and penetrations should also be considered.

5.26. In containments with a pressure suppression pool, features should be provided for periodically assessing any leakage that might lead to bypassing of the pool, so as to ensure that the bypass rate of the pool is consistent with the value considered in the safety analysis.

Functional tests of the equipment in containment systems

5.27. The design should permit the functional testing of the equipment in containment systems during normal plant operation.

Visual inspection

5.28. Where it is technically feasible, the design should provide for the visual inspection of containment structures (including the tendons for prestressed concrete containments), penetrations and isolation devices.

5.29. Visual inspection of the containment envelope, including appurtenances and penetrations, should be made in conjunction with each of the tests specified in paras 5.18–5.24. Visual inspections are important for the proper monitoring of ageing effects.

Availability tests

5.30. The design should provide a capability for monitoring or testing all items of equipment in containment systems at intervals that reflect their importance to safety, or for otherwise demonstrating the necessary reliability for the containment systems individually or as a whole.

5.31. A capability for testing isolation valves during plant operation, such as by actuating them to function with a partial stroke, may contribute greatly to the assurance of the reliability of the system.

6. DESIGN CONSIDERATIONS FOR SEVERE ACCIDENTS

GENERAL

6.1. Safety of Nuclear Power Plants: Design [1] states in para. 5.31 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 mitigatory measures can be identified". The occurrence of accidents with severe environmental consequences should be made extremely unlikely by means of preventive and mitigatory measures.

6.2. Severe accidents should be evaluated by means of the best estimate approach[13]. In a best estimate approach, the combination of assumptions, computer codes and methods chosen for evaluating the consequences of a sequence should be such as to provide reasonable confidence that the results will reflect the probable occurrence of phenomena. In adopting best estimate approaches, special attention should be paid to ensuring that:

— Input parameters are in the range of what might be expected on the basis of present knowledge.
— Computer codes reflect an internationally accepted state of knowledge based on accepted research and development (in particular, the modelling of phenomena should not be controversial).
— All relevant aspects of the severe accident are considered (e.g. by the application of integral computer codes covering the hydraulics of the containment and the behaviour of fission products).
— The uncertainties in the values calculated are taken into consideration.

6.3. The validation domain of the computer codes used for evaluating all pertinent parameters should be verified to cover their expected range of variation adequately. Computer codes should not be used beyond their validation domain. As an exception, the use of computer codes beyond their range of validation might possibly be acceptable in areas for which it is widely recognized that there is a lack of coherent data. Such exceptions should be allowed only on the following conditions:

— The exception is clearly specified.
— A comprehensive sensitivity analysis is carried out to evaluate the effects of variations in the assumptions and in the modelling.
— An independent assessment is made of the credibility of the results.
— Appropriate margins are introduced if knowledge is limited.

6.4. For existing plants, the phenomena relating to possible severe accidents and their consequences should be carefully analysed to identify design margins and measures for accident management that can be carried out to prevent or

[13] Recommendations for conducting safety analyses for severe accidents are provided in paras 4.104–4.122 of Ref. [3].

mitigate the consequences of severe accidents. For these accident management measures, full use should be made of all available equipment, including alternative 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 capabilities of the containment systems for preventing or mitigating the consequences of severe accidents.

6.5. For new plants, possible severe accidents should be considered at the design stage of the containment systems. The consideration of severe accidents should be aimed at practically eliminating[14] the following conditions:

— Severe accident conditions that could damage the containment in an early phase as a result of direct containment heating, steam explosion or hydrogen detonation;
— Severe accident conditions that could damage the containment in a late phase as a result of basemat melt-through or containment overpressurization;
— Severe accident conditions with an open containment — notably in shutdown states;
— Severe accident conditions with containment bypass, such as conditions relating to the rupture of a steam generator tube or an interfacing system LOCA.

6.6. For severe accidents that cannot be practically eliminated, the containment systems should be capable of contributing to the reduction of the radioactive releases to such a level that the extent of any necessary off-site emergency measures needed is minimal.

6.7. Severe accident conditions may pose a threat to the survivability of equipment inside the containment owing to the high pressures, high temperatures, high levels of radiation (the effects of deposition of aerosols should be taken into account in estimating the values of temperatures and levels of radiation) and hazardous concentrations of combustible gases. Furthermore, the larger uncertainties in relation to the conditions in the containment following severe accidents should be taken into account by using appropriate

[14] In this context, the possibility of certain conditions occurring is considered to have been practically eliminated if it is physically impossible for the conditions to occur or if the conditions can be considered with a high degree of confidence to be extremely unlikely to arise.

margins in the survivability demonstration or in specifying protective measures (such as shielding). These factors should be taken into account in verifying the necessary survivability of equipment and instrumentation.

STRUCTURAL BEHAVIOUR OF THE CONTAINMENT

6.8. For existing plants, the ultimate load bearing capacity (structural integrity Level III) and retention capacity (leaktightness Level II) of the containment structure should not be exceeded in severe accidents, to the extent that this can be achieved by practicable means. Furthermore, the molten core material and core debris should be stabilized within the containment.

6.9. To determine the ultimate load bearing capacity and retention capacity beyond the design pressure, it should be considered whether to make a global evaluation of the structural behaviour of the containment in order to identify the most limiting components so as to evaluate margins, and to study the failure mode of the structure. Local effects, thermal gradients and details of component design should also be considered so as to identify possible mechanisms for large leaks. In this regard, special attention should be paid to the behaviour of piping penetrations, soft sealing materials and electrical penetrations.

6.10. For new plants, the integrity and leaktightness of the containment structure should be ensured for those severe accidents that cannot be practically eliminated (para. 6.5). The long term pressurization of the containment should be limited to a pressure below the value corresponding to Level II for structural integrity.

6.11. Load combinations for severe accidents are design specific and should be considered in addition to the load combinations for design basis accidents. Appropriate combinations, including loads such as those due to the pressures, temperatures and pipe reactions resulting from the severe accidents that are considered in the design basis, should be taken into account. For these combinations the structural integrity criteria for Level II should be met (see para. 4.66 for the definitions of acceptance criteria). For combinations that also include local effects derived from severe accidents, the structural integrity criteria of Level III should be met. Level II criteria for leaktightness should be met for load combinations including dead loads, live loads, prestressing (if applicable), test temperatures and accident pressures.

6.12. Consideration should be given to incorporating into the plant design the following provisions to enhance the capability to cool molten core material and core debris, and to mitigate the effects of its interaction with concrete:

(a) A means of flooding the reactor cavity with water to assist in the cooling process or of providing enough water early in an accident to immerse the lower head of the reactor vessel and to prevent breach of the vessel;
(b) Protection for the containment liner and other structural members with concrete, if necessary;
(c) Sufficient floor space on the basemat to spread core debris and to increase the capability of cooling the debris by means of flooding with water;
(d) Design features of the containment and the reactor cavity to reduce the amount of core debris that reaches the upper containment (i.e. ledges, baffles and subcompartments);
(e) A reinforced sump or cavity to catch and retain molten core material and core debris (a core catcher);
(f) Use of a type of concrete for the containment floor that minimizes adverse effects due to interactions between molten core material and core debris and concrete.

ENERGY MANAGEMENT

6.13. Highly energetic severe accident conditions with the potential for damaging the containment should be virtually eliminated for new plants. Reliable depressurization of the reactor coolant system to prevent the ejection of molten core material and core debris and direct containment heating should be ensured as an accident management measure for existing and new plants.

6.14. The interaction of molten core material with water can cause highly energetic events (e.g. steam explosions; see para. III–9 of Annex III). There is an international consensus that in-vessel interactions of this type are unlikely to cause a containment failure, however, and that therefore no specific provisions are necessary. The effects of ex-vessel steam explosions are plant specific and are more difficult to predict. Therefore, for a specific plant design, if it cannot be shown that the threat associated with a steam explosion is low, special care should be taken in defining accident management provisions to balance the risk of a steam explosion with the necessity to cool the molten core material.

6.15. The combustion or deflagration of hydrogen, which would be potentially damaging to the containment systems, should also be dealt with by means of prevention (see also paras 6.22–6.27).

6.16. In the course of a postulated severe accident, the residual heat must be removed to prevent damage to the containment. Since the various cooling systems may not be operable, guidelines for the management of severe accidents should be developed for existing plants to help restore adequate core cooling and to reach a controlled state (paras 6.28–6.34). To this end, all possible means should be considered, including the unconventional use of safety systems and other plant equipment. If (probabilistic) analyses show that the risk of containment overpressurization is still too high for existing plants, the installation of a filtered containment venting system to prevent irreversible damage to the containment and uncontrolled releases of radioactive material should be considered.

6.17. For new plants an energy management system should be incorporated as the primary means of meeting the Level II acceptance criteria for structural integrity for loads derived from the pressures in the containment during accidents, as discussed in para. 6.10. In severe accidents, the systems for energy management in the containment and their support systems (the cooling water systems and power supply systems) should be independent of the systems used to prevent melting of the core. If this is not the case, the design of the containment should provide a sufficient period of time for measures to recover failed systems for energy management so as to be able to guarantee the operability of the energy management system under severe accident conditions. Venting systems should not be necessary for new plants.

MANAGEMENT OF RADIONUCLIDES

6.18. The management of radionuclides present in the containment after a severe accident is similar to the management of radionuclides in the event of a design basis accident. The aim is still to limit leakage from the containment and to avoid, as far as possible, the creation of unfiltered leakage paths to the environment. The main differences in comparison with design basis accidents are the source term (the magnitudes and physicochemical forms of the radioactive releases to the containment) and the possible unavailability of some containment systems.

6.19. An assessment of possible radioactive releases from the containment should be made for selected severe accident sequences in order to identify any potential weaknesses with regard to the leaktightness of the containment and to determine ways to eliminate them. In this assessment, a best estimate approach should be used to evaluate possible leaks from the containment and the systems that may be unavailable for each specific sequence (such as the potential loss of containment isolation in the event of a plant power blackout).

6.20. For existing plants, any release through the containment vents should be filtered. Moreover, a strategy should be adopted to optimize the effectiveness of passive features (such as the retention capacity of compartments and buildings) and of active systems (such as dynamic confinement by means of an internal filtered ventilation system, if available).

6.21. For new plants, a secondary confinement should be used.

MANAGEMENT OF COMBUSTIBLE GASES

6.22. In a severe accident, a large amount of hydrogen might be released to the atmosphere of the containment, possibly exceeding the ignition limit and jeopardizing the integrity of the containment. In the event of interactions between molten core material and concrete, carbon monoxide might also be released, contributing to the hazard. To assess the need to install special features to control combustible gases, an assessment of the threats to the containment posed by such gases should be made for selected severe accident sequences. The assessment should cover the generation, transport and mixing of combustible gases in the containment, combustion phenomena (diffusion flames, deflagrations and detonations) and the consequent thermal and mechanical loads, and the efficiency of systems for the prevention of accidents and the mitigation of their consequences.

6.23. Uncertainties remain concerning the production of hydrogen during severe accident sequences; these uncertainties are essentially linked to such phenomena as flooding of a partially damaged core at high temperatures, the late phase of core degradation, the slumping of molten core material into residual water in the lower head of the reactor pressure vessel, and the long term interactions between molten core material and concrete. For new plants, these uncertainties should be taken into account in the design and layout of the means of mitigation of the consequences of the combustion or deflagration of hydrogen, and in the design of the containment.

6.24. The efficiency of the means of mitigation of the consequences of combustion or deflagration should be such that the concentrations of hydrogen in the compartments of the containment would at all times be low enough to preclude fast global deflagration or detonation. Possible provisions in the design for achieving this goal are, for example, an enhanced natural mixing capability of the containment atmosphere coupled with a sufficiently large free volume, passive autocatalytic recombiners and/or igniters suitably distributed in the containment, and inerting. For new plants the amount of hydrogen expected to be generated should be estimated on the basis of the assumption of total oxidation of the fuel cladding.

6.25. The leaktightness of the containment for the most representative accident sequences should be ensured with sufficient margins to accommodate severe dynamic phenomena such as a fast local deflagration, if these phenomena cannot be excluded.

6.26. Even in an inerted containment, the concentrations of hydrogen and oxygen generated over a long period of time by water radiolysis may eventually exceed the ignition limit. If this is a possible threat, a hydrogen control system, passive hydrogen recombiners or other appropriate systems for mitigation and monitoring (e.g. systems for oxygen control and measurement) should be installed.

6.27. Provision should be made for hydrogen monitoring or sampling. The concentrations of other combustible gases and oxygen should also be monitored.

INSTRUMENTATION

6.28. For the management of severe accidents, appropriate instrumentation and procedures should be available to guide operator actions to initiate preventive or mitigatory measures. The instrumentation necessary for the management of severe accidents falls into four categories:

(1) Instrumentation for monitoring the general conditions in the containment;
(2) Instrumentation for monitoring the progression in the values of parameters of interest, specifically in relation to severe accidents;
(3) Instrumentation necessary for operators to execute emergency procedures;

(4) Instrumentation for assessing radiological consequences.

6.29. During and following a severe accident, in order to follow the general conditions in the containment and to facilitate the use of guidelines for the management of severe accidents, essential parameters for the containment such as pressures, temperatures, hydrogen concentrations, water levels and radiation dose rates should be monitored.

6.30. To follow the progression in the values of parameters specific to severe accidents, consideration should be given to the installation of instrumentation to measure the following parameters:

— The status of core depressurization devices (such as relief valves) for the early indication of possible high pressure melting of the core;
— The concentration of combustible gases, in order to assess the likelihood of fast deflagration or detonation;
— Pressure and temperature signals over a wide range, in order to detect possible late failure of the containment;
— The sump water level, as an indication of the amount of water available for long term injection into the core and for containment spraying.

6.31. In order to execute emergency procedures, the operator should have available controls and instrumentation for the containment systems provided specifically for the prevention and mitigation of severe accidents. These may include, for example:

— A filtered venting system;
— A monitoring and control system for combustible gases.

6.32. An assessment of the radiological consequences of a possible severe accident should be conducted in a timely manner to assist in decisions on long term actions for the protection of the population (off-site emergency measures). Instruments for assessing radiological consequences may include:

— Dose rate meters in the containment and in peripheral buildings housing systems that have interfaces with the primary systems;
— Instruments for monitoring conditions in the containment sump water (e.g. temperature and pH);
— Activity monitors for noble gases, iodine and aerosols in the stack(s).

6.33. The larger uncertainties with regard to conditions in the containment following a severe accident should be taken into account by means of appropriate margins in the ranges of operation of the instrumentation, in the domain for which its survivability is demonstrated and/or through protective measures for the instruments (such as shielding). Owing to these uncertainties and the different parameters that it may be necessary to monitor during severe accidents, it may or may not be possible under severe accident conditions to use the instrumentation provided for use in design basis accidents. If instrumentation provided for use in design basis accidents is intended to be used in severe accidents, the survivability domain of the instrumentation of the containment systems should be extended as far as is practicable to cope with the containment conditions expected in severe accidents.

GUIDELINES FOR SEVERE ACCIDENT MANAGEMENT

6.34. Guidelines for the management of severe accidents (severe accident management guidelines (SAMGs)) should be aimed primarily at maintaining or restoring the performance of the containment. SAMGs should be developed for managing accident conditions in co-ordination with on-site and off-site emergency organizations. SAMGs should be established to supplement, but not to replace, provisions in the design to prevent the failure of containment systems during or following a severe accident or to mitigate the consequences of such an accident.

Appendix

INSTRUMENTATION FOR MONITORING OF THE CONTAINMENT

A.1. This appendix provides recommendations for the measurement of parameters for the containment systems, to allow diagnosis by the operator of developing deviations from normal operation; in particular, to allow detection of releases of coolant or other radioactive fluids within the containment. The operator can evaluate these parameters and take corrective actions at an early stage to prevent a minor failure from developing into a serious plant failure or even an accident condition. In addition, these measured parameters are used as inputs to the automatic containment isolation system and other reactor protection systems.

PHYSICAL PARAMETERS

A.2. Typical conditions causing deviations from normal operation include:

— Release of high temperature fluids,
— Leakage of high pressure fluids,
— Presence of radioactive gases or liquids,
— Fire,
— Mechanical failure of components.

A.3. The physical parameters that should be monitored within the containment differ in different reactor systems. Parameters that are typically monitored include:

— The temperatures of the containment atmosphere and of the fluid drains,
— The pressure in the containment building,
— The humidity in the containment building,
— The hydrogen concentration in the containment building,
— Water levels in the drains,
— Rates of fluid flow,
— Radiation levels and activity of airborne radioactive material,
— Radiochemical analysis of drain water,
— Visible abnormalities,
— Noise and vibrations,
— Fire.

A.4. The measurement sensitivities necessary to detect a developing deviation should be estimated by appropriate analytical methods.

Temperatures of the containment atmosphere and fluid drains

A.5. Both atmospheric temperatures and the temperatures of fluid drains should be measured.

(a) *Atmospheric temperatures.* A sufficient number of temperature sensors should be installed to measure the atmospheric temperature distribution throughout the containment building. In addition, measurements of the fluid temperatures of the containment air coolers may be used to estimate the temperature of the atmosphere. The data display should present the temperature distribution and the local trends in atmospheric temperatures and fluid temperatures.

(b) *Drain temperatures.* The temperatures should be measured in selected fluid drains (system drains and floor drains) in order to determine whether there is in-containment leakage from any steam system or pressurized water system. These temperature measurements should be recorded to show trends.

Pressure in the containment building

A.6. Leakage of fluids such as compressed air, nitrogen or water may be the cause of pressure increases. To detect leaks, measurements of the ambient pressure in the appropriate compartments in the containment building should be obtained. These measurements should account for variations in other parameters such as temperature, humidity, or levels of ionizing or electromagnetic radiation. The pressure measurements should be recorded to show trends.

Humidity in the containment building

A.7. Humidity is a highly significant factor for the detection of leaks from the primary circuit. Parameters that indicate changes in humidity include:

— The dew point temperature of the containment atmosphere,
— Electrical parameters (such as impedance or resistance) of sensors,
— The amount of condensate in the air coolers of the containment building.

A.8. Humidity levels should be monitored in appropriate compartments in the containment buildings (in the primary containment, and in the secondary containment if applicable), and the measured values should be recorded to show trends.

Water levels in drain sumps and spray tanks

A.9. Storage tanks and the drain sump of each safety system as well as the condensate collector of each air cooler should be provided with a water level indicator.

Balance of fluid flow

A.10. The periodic calculation of a mass balance can show quantitatively the amount of identified and/or unidentified small leaks in a given volume. For the calculation of a mass balance, fluid flows should be measured to establish the mass balances in the different systems. Measurements of temperature, pressure and humidity are combined to monitor for leaks from the containment in most operational states by enabling the periodic calculation of the mass of the containment atmosphere.

Activity measurements

A.11. Activity measurements are especially useful for detecting breaches that could otherwise go undetected by the measurement of other parameters. Activity should be measured to detect breaches in, and releases from, any of the multiple protective barriers. Hence, measurement locations should include:

— The reactor cooling circuit, to detect fuel failures;
— The containment atmosphere and drains, to detect failures in the primary circuit and connected circuits inside the containment;
— The secondary side circuit, to detect primary to secondary side leaks.

A.12. To detect leaks from the containment structure, the activity in the stack or in connected ventilated buildings should also be measured. Measurements of activity in the stack can be used to detect releases into the containment atmosphere before isolation and to detect leaks from the valves following isolation.

A.13. For double wall containments, it should be considered whether to make measurements of activity in the annulus ventilation system to detect leaks of radioactive material from the primary containment.

A.14. Provisions should be considered for obtaining samples of the containment atmosphere from outside the containment building, to be used for radiochemical analysis.

A.15. In addition, activity measurements in the following areas should be considered:

- In or around systems into which high energy contaminated fluids could enter owing to a lower functional pressure;
- In or around parts of systems connected to the primary circuit or the containment atmosphere but extending outside the containment.

Chemical analysis of water in drain sumps

A.16. Sampling from the drain sumps should be possible from outside the containment building so that leak sources can be identified by measurements of activity and of the concentrations of boron, lithium, potassium or other chemical elements or compounds.

A.17. Provision should be made for sampling and analysis of the drain waters outside the containment building.

Visible abnormalities

A.18. Video cameras, to facilitate visual inspection, should be installed at locations where leaks or other malfunctions can be expected and/or where personnel access is difficult. Mobile cameras should be available for use if and when the demand for them arises.

Noise and vibration

A.19. Acoustic analyses of noise should be performed to detect loose parts or abnormal behaviour of operating equipment.

A.20. The use of audio signals from the containment building for the detection of abnormalities should be considered. In addition, the use of spectral and Fourier transform analyses for acoustic noise signals may be considered.

Fire

A.21. Sensors to detect heat, smoke and/or flames should be installed in each compartment where there may be a risk of fire.

SELECTION OF INSTRUMENTATION

A.22. The following factors should be taken into account in the choice of instrumentation:

(a) The adequacy and sufficiency of the measuring range, sensitivity and accuracy;
(b) The need to extend the ranges of instrumentation in special operational situations, and the procedures necessary to accomplish this;
(c) Response times;
(d) Environmental qualification.

A.23. The instrumentation should be readily identifiable (e.g. by means of colour coding). In the design for the display of information to the operator in the control room, ergonomic considerations should be taken into account.

SAFETY CLASSIFICATION OF EQUIPMENT

A.24. The hardware items necessary to perform the functions mentioned in this Safety Guide belong essentially to instrumentation systems for safety related information and protection systems. However, this hardware may be partially shared with other systems of a higher safety category. In this case, the higher safety category should be adopted for the common part, and the remaining hardware should not unacceptably reduce the reliability of instrumentation systems classified in the higher category. Reference [17] should be used to establish the importance to safety of, and the appropriate design recommendations for, the monitoring instrumentation. These recommendations should cover:

— Failure rate analysis;
— Environmental qualification;
— Quality assurance;
— Checking, testing and calibration;
— In-service inspection.

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Annex I

EXAMPLES OF CONTAINMENT DESIGNS

I–1. This annex presents short descriptions of several concepts for containment systems now in use or in an advanced stage of design. The descriptions are not comprehensive but are intended to provide a general overview of how certain containment subsystems have been combined to carry out the containment functions.

FULL PRESSURE DRY CONTAINMENT IN PRESSURIZED WATER REACTORS

I–2. In this concept (Fig. I–1), the primary containment envelope is a steel shell or a concrete building (cylindrical or spherical) with a steel liner that surrounds the nuclear steam supply system. The containment encompasses all components of the reactor coolant system under primary pressure. It is designed as a full pressure containment; i.e. it is able to withstand the increases in pressure and temperature that occur in the event of any design basis accident, especially a LOCA. The atmospheric pressure in the containment envelope is usually maintained at a substantial negative gauge pressure during normal operations by means of a filtered air discharge system (i.e. a fan and HEPA filter).

I–3. Energy management in the building can be accomplished by an air cooler system or by a water spray system. In addition, the free volume of the containment and the structural heat sinks (the containment envelope and the structures within it) are used to limit peak pressures and temperatures in postulated conditions for pipe rupture accidents. The initial supply of water for the spray system and for the emergency core cooling system is held in a large tank. When this water has been used, suction for both the spray system and the emergency core cooling system is switched to the containment building sump. Water that is recirculated to the reactor vessel is sometimes cooled by means of heat exchangers. In most designs the recirculation water for the spray headers – which is also used to limit contamination of the containment atmosphere – is cooled by means of heat exchangers. When pipes rupture in systems other than the reactor coolant system, only the spray system is operated in the recirculation mode.

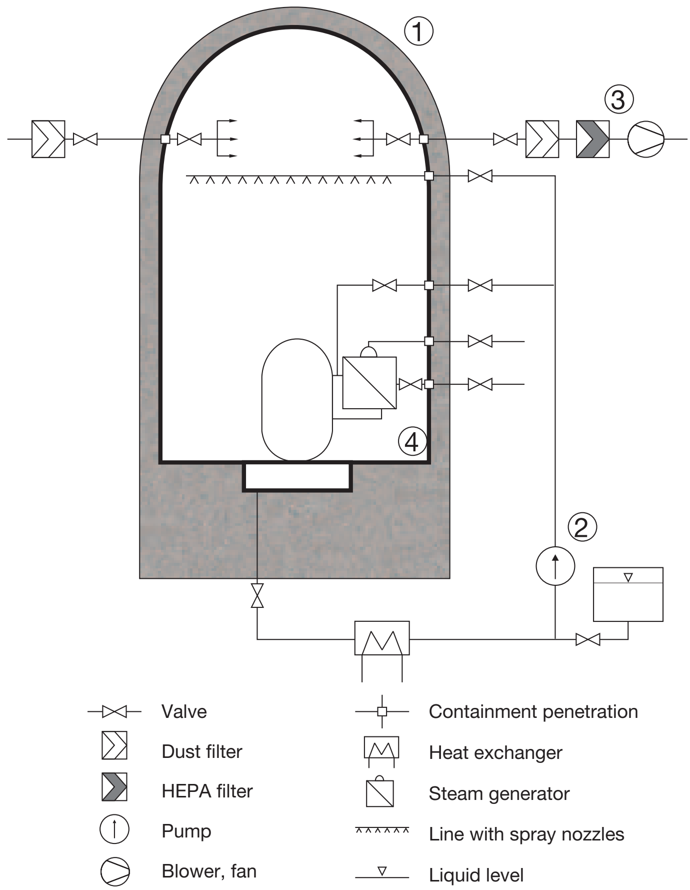


FIG. I–1. Schematic diagram of a full pressure dry containment system for a pressurized water reactor: 1, containment; 2, containment spray system; 3, filtered air discharge system; 4, liner.

FULL PRESSURE DOUBLE WALL CONTAINMENT IN PRESSURIZED WATER REACTORS

I–4. A typical full pressure double wall containment (Fig. I–2) consists of:

- A steel or concrete shell, basically cylindrical or spherical in shape (the containment);
- A concrete shell surrounding this containment (the secondary confinement);

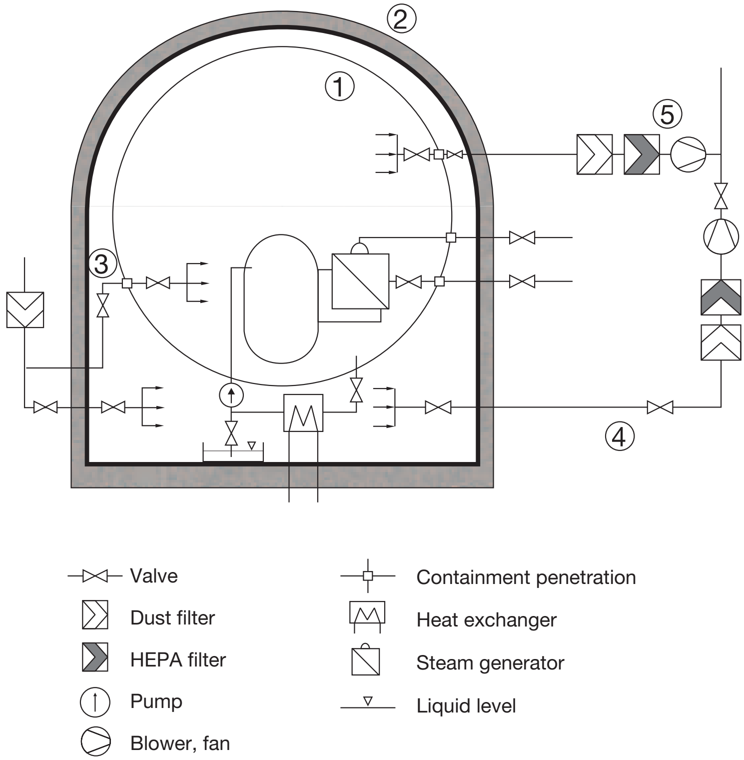


FIG. I–2. Schematic diagram of a full pressure double wall containment system for a pressurized water reactor: 1, full pressure containment; 2, secondary confinement; 3, annulus; 4, annulus evacuation system; 5, filtered air discharged system.

— An air extraction system for the annulus (the space between the containment and the secondary confinement).

I–5. The principle of the primary containment is similar to that of the full pressure dry containment in pressurized water reactors (paras I–2 and I–3). The secondary confinement fulfils the following three functions:

— In combination with the containment, it provides radiation shielding for plant personnel and the environment in normal operation and under accident conditions.
— It protects the systems and components that it contains against external postulated initiating events.

— It captures leakage from the containment in the annulus between the two shells.

I–6. Safety systems such as the emergency core cooling system and the high pressure boron injection system may be located in the annulus between the two shells if they can withstand the thermal loads and pressure loads calculated for design basis accidents. Leaks from the containment into the annulus are extracted and filtered under accident conditions by an air removal system, and their emission through the plant stack is controlled.

ICE CONDENSER CONTAINMENT IN PRESSURIZED WATER REACTORS

I–7. The ice condenser containment (Fig. I–3) system in pressurized water reactors uses a concept for the pressure suppression system in which the high pressure steam–air mixture resulting from an accident conditions pipe rupture is directed through vent doors into chambers containing baskets filled with ice. The steam condenses onto the surface of the ice in the baskets.

I–8. The containment is formed by a cylindrical structure divided into three isolated compartments: the lower area, which contains all the major components of the reactor coolant system, the ice condenser chambers and the main upper containment volume. Non-condensable gases (including noble gas fission products), which are forced into the ice condenser chambers, are vented through doors into the main upper containment volume.

I–9. An active spray system is used in the lower containment volume to reduce pressures and temperatures and to remove airborne radioiodine from the containment volume. The initial source of water for this system is a water storage tank.

I–10. After exhaustion of this water supply, a recirculation mode is initiated wherein the water is pumped from the building sump through a heat exchanger and then returned to the spray headers.

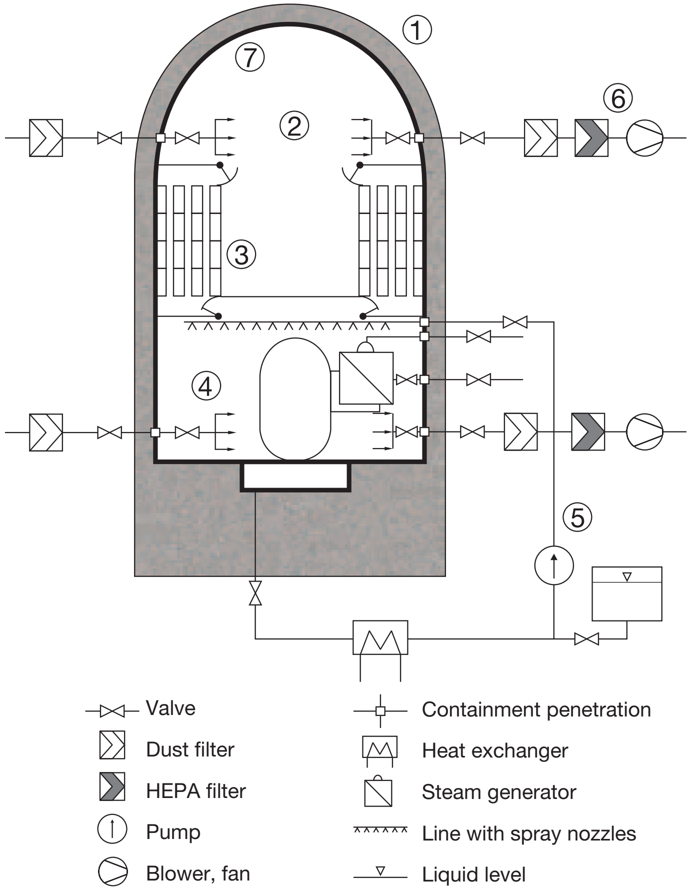


FIG. I–3. Schematic diagram of an ice condenser containment system for a pressurized water reactor; 1, containment; 2, upper containment volume; 3, ice condenser; 4, lower containment volume; 5, lower containment spray system; 6, filtered air discharge system; 7, liner.

BUBBLING CONDENSER CONTAINMENT IN PRESSURIZED WATER REACTORS

I–11. The bubbling condenser containment system (Fig. I–4) in pressurized water reactors uses a concept for the suppression pool in which the high pressure steam–air mixture resulting from the conditions following a LOCA is directed through submerged tubes into pools of water. The steam is condensed in the bubbling condenser pools.

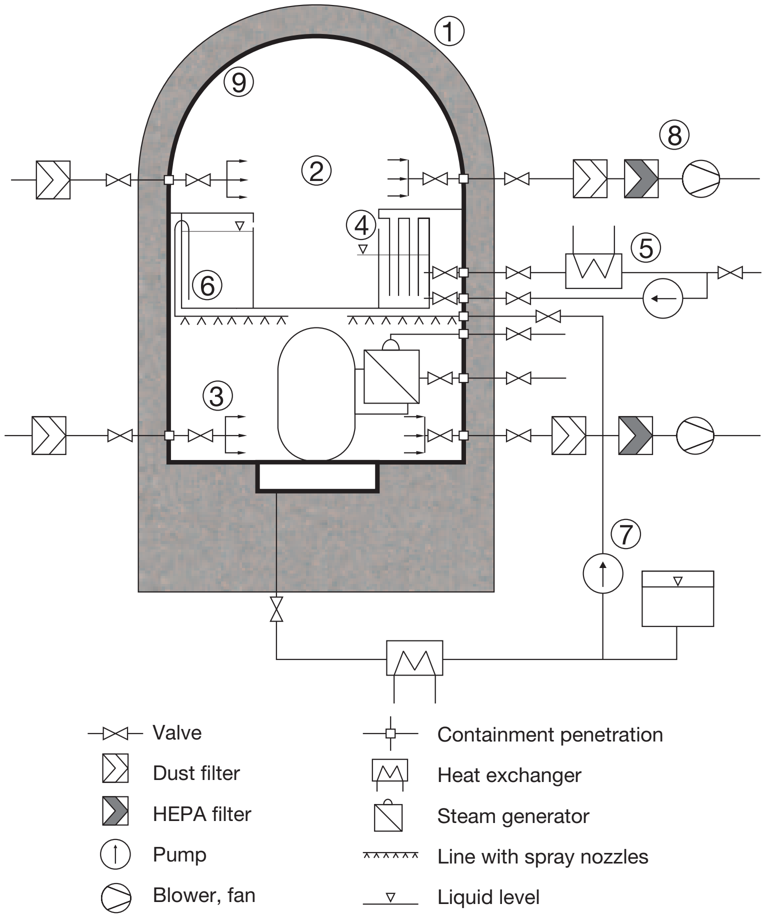


FIG. I–4. Schematic diagram of a bubbling condenser containment system for a pressurized water reactor: 1, containment; 2, upper containment volume (wet well); 3, lower containment volume (dry well); 4, bubbling condenser system (suppression pool); 5, suppression pool cooling system (not required if the heat capacity of the condenser system (4) is sufficiently large); 6, passive spray system; 7, active spray system; 8, filtered air discharge system; 9, liner.

I–12. The containment is a cylindrical concrete structure divided into three isolated volumes: the lower volume (dry well), which contains all the major components of the primary reactor coolant system, the bubbling condensers (suppression pools) and the main upper containment volume (wet well). Non-condensable gases (including noble gas fission products) that are driven into the bubbling condenser chambers are vented through openings into the main upper containment volume. Radioiodine and other soluble or particulate fission products are trapped in the bubbling condenser water pools.

I–13. Open tanks located in the upper containment volume are connected through U tubes to water spray nozzles in the lower containment volume. During fast pressure transients in the containment system, the passive sprinkler system is activated by the pressure differences between the water inlet of the U tubes submerged in the tanks and the nozzle outlet. An active spray system, with an independent stored water supply, is used to provide the functions of both energy management and radionuclide management. When the water supply in the spray tanks is exhausted, a recirculation mode is initiated and water from the building sump is pumped through a heat exchanger and sprayed into the lower containment volume. After a few minutes, the pressure in the lower volume falls below atmospheric pressure and an inverse pressure differential is created between the upper volume and the lower volume. Air is prevented from returning from the upper volume to the lower volume by hydroseals formed in the bubble tubes. Once the pressure in the lower volume has been reduced below atmospheric pressure, the leakage of radionuclides from it will cease.

PRESSURE SUPPRESSION CONTAINMENT IN BOILING WATER REACTORS

I–14. The pressure suppression containment system (Fig. I–5) in boiling water reactors is divided into two main compartments: a dry well housing the reactor coolant system and a wet well partly filled with water, whose function is to condense steam in the event of a LOCA. The two compartments are connected by pipes that are submerged in the water of the wet well. Spray systems are usually installed in both the dry well and the wet well. The reactor building surrounding the containment forms a secondary confinement which captures leaks from the containment. The containment envelope usually consists of either a concrete structure with a steel liner for leaktightness or a steel shell.

I–15. The purpose of the pressure suppression system is to reduce the pressure if a pipe in the reactor coolant system ruptures. The steam from a leak in these pipes enters the dry well and is passed through pipes into the water of the suppression pool (wet well), where it condenses, and the pressure in the dry well is reduced. The pressure suppression system helps in reducing the concentrations of airborne radioiodines by scrubbing radionuclides from the steam.

I–16. The wet well is also used as a heat sink for the automatic pressure relief system. This serves to limit the pressure rise in the reactor coolant system when the reactor cannot discharge steam to the turbine condenser system. The steam still produced by residual heat after shutdown of the reactor is passed into the water in the wet well via safety relief valves connected to the steam pipes within the dry well.

I–17. The concrete or steel structure of the reactor building surrounding the containment serves as protection against external events.

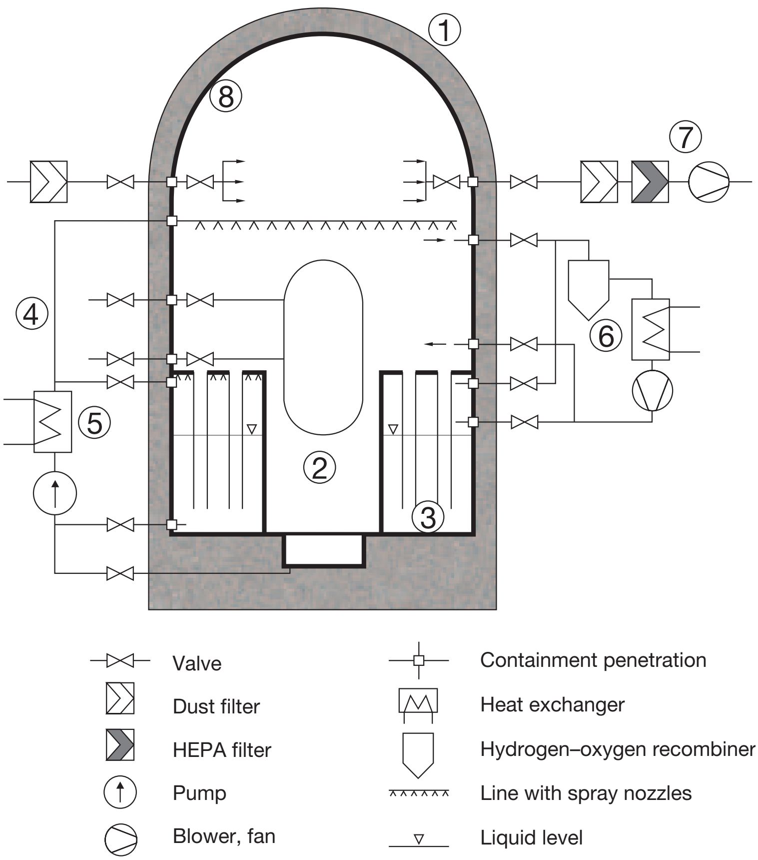


FIG. I–5. Schematic diagram of a pressure suppression containment system (the reactor building with its confinement function is not shown) for a boiling water reactor: 1, containment; 2, dry well; 3, suppression pool (wet well); 4, containment spray system; 5, suppression pool cooling system; 6, hydrogen control system; 7, filtered air discharge system; 8, liner.

I–18. The reactor building is held at a slightly negative gauge pressure in both operational states and accident conditions. In the event of an accident, leaks from the dry well into the reactor building are extracted and filtered by an air removal system to permit the use of controlled emission from the plant stack.

WEIR WALL PRESSURE SUPPRESSION CONTAINMENT IN BOILING WATER REACTORS

I–19. The weir wall pressure suppression containment system (Fig. I–6) in boiling water reactors consists of three different structures: the dry well, the containment envelope and the reactor building.

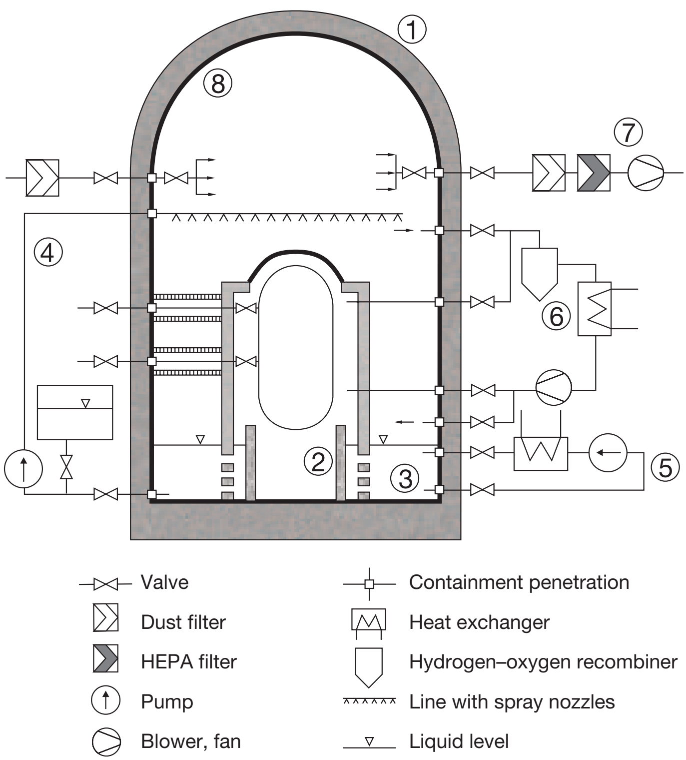


FIG. I–6. Schematic diagram of a weir wall pressure suppression containment system (the reactor building with its confinement function is not shown) for a boiling water reactor: 1, containment; 2, dry well; 3, suppression pool (weir well type); 4, containment spray system; 5, suppression pool cooling system; 6, hydrogen control system; 7, filtered air discharge system; 8, liner.

I–20. The function of the dry well structure is to enclose the reactor pressure vessel completely, and to create a pressure boundary to separate the reactor pressure vessel and its recirculation system from the containment vessel and the main body of the suppression pool. The dry well structure vents the steam–air mixture to the suppression pool. It also provides radiation shielding from the reactor and the piping of the nuclear steam supply system. The weir wall portion of the dry well structure functions as the inner wall of the suppression pool and serves to channel the steam released by a postulated LOCA through horizontal submerged vents into the suppression pool for condensation.

I–21. One of the functions of the reactor building is to provide protection against external missiles for the containment envelope, personnel and equipment. It also provides shielding from the fission products in the secondary confinement envelope, functions as a secondary containment barrier and provides a means for the collection and filtration of leaks of fission products from the steel containment vessel following a LOCA.

I–22. In postulated LOCA conditions, the pressure rise in the dry well reduces the water level between the weir wall and the wall of the dry well structure, uncovering the vents in the wall of the dry well structure, and forces the steam–air mixture in the dry well structure through the vents and into the suppression pool. The steam is condensed in the suppression pool water. Fission product noble gases and other non-condensables from the dry well structure escape from the surface of the pressure suppression pool into the containment envelope.

I–23. In the long term, an active spray system is used to reduce pressure and to reduce the concentration of airborne radionuclides within the containment envelope. This system takes water from the suppression pool by suction through a heat exchanger, following which the water is pumped to spray headers located in the dome of the containment envelope.

NEGATIVE PRESSURE CONTAINMENT FOR PRESSURIZED HEAVY WATER REACTORS

I–24. The term ‘negative pressure containment’ is used to describe a containment system that typically consists of the following subsystems (Fig. I–7):

(a) A containment envelope that comprises the reactor buildings, the connecting pressure relief duct, vacuum ducts, the vacuum building and all the containment extensions.
(b) A pressure relief system which comprises the pressure relief blowout panels that isolate the reactor buildings from the connecting pressure relief duct and the pressure relief valves that isolate this relief duct from the vacuum building.
(c) A vacuum system that maintains a subatmospheric pressure inside the vacuum building, so that when this building is connected to the

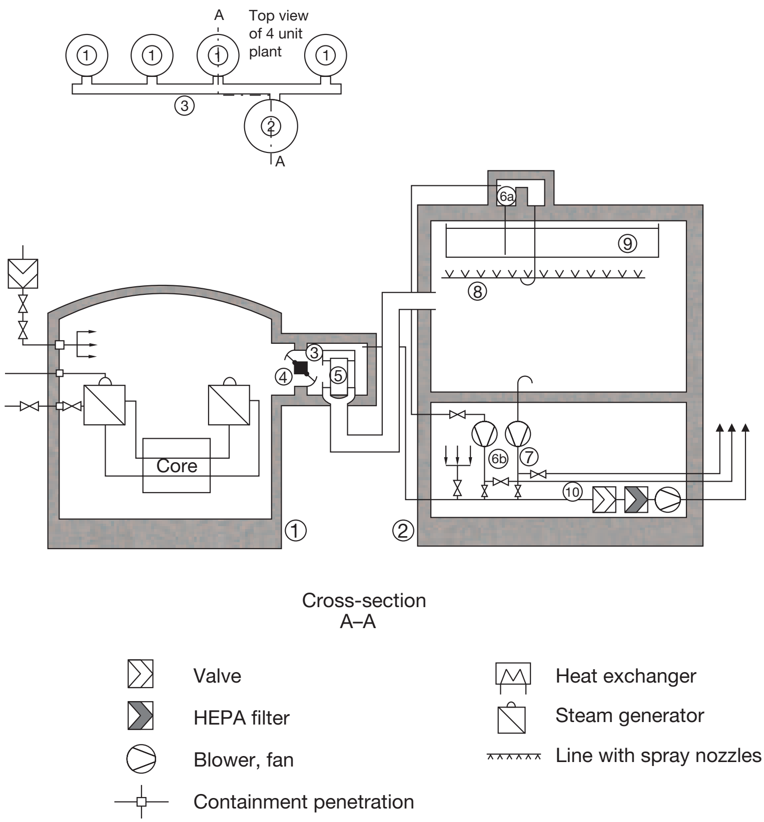


FIG. I–7. Schematic diagram of a negative pressure containment system for a pressurized heavy water reactor: 1, reactor buildings; 2, vacuum building; 3, pressure relief duct; 4, blow-out and blow-in panels; 5, pressure relief valve; 6a, upper chamber; 6b, evacuation system; 7, vacuum building evacuation system; 8, vacuum building spray system; 9, dousing tank; 10, filtered air discharge system.

containment the atmosphere from the containment passes into the vacuum building.

(d) An energy suppression system, comprising a dousing tank, upper chamber vacuum system and spray header, which is housed inside the vacuum building and which can absorb all the energy released to the vacuum building.

(e) An atmospheric control system that controls the atmosphere within the reactor buildings.

(f) A filtered air discharge system to help to maintain subatmospheric pressure within the containment envelope in the long term after an accident. The reactor buildings are maintained at slightly negative gauge pressures in both operational states and post-accident conditions.

I–25. Energy management is achieved by relieving the peak pressure in the reactor building to the vacuum building via the pressure relief system, which is actuated by a small increase in pressure in the reactor building. Additional energy suppression takes place when the steam drawn into the vacuum building is condensed by the spray system, which is automatically actuated by a change in pressure in the vacuum building. Long term heat removal from the containment is achieved by the atmospheric control system that cools the building air and by the heat exchangers in the recirculation system of the emergency core cooling system. Radionuclide management is accomplished by plate-out on the internal surfaces of the containment envelope, by washout afforded by the spray and by the leaktightness of the containment envelope.

PRESSURIZED CONTAINMENT IN PRESSURIZED HEAVY WATER REACTORS

I–26. The pressurized containment system (Fig. I–8) used in pressurized heavy water reactors for single unit plant designs typically consists of the following subsystems:

(a) A containment envelope comprising a prestressed, post-tensioned concrete reactor building and its extensions;

(b) An energy suppression system that consists of a dousing tank and a spray system that suppress the initial peak pressure;

(c) A reactor building cooling system to depressurize the containment in the longer term;

(d) A filtered air discharge system to help to maintain subatmospheric pressure within the containment envelope in the long term after an accident, and an atmospheric control system to aid in cleanup operations for the containment.

I–27. Upon the detection of radioactivity or high pressure in the reactor building, the isolation system closes the appropriate penetrations of the containment envelope.

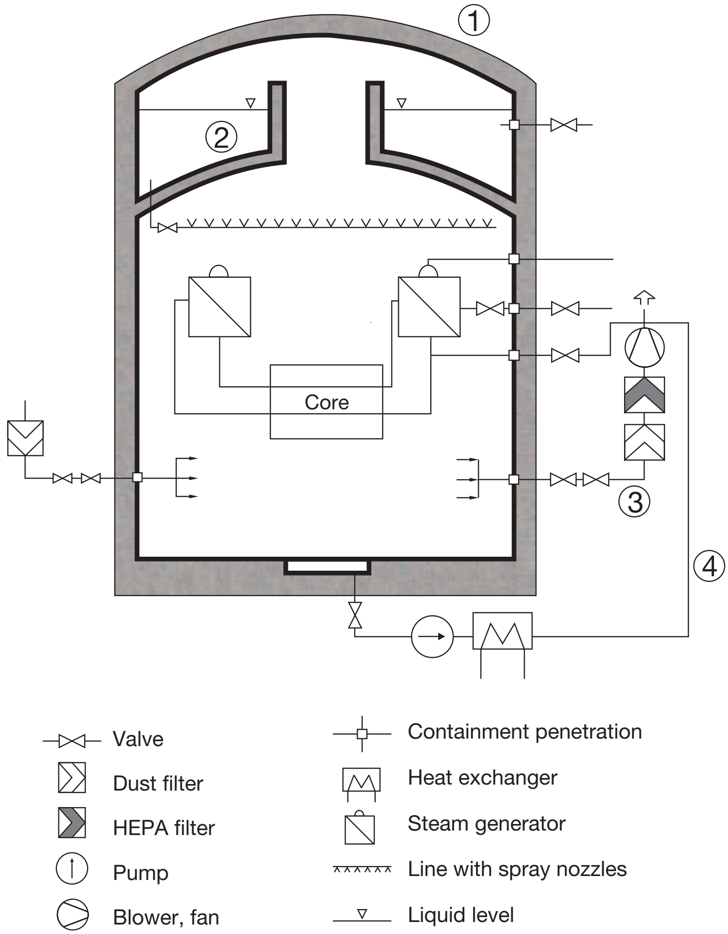


FIG. I–8. Schematic diagram of a pressurized containment system for a pressurized heavy water reactor: 1, containment; 2, dousing tank and spray system; 3, filtered air discharge system; 4, emergency core cooling system.

I–28. When high pressure is detected in the reactor building, the dousing system is also activated. The initial peak pressure following a LOCA is suppressed by the condensation of steam through the dousing spray system. Long term energy management is provided by the atmosphere control system (building air coolers) and by the heat exchangers in the recirculation system of the emergency core cooling system. Radionuclide management is accomplished by plate-out on the internal surfaces of the containment envelope, by washout afforded by the dousing spray system, by the leaktightness of the containment envelope and, in some plants, by pH control buffers in the sump.

FULL PRESSURE DOUBLE WALL CONTAINMENT IN PRESSURIZED WATER REACTORS FOR MITIGATION OF SEVERE ACCIDENTS

I–29. This type of containment works for control of design basis accidents largely in the same way as the double wall containment described in paras I–4 to I–6. The main differences are (Fig. I–9):

— The water storage for the emergency core cooling system at the bottom of the containment, which takes over the sump function and makes a switchover from injection to recirculation by the emergency core cooling system unnecessary;
— The location of the emergency core cooling system outside the annulus in safeguarded buildings.

I–30. Mitigation of severe accidents is achieved mainly by:

— A primary depressurization device that prevents containment bypasses via the steam generator tubes and failure of the reactor pressure vessel at high pressure, and thereby minimizes the consequences of missiles in the reactor pressure vessel and direct containment heating;
— Passive autocatalytic recombiners which prevent global detonation of hydrogen as well as local fast deflagration and the deflagration–detonation transition in combination with steam inerting, and the possibility of passive global convection within the containment;
— A core catcher in the molten core spreading compartment which stabilizes the material after temporary retention within the reactor pit by passive flooding and cooling with water from the in-containment water storage tank;
— An active containment heat removal system that ensures long term cooling of the containment atmosphere and of molten core material;

— An annulus subpressure system that exhausts the filtered containment leakage.

PASSIVE SIMPLIFIED BOILING WATER REACTORS

I–31. The containment of passive simplified boiling water reactors is constructed of reinforced concrete with an internal steel liner (Fig. I–10). The containment is usually subdivided into a dry well and a pressure suppression

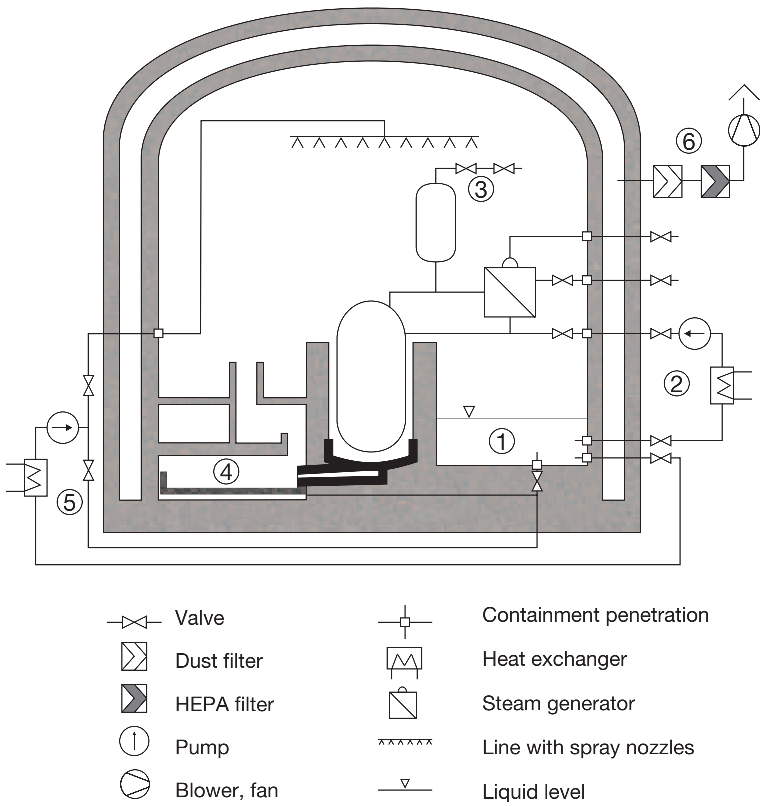


FIG. I–9. Schematic diagram of a full pressure double wall containment system for a pressurized water reactor with provision for mitigation of the consequences of a severe accident: 1, in-containment emergency core cooling system (ECCS) water storage; 2, ECCS; 3, primary depressurization device; 4, core catcher; 5, containment heat removal system; 6, annulus filtered air extraction system.

pool, which acts as a heat sink in accident conditions and provides water for active make-up for the reactor pressure vessel.

I–32. Passive cooling and core flooding features are commonly provided by core flooding pools, which act as heat sinks for the passive emergency condensers and also for the safety relief valve system. In addition, the flooding pool water is used for passive flooding of the reactor core following depressurization of the reactor pressure vessel in the event of a LOCA. Energy management in the containment is provided by passive containment cooling

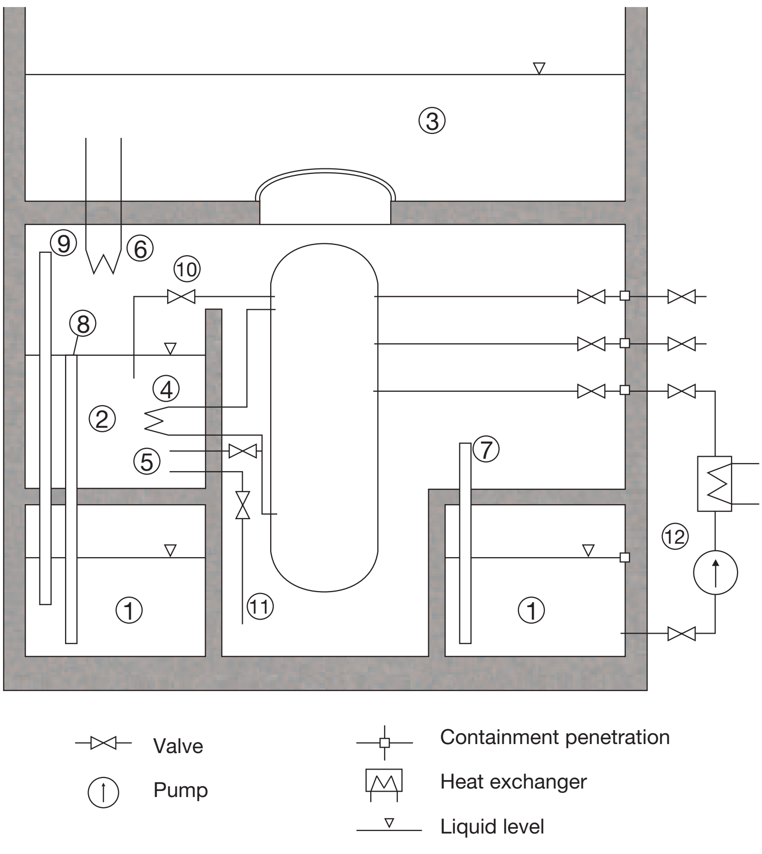


FIG. I–10. Schematic diagram of a passive simplified boiling water reactor: 1, pressure suppression pool; 2, core flooding pool; 3, dryer–separator storage pool; 4, emergency condensers; 5, core flooding lines; 6, containment cooling condenser; 7, vent pipes; 8, overflow pipes; 9, H_2 vent pipes; 10, safety relief valves; 11, dry well flooding line; 12, active residual heat removal system.

condensers that transfer the heat to the dryer–separator storage pool on top of the containment and transfer the condensate back into the core flooding pools.

I–33. For severe accident control, passive simplified boiling water reactors rely on external cooling of the reactor pressure vessel. The lower part of the dry well is flooded from the core flooding pools, and natural circulation inside the insulation of the reactor pressure vessel ensures the transfer of steam to the containment cooling condensers.

I–34. The containment is inerted during power operation to prevent the risk of hydrogen combustion. Hydrogen collected in the upper part of the containment is flushed through dedicated vent pipes into the wet well to avoid impairment of the function of the containment cooling condensers.

PASSIVE SIMPLIFIED PRESSURIZED WATER REACTORS

I–35. In the passive simplified pressurized water reactor concept (Fig. I–11), the containment vessel consists of a metallic shell surrounding the nuclear steam supply system. While the operational systems rely on proven pressurized water reactor technology, the safety systems for such reactors work passively, and do not depend on active components and safety grade support systems.

I–36. In accidents, the residual heat is transferred via steam to the containment atmosphere, either through the leak or through the passive core cooling system, which uses the in-containment refuelling water storage tank as a heat sink. The in-containment refuelling water storage tank is also used as a water source to provide the safety injection in the event of a LOCA, and flooding of the reactor cavity for external cooling of the reactor pressure vessel in the event of a severe accident.

I–37. Containment energy management is provided by passive external containment cooling, either by means of passive air circulation in the annulus or supported by external gravity spraying of the containment vessel. The design features of the containment promote flooding of the containment cavity region in accidents and submersion of the lower head of the reactor pressure vessel in water. The liquid effluents released during a LOCA through the break are also directed to the reactor cavity. After collection of the water in the lower part of the containment during an accident, a water level is reached that ensures that the water is drained back via sump screens into the reactor coolant system.

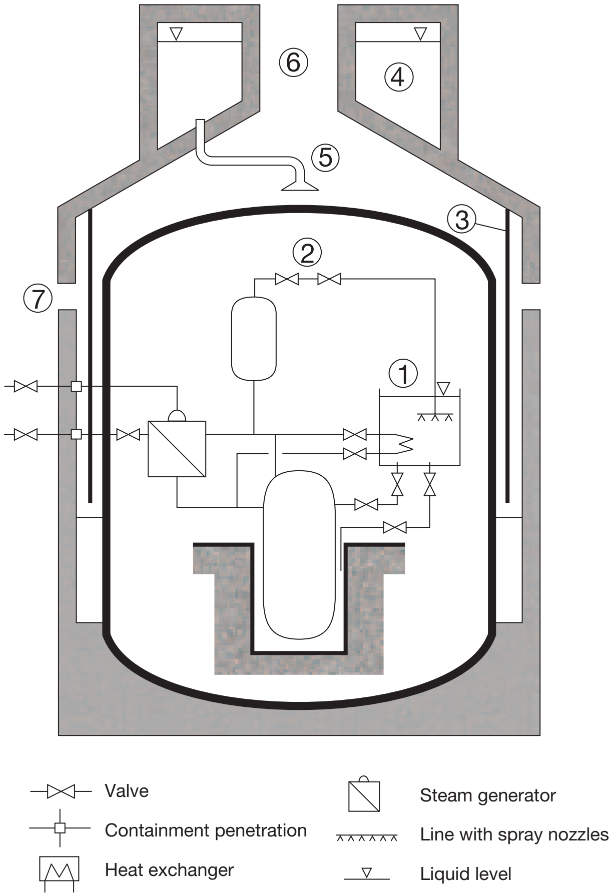
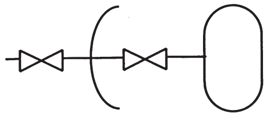
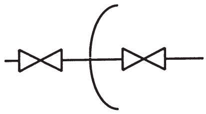
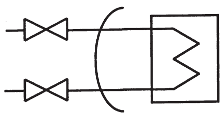
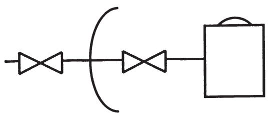
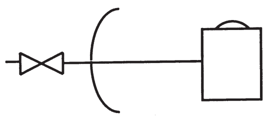
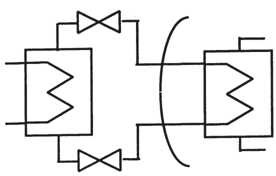


FIG. I–11. Schematic diagram of a passive simplified pressurized water reactor: 1, in-containment refuelling water storage tank; 2, primary circuit depressurization system; 3, air baffle; 4, passive containment cooling system: gravity drain water tank; 5, containment vessel gravity spray; 6, natural convection air discharge; 7, natural convection air intake.

Annex II

ILLUSTRATION OF CATEGORIES OF ISOLATION FEATURES

TABLE II–1. CATEGORIES OF ISOLATION FEATURES

See para.	Schematic configuration	Example
4.171(a)		Chemical and volume control system (pressurized water reactors). Main steam line (boiling water reactors)
4.171(b)		Ventilation duct
4.172		Ventilation cooling inside containment
4.172		Steam generator blowdown line
4.172		Main steam line (pressurized water reactors)
4.173		Intermediate cooling

Annex III

SEVERE ACCIDENT PHENOMENA

III–1. A severe accident is defined as one for which the accident conditions are more severe than those for a design basis accident and involve significant core degradation. Severe accidents begin with loss of cooling for the reactor core and initial heating-up of the fuel, and continue until either:

(a) The degraded core is stabilized and cooled within the reactor pressure vessel, or
(b) The fuel overheats to the point of melting, the reactor pressure vessel is breached and molten core material is released into the containment.

The potential detrimental effects of a severe accident include:

— Overheating and overpressurization of the containment due to molten core material settling into the reactor cavity,
— The generation of significant amounts of hydrogen and other non-condensable gases owing to the interaction between molten core material and concrete,
— Structural damage to metallic components of the containment due to direct contact with molten core material,
— High pressure ejection of molten core material and subsequent rapid direct heating of the containment.

III–2. The phase of progressive in-vessel heating-up and melting establishes the initial conditions for the assessment of the thermal and mechanical loads that may ultimately threaten the integrity of the containment.

III–3. The ex-vessel progression of severe accidents is affected by the mode and timing of the failure of the reactor pressure vessel, the pressure in the reactor coolant system at vessel failure, the composition, amount and nature of the molten core debris expelled, the type of concrete used in the construction of the containment, and the availability of water in the reactor cavity. Some highly energetic phenomena may be caused by severe accidents. Such phenomena could cause the ultimate load bearing capacity of containments constructed by means of existing technologies to be exceeded, and consequently lead to a large early release of radionuclides to the environment.

HIGH PRESSURE MELT EJECTION

III–4. For some reactor types the risks associated with severe accidents occurring in conjunction with high pressures in the reactor coolant system would, without countermeasures, contribute significantly to the overall risks associated with severe accidents. Severe accidents occurring in conjunction with high pressures in the reactor coolant system could give rise to unacceptable challenges to the containment barrier.

III–5. At high pressures in the reactor coolant system, the molten core material from the reactor vessel could be ejected in jet form, causing fragmentation into small particles. It may be possible for the core debris ejected from the vessel to be swept out of the reactor cavity and into the upper containment. Finely fragmented and dispersed core debris could cause the containment atmosphere to heat up, leading to large pressure spikes. In addition, chemical reactions of the particulate core debris with oxygen and steam could add to the pressurization loads. Hydrogen, either pre-existing in the containment or produced during the direct heating of the containment, could ignite, adding to the loads on the containment. This phenomenon is known as high pressure melt ejection with direct containment heating.

III–6. Loads due to a direct containment heating event may be mitigated by using a design of reactor cavity that reduces the amount of ejected core debris that reaches the upper containment, to the extent that the features of any such design do not unduly interfere with plant operations, including refuelling, maintenance or surveillance activities. Examples of design features of the cavity that would reduce the amount of ejected core debris that reaches the upper containment include:

(a) Ledges or walls to deflect core debris,
(b) Indirect paths from the lower reactor cavity to the upper containment.

CONTAINMENT BYPASS

III–7. For pressurized water reactors, the likelihood of creep failure of steam generator tubes for some severe accidents at high pressure of the reactor coolant is not negligible, with the possible consequence of a containment bypass.

III–8. To minimize the potential for containment failure or containment bypass in severe accidents at high pressures of the reactor coolant, the plant features may be enhanced, if necessary, to depressurize the reactor coolant system reliably so as to prevent this process from occurring.

STEAM EXPLOSIONS

III–9. Postulated in-vessel steam explosions are generally judged not to threaten the integrity of the containment.

III–10. Failure of the reactor vessel at high or low pressures, in conjunction with the presence of water within the reactor cavity, may lead to interactions between fuel and coolant with the potential for rapid steam generation or steam explosions. Rapid steam generation may give rise to the pressurization of containment compartments beyond the capability of the containment to relieve the pressure, so that the containment fails due to local overpressurization. Steam explosions may be caused by the rapid mixing of finely fragmented core material with surrounding water, resulting in the rapid vaporization and acceleration of the surrounding water, creating substantial pressure and impact loads.

III–11. The presence of water in the reactor cavity can be avoided by means of a suitable layout if important components of the containment, such as the supporting reactor cavity wall and the containment liner, are not capable of resisting these high impulse loads.

GENERATION OF COMBUSTIBLE GASES

III–12. The generation and combustion of large volumes of hydrogen and carbon monoxide are severe accident phenomena that can threaten the integrity of the containment. The major cause of the generation of hydrogen is the oxidation of zirconium metal and, to a lesser extent, the interaction of steel or any other metallic component with steam when the metal reaches temperatures well above normal operating temperatures.

III–13. In addition, ex-vessel hydrogen generation needs to be considered. Such hydrogen is produced mainly as a result of the reactions of ex-vessel metallic core debris with steam, and in the long term by molten core–concrete interactions (para. III–17) and by the extended radiolysis of sump water.

III–14. Molten core–concrete interactions may also produce carbon monoxide, which is also combustible under certain conditions.

III–15. Under severe accident conditions, significant hydrogen concentrations could be reached locally in a short time (of the order of some minutes to an hour, depending on the containment design, the scenario and the location) and globally in a longer period of time.

III–16. When the ignition limit is exceeded, combustion of hydrogen is possible and can take different forms, depending on the concentrations, the atmospheric conditions in the containment and the geometry: diffusion flames (which are mainly responsible for thermal loads), slow deflagrations (which are mainly responsible for quasi-static pressure loads), fast deflagrations (for which dynamic effects become important) and detonations (for which the velocity of the flame front exceeds the speed of sound in the unburnt gas, giving rise to extremely severe dynamic effects). Depending on the mode of combustion, the integrity of the containment may be threatened by stresses beyond the structural design limits.

MOLTEN CORE–CONCRETE INTERACTIONS

III–17. Contact between molten core material and concrete in the reactor cavity will result in molten core–concrete interactions. This process involves the decomposition of concrete from core debris and can challenge the containment by various mechanisms, including the following:

(a) Pressurization as a result of the production of steam and non-condensable gases to the point of containment rupture;
(b) Transport of high temperature gases and aerosols into the containment, leading to high temperature failure of the containment seals and penetrations;
(c) Melt-through of the containment liner or the basemat;
(d) Melt-through of reactor support structures, leading to relocation of the reactor vessel and the tearing of containment penetrations;
(e) Production of combustible gases such as hydrogen and carbon monoxide.

Molten core–concrete interactions are affected by many factors, including the availability of water in the reactor cavity, the geometry and physical layout of the containment, the composition and amount of the core debris, the temperature of the core debris, and the type of concrete.

PRESSURIZATION OF THE CONTAINMENT

III–18. Potential longer term challenges to the containment involve slow releases of mass and energy, typified by the generation of decay heat and non-condensable gases. The risks associated with these specific challenges can be judged on the basis of probabilistic safety assessments and research studies on severe accidents relevant to the specific design of the plant. Generally, the effectiveness of any proposed design feature can be assessed by means of a combination of probabilistic safety assessment, best estimate models and computer codes, together with consideration of the effects of initial boundary conditions and uncertainties in the modelling.

III–19. The long term pressurization of the containment may also be affected by the availability or unavailability of containment sprays (or heat exchangers) and air coolers.

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