

IAEA Safety Standards

for protecting people and the environment

Design of the Reactor Core for Nuclear Power Plants

Specific Safety Guide

No. SSG-52



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IAEA SAFETY STANDARDS

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DESIGN OF THE REACTOR CORE FOR NUCLEAR POWER PLANTS



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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA SAFETY STANDARDS SERIES No. SSG-52

DESIGN OF THE REACTOR CORE FOR NUCLEAR POWER PLANTS

SPECIFIC SAFETY GUIDE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2019

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FOREWORD

The IAEA's Statute authorizes the Agency to “establish or adopt... standards of safety for protection of health and minimization of danger to life and property” — standards that the IAEA must use in its own operations, and which States can apply by means of their regulatory provisions for nuclear and radiation safety. The IAEA does this in consultation with the competent organs of the United Nations and with the specialized agencies concerned. A comprehensive set of high quality standards under regular review is a key element of a stable and sustainable global safety regime, as is the IAEA's assistance in their application.

The IAEA commenced its safety standards programme in 1958. The emphasis placed on quality, fitness for purpose and continuous improvement has led to the widespread use of the IAEA standards throughout the world. The Safety Standards Series now includes unified Fundamental Safety Principles, which represent an international consensus on what must constitute a high level of protection and safety. With the strong support of the Commission on Safety Standards, the IAEA is working to promote the global acceptance and use of its standards.

Standards are only effective if they are properly applied in practice. The IAEA's safety services encompass design, siting and engineering safety, operational safety, radiation safety, safe transport of radioactive material and safe management of radioactive waste, as well as governmental organization, regulatory matters and safety culture in organizations. These safety services assist Member States in the application of the standards and enable valuable experience and insights to be shared.

Regulating safety is a national responsibility, and many States have decided to adopt the IAEA's standards for use in their national regulations. For parties to the various international safety conventions, IAEA standards provide a consistent, reliable means of ensuring the effective fulfilment of obligations under the conventions. The standards are also applied by regulatory bodies and operators around the world to enhance safety in nuclear power generation and in nuclear applications in medicine, industry, agriculture and research.

Safety is not an end in itself but a prerequisite for the purpose of the protection of people in all States and of the environment — now and in the future. The risks associated with ionizing radiation must be assessed and controlled without unduly limiting the contribution of nuclear energy to equitable and sustainable development. Governments, regulatory bodies and operators everywhere must ensure that nuclear material and radiation sources are used beneficially, safely and ethically. The IAEA safety standards are designed to facilitate this, and I encourage all Member States to make use of them.

THE IAEA SAFETY STANDARDS

BACKGROUND

Radioactivity is a natural phenomenon and natural sources of radiation are features of the environment. Radiation and radioactive substances have many beneficial applications, ranging from power generation to uses in medicine, industry and agriculture. The radiation risks to workers and the public and to the environment that may arise from these applications have to be assessed and, if necessary, controlled.

Activities such as the medical uses of radiation, the operation of nuclear installations, the production, transport and use of radioactive material, and the management of radioactive waste must therefore be subject to standards of safety.

Regulating safety is a national responsibility. However, radiation risks may transcend national borders, and international cooperation serves to promote and enhance safety globally by exchanging experience and by improving capabilities to control hazards, to prevent accidents, to respond to emergencies and to mitigate any harmful consequences.

States have an obligation of diligence and duty of care, and are expected to fulfil their national and international undertakings and obligations.

International safety standards provide support for States in meeting their obligations under general principles of international law, such as those relating to environmental protection. International safety standards also promote and assure confidence in safety and facilitate international commerce and trade.

A global nuclear safety regime is in place and is being continuously improved. IAEA safety standards, which support the implementation of binding international instruments and national safety infrastructures, are a cornerstone of this global regime. The IAEA safety standards constitute a useful tool for contracting parties to assess their performance under these international conventions.

THE IAEA SAFETY STANDARDS

The status of the IAEA safety standards derives from the IAEA's Statute, which authorizes the IAEA to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property, and to provide for their application.

With a view to ensuring the protection of people and the environment from harmful effects of ionizing radiation, the IAEA safety standards establish fundamental safety principles, requirements and measures to control the radiation exposure of people and the release of radioactive material to the environment, to restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, and to mitigate the consequences of such events if they were to occur. The standards apply to facilities and activities that give rise to radiation risks, including nuclear installations, the use of radiation and radioactive sources, the transport of radioactive material and the management of radioactive waste.

Safety measures and security measures¹ have in common the aim of protecting human life and health and the environment. Safety measures and security measures must be designed and implemented in an integrated manner so that security measures do not compromise safety and safety measures do not compromise security.

The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. They are issued in the IAEA Safety Standards Series, which has three categories (see Fig. 1).

Safety Fundamentals

Safety Fundamentals present the fundamental safety objective and principles of protection and safety, and provide the basis for the safety requirements.

Safety Requirements

An integrated and consistent set of Safety Requirements establishes the requirements that must be met to ensure the protection of people and the environment, both now and in the future. The requirements are governed by the objective and principles of the Safety Fundamentals. If the requirements are not met, measures must be taken to reach or restore the required level of safety. The format and style of the requirements facilitate their use for the establishment, in a harmonized manner, of a national regulatory framework. Requirements, including numbered ‘overarching’ requirements, are expressed as ‘shall’ statements. Many requirements are not addressed to a specific party, the implication being that the appropriate parties are responsible for fulfilling them.

Safety Guides

Safety Guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus that it

¹ See also publications issued in the IAEA Nuclear Security Series.

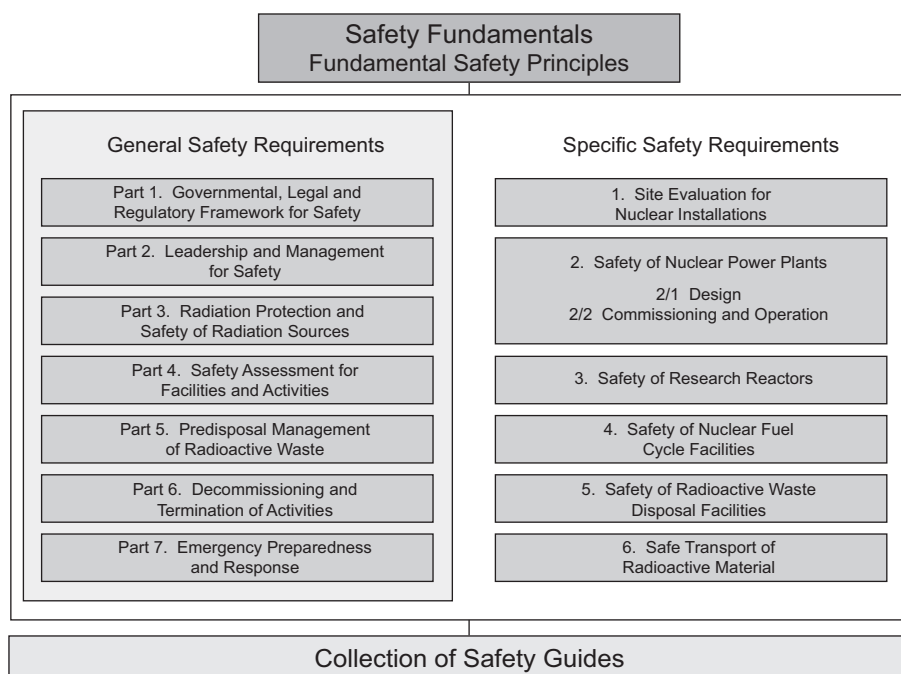


FIG. 1. The long term structure of the IAEA Safety Standards Series.

is necessary to take the measures recommended (or equivalent alternative measures). The Safety Guides present international good practices, and increasingly they reflect best practices, to help users striving to achieve high levels of safety. The recommendations provided in Safety Guides are expressed as ‘should’ statements.

APPLICATION OF THE IAEA SAFETY STANDARDS

The principal users of safety standards in IAEA Member States are regulatory bodies and other relevant national authorities. The IAEA safety standards are also used by co-sponsoring organizations and by many organizations that design, construct and operate nuclear facilities, as well as organizations involved in the use of radiation and radioactive sources.

The IAEA safety standards are applicable, as relevant, throughout the entire lifetime of all facilities and activities — existing and new — utilized for peaceful purposes and to protective actions to reduce existing radiation risks. They can be

used by States as a reference for their national regulations in respect of facilities and activities.

The IAEA's Statute makes the safety standards binding on the IAEA in relation to its own operations and also on States in relation to IAEA assisted operations.

The IAEA safety standards also form the basis for the IAEA's safety review services, and they are used by the IAEA in support of competence building, including the development of educational curricula and training courses.

International conventions contain requirements similar to those in the IAEA safety standards and make them binding on contracting parties. The IAEA safety standards, supplemented by international conventions, industry standards and detailed national requirements, establish a consistent basis for protecting people and the environment. There will also be some special aspects of safety that need to be assessed at the national level. For example, many of the IAEA safety standards, in particular those addressing aspects of safety in planning or design, are intended to apply primarily to new facilities and activities. The requirements established in the IAEA safety standards might not be fully met at some existing facilities that were built to earlier standards. The way in which IAEA safety standards are to be applied to such facilities is a decision for individual States.

The scientific considerations underlying the IAEA safety standards provide an objective basis for decisions concerning safety; however, decision makers must also make informed judgements and must determine how best to balance the benefits of an action or an activity against the associated radiation risks and any other detrimental impacts to which it gives rise.

DEVELOPMENT PROCESS FOR THE IAEA SAFETY STANDARDS

The preparation and review of the safety standards involves the IAEA Secretariat and five safety standards committees, for emergency preparedness and response (EPReSC) (as of 2016), nuclear safety (NUSSC), radiation safety (RASSC), the safety of radioactive waste (WASSC) and the safe transport of radioactive material (TRANSSC), and a Commission on Safety Standards (CSS) which oversees the IAEA safety standards programme (see Fig. 2).

All IAEA Member States may nominate experts for the safety standards committees and may provide comments on draft standards. The membership of the Commission on Safety Standards is appointed by the Director General and includes senior governmental officials having responsibility for establishing national standards.

A management system has been established for the processes of planning, developing, reviewing, revising and establishing the IAEA safety standards.

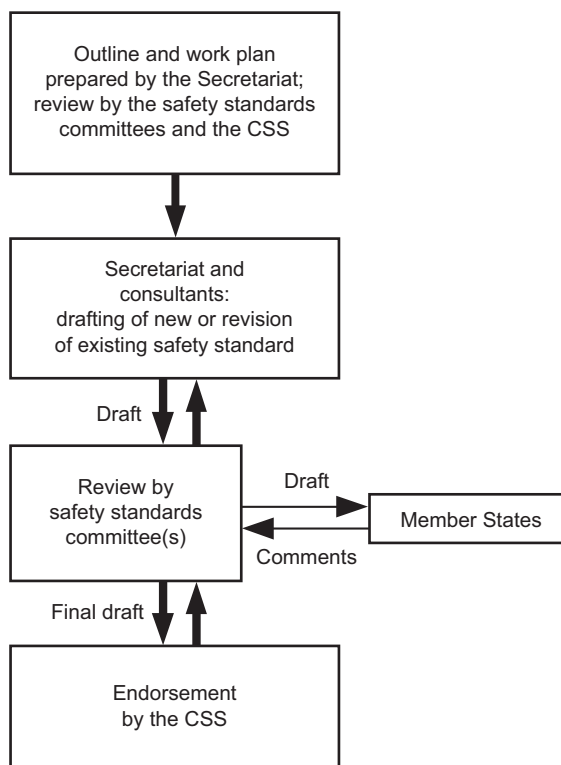


FIG. 2. The process for developing a new safety standard or revising an existing standard.

It articulates the mandate of the IAEA, the vision for the future application of the safety standards, policies and strategies, and corresponding functions and responsibilities.

INTERACTION WITH OTHER INTERNATIONAL ORGANIZATIONS

The findings of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the recommendations of international expert bodies, notably the International Commission on Radiological Protection (ICRP), are taken into account in developing the IAEA safety standards. Some safety standards are developed in cooperation with other bodies in the United Nations system or other specialized agencies, including the Food and Agriculture Organization of the United Nations, the United Nations Environment Programme, the International Labour Organization, the OECD Nuclear Energy Agency, the Pan American Health Organization and the World Health Organization.

INTERPRETATION OF THE TEXT

Safety related terms are to be understood as defined in the IAEA Safety Glossary (see <http://www-ns.iaea.org/standards/safety-glossary.htm>). Otherwise, words are used with the spellings and meanings assigned to them in the latest edition of The Concise Oxford Dictionary. For Safety Guides, the English version of the text is the authoritative version.

The background and context of each standard in the IAEA Safety Standards Series and its objective, scope and structure are explained in Section 1, Introduction, of each publication.

Material for which there is no appropriate place in the body text (e.g. material that is subsidiary to or separate from the body text, is included in support of statements in the body text, or describes methods of calculation, procedures or limits and conditions) may be presented in appendices or annexes.

An appendix, if included, is considered to form an integral part of the safety standard. Material in an appendix has the same status as the body text, and the IAEA assumes authorship of it. Annexes and footnotes to the main text, if included, are used to provide practical examples or additional information or explanation. Annexes and footnotes are not integral parts of the main text. Annex material published by the IAEA is not necessarily issued under its authorship; material under other authorship may be presented in annexes to the safety standards. Extraneous material presented in annexes is excerpted and adapted as necessary to be generally useful.

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1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide provides recommendations on the design of the reactor core to meet the requirements established in IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design [1]. This publication is a revision of IAEA Safety Standards Series No. NS-G-1.12¹, which it supersedes.

OBJECTIVE

1.2. The objective of this Safety Guide is to provide recommendations on meeting the safety requirements established in SSR-2/1 (Rev. 1) [1] for the design of the reactor core for nuclear power plants.

SCOPE

1.3. This Safety Guide is applicable primarily to land based stationary nuclear power plants with water cooled reactors for electricity generation or for other heat production (such as district heating or desalination). All recommendations are applicable to light water reactors (i.e. pressurized water reactors and boiling water reactors) and are generally applicable to pressurized heavy water reactors unless otherwise specified. This Safety Guide may also be applied, with judgement, to other reactor types (e.g. gas cooled reactors, floating reactors, small and modular reactors, innovative reactors) to contribute to the interpretation of the requirements that have to be considered in developing the design of the reactor core.

1.4. The reactor core is the central part of a nuclear reactor where nuclear fission occurs. The reactor core consists of four basic systems and components (i.e. the fuel (including fuel rods and the fuel assembly structure), the coolant, the moderator and the control rods), as well as additional structures (e.g. reactor pressure vessel internals, core support plates, and the lower and upper internal structure in light water reactors). This Safety Guide addresses the safety aspects

¹ INTERNATIONAL ATOMIC ENERGY AGENCY, Design of the Reactor Core for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-1.12, IAEA, Vienna (2005).

of the core design and includes neutronic aspects, thermohydraulic aspects, thermomechanical aspects, structural mechanical aspects, aspects relating to reactor core control, shutdown and monitoring, and core management aspects for the safe design of the reactor core for nuclear power plants. Specifically, the following structures, systems and components (SSCs) are covered:

- (a) Fuel rods, containing fuel pellets with or without burnable absorbers in cladding tubes, which generate and transfer heat to the coolant.
- (b) Fuel assemblies, comprising bundles of fuel rods, along with structures and components (e.g. guide tubes, spacer grids, bottom and top nozzles, fuel channels) that maintain the fuel rods and fuel assemblies in a predetermined geometrical configuration.
- (c) The reactor core control system, the shutdown system and the monitoring system, including components and equipment used for reactivity control and shutdown, comprising neutron absorbers (solid or liquid), the associated structure and the drive mechanism.
- (d) Support structures that provide the foundation for the core within the reactor vessel (within the calandria for pressurized heavy water reactors), the structure for guiding the flow (for pressurized water reactors) and the guide tubes for reactivity control devices (for pressurized heavy water reactors).
- (e) The coolant.
- (f) The moderator.
- (g) Other core components such as steam separators (for boiling water reactors) and neutron sources. These are considered only to a limited extent in this Safety Guide.

1.5. This Safety Guide is intended mainly for NPPs that use natural and enriched UO_2 fuels and plutonium-blended UO_2 fuel (mixed oxide fuel) with zirconium based alloy cladding. Unless otherwise specified, all recommendations apply to these fuel types.

1.6. For innovative fuel materials, such as uranium nitride fuel or inert matrix fuel, or cladding materials other than zirconium based alloys, this Safety Guide can be applied with judgement.

1.7. The design of the reactor core may interface with the design of other reactor systems and other related aspects. In this Safety Guide, recommendations on these interfacing systems and aspects are provided mainly to identify their functional interface. The relevant Safety Guides are referenced, as appropriate, in order to clarify the interfaces.

1.8. The terms used in this Safety Guide are to be understood as defined in the IAEA Safety Glossary [2]. Explanations of additional technical terminology are provided in Annex I.

STRUCTURE

1.9. Section 2 describes general considerations for safe core design based on requirements for the management of safety, principal technical requirements and general design requirements established in sections 3, 4 and 5 of SSR-2/1 (Rev. 1) [1], respectively. Section 3 describes specific considerations for the safe design of fuel rods, fuel assemblies, core structures and core components, and the core control system and the reactor shutdown system based on specific design requirements (i.e. Requirements 43–46) of SSR-2/1 (Rev. 1) [1]. Section 4 provides recommendations on the qualification and testing of the SSCs of the reactor core.

1.10. Annex I provides supplementary technical information for clarification of the terminology used in this Safety Guide, additional background information and examples supporting specified design recommendations. Annex II describes important items that need to be addressed within the design of the fuel rod, fuel assembly, reactivity control assembly, neutron source assembly and hydraulic plug assembly.

2. GENERAL SAFETY CONSIDERATIONS IN THE DESIGN OF THE REACTOR CORE

MANAGEMENT SYSTEM

2.1. The design of the reactor core should take into account the recommendations of IAEA Safety Standards Series Nos GS-G-3.1, Application of the Management System for Facilities and Activities [3], and GS-G-3.5, The Management System for Nuclear Installations [4] to meet Requirements 1–3 of SSR-2/1 (Rev. 1) [1], and the requirements of IAEA Safety Standards Series No. GSR Part 2, Leadership and Management for Safety [5].

DESIGN OBJECTIVES

Fundamental safety functions

2.2. The three fundamental safety functions, described in Requirement 4 of SSR-2/1 (Rev. 1) [1], are required to be ensured in the design of the reactor core for operational states and for a wide range of accident conditions. The fundamental safety functions as they apply specifically to the design of the reactor core are as follows:

- (a) Control of reactivity;
- (b) Removal of heat from the reactor core;
- (c) Confinement of radioactive material.

Adequate design based on the concept of defence in depth

2.3. Adequate design (i.e. capable, reliable and robust design) of the reactor core, based on the concept of defence in depth, will enable achievement of the fundamental safety functions, together with provision for associated reactor safety features.

2.4. Physical barriers considered as part of, or affecting the design of, the reactor core include the fuel matrix, the fuel cladding and the boundary of the reactor coolant system. For normal operation and anticipated operational occurrences, fuel rods are required to be designed such that their structural integrity and a leaktight barrier are maintained to prevent the transport of fission products into the coolant (see Requirement 43 of SSR-2/1 (Rev. 1) [1]).

2.5. For design basis accidents, fuel cladding failures should be kept to a minimum. Components of the reactor core and its associated structures should be designed with account taken of the safety functions to be achieved. In addition, the reactor core is required to be designed to maintain a configuration such that it can be shut down and remains coolable for design basis accidents and design extension conditions without significant fuel degradation (see Requirement 44 of SSR-2/1 (Rev. 1) [1]).

Proven engineering practices

2.6. The reactor core should be of a design that has been proven either in equivalent applications, by means of operating experience or the results of relevant research programmes, or, as appropriate, in accordance with the design,

design verification and validation processes stated in applicable codes and standards (in accordance with paras 4.14 and 4.16 of SSR-2/1 (Rev. 1) [1]).

Safety assessment in the design process

2.7. Paragraph. 4.17 of SSR-2/1 (Rev. 1) [1] states (footnote omitted):

“The safety assessments shall be commenced at an early point in the design process, with iterations between design activities and confirmatory analytical activities, and shall increase in scope and level of detail as the design programme progresses.”

Recommendations on safety assessment methods are provided in IAEA Safety Standards Series No. SSG-2 (Rev. 1), Deterministic Safety Analysis for Nuclear Power Plants [6].

Features to facilitate radioactive waste management

2.8. The design of fuel rods and fuel assemblies should provide features that will facilitate future waste management (including reprocessing when applicable). The physical condition of discharged fuel assemblies from the reactor core will influence the design of the storage and disposal systems for the used fuel. Recommendations on taking into account the impact of the condition of used fuel on the design of spent fuel handling and storage systems are provided in IAEA Safety Standards Series Nos SSG-63, Design of Fuel Handling and Storage Systems for Nuclear Power Plants [7], and SSG-15 (Rev. 1), Storage of Spent Nuclear Fuel [8].

DESIGN BASIS FOR STRUCTURES, SYSTEMS AND COMPONENTS OF THE REACTOR CORE

2.9. In accordance with Requirement 14 of SSR-2/1 (Rev. 1) [1], the design basis for the reactor core is required to specify the necessary capability, reliability and functionality for all applicable plant states (see para. 2.10) in order to meet the specific acceptance criteria.

Plant states and postulated initiating events

2.10. As stated in Requirement 13 of SSR-2/1 (Rev. 1) [1], plant states are required to be identified and grouped into categories. The plant states typically

considered for the design of the reactor core are normal operation, anticipated operational occurrences, design basis accidents and design extension conditions without significant fuel degradation. These four states are referred to as ‘all applicable plant states’ throughout this Safety Guide. Accidents with significant core melting are outside the scope of the design of the reactor core.

2.11. The design process should include an analysis of the effects of postulated initiating events on the reactor core for all applicable plant states. Recommendations on the identification of the postulated initiating events for all applicable plant states and relevant safety analyses are provided in SSG-2 (Rev. 1) [6].

External hazards

2.12. The consequences of earthquakes should be taken into account in the design of the reactor core. Seismic categorization of the SSCs of the reactor core should be determined in accordance with IAEA Safety Standards Series No. NS-G-1.6, Seismic Design and Qualification for Nuclear Power Plants [9].

Design limits

2.13. Design limits on relevant physical parameters for individual SSCs of the reactor core are required to be specified for all applicable plant states, in accordance with Requirement 15 of SSR-2/1 (Rev. 1) [1]. Adherence to these limits with appropriate provisions will ensure that the concept of defence in depth, as stated in paras 2.4 and 2.5, is successfully applied with adequate margins. Typical examples of relevant parameters with quantitative or qualitative limits are provided in paras 3.33 and 3.65–3.76.

Safety classification aspects of the reactor core

2.14. The SSCs of the reactor core are required to be classified on the basis of their function and their safety significance (see Requirement 22 of SSR-2/1 (Rev. 1) [1]). The safety classification process is described in IAEA Safety Standards Series No. SSG-30, Safety Classification of Structures, Systems and Components in Nuclear Power Plants [10].

2.15. Fuel rods and fuel assemblies should be classified in safety class 1, the highest safety class, since they are essential for achieving the three fundamental safety functions in para. 2.2.

2.16. The failure of control rods has the potential to endanger the control of reactivity in the core and the integrity of the fuel rods, which are safety class 1 barriers; from this perspective, control rods should be classified in safety class 1.

2.17. For all safety classes identified in accordance with the method described in SSG-30 [10], corresponding engineering design rules should be specified and applied.

Engineering design rules

2.18. The engineering design rules for the SSCs of the reactor core represent methods to achieve the adequacy of the design and should include the following, as appropriate:

- (a) The use of applicable codes and standards, and proven engineering practices;
- (b) Conservative safety assessment;
- (c) Specific design analyses for reliability;
- (d) Qualification and testing;
- (e) Operational limits and conditions.

Design for reliability

2.19. In accordance with para. 5.37 of SSR-2/1 (Rev. 1) [1], fuel rods and assemblies, and components and systems for reactor control and shutdown are required to be designed with high reliability, in consideration of their safety significance. Provisions for achieving high reliability in these designs are set out in paras 3.39 and 3.112 of this Safety Guide, respectively.

Operational limits and conditions

2.20. In accordance with Requirement 28 of SSR-2/1 (Rev. 1) [1], operational limits and conditions are required to be established in order to ensure that the reactor core operates safely in accordance with design assumptions and intent. Relevant guidance on the operational limits and conditions is provided in IAEA Safety Standards Series No. NS-G-2.2, Operational Limits and Conditions and Operating Procedures for Nuclear Power Plants [11].

DESIGN FOR SAFE OPERATION

2.21. The SSCs of the reactor core should be designed such that their required testing, inspection, repair, replacement, calibration or maintenance is facilitated.

2.22. The design of the reactor core should be reviewed and modified when a significant configuration change occurs during the operating lifetime of the plant, as a result of, for example:

- (a) Major modifications to the plant design or to equipment, or operational modifications, such as the following:
 - (i) Replacement of the steam generator (not for boiling water reactors);
 - (ii) An increase in the rated power of the plant;
 - (iii) A significant change in the operating domain.
- (b) A new fuel type or a significant change in fuel type (e.g. the introduction of mixed oxide or gadolinium fuel, new design of the fuel rods or the fuel assembly with modified geometrical or thermohydraulic characteristics).
- (c) An increase of the fuel discharge burnup beyond the design limit.
- (d) Major fuel management changes such as a large extension to the length of the reloading cycle.

2.23. Fuel rods and fuel assemblies should be designed to prevent the potential for fuel failures due to specific operational conditions (e.g. startup rates, degraded coolant chemistry conditions or the presence of foreign materials) during operational states.

REACTOR CORE SAFETY ANALYSIS

2.24. In accordance with Requirement 42 of SSR-2/1 (Rev. 1) [1], safety analysis is required to be conducted to evaluate and assess challenges to safety in all applicable plant states using deterministic approaches and including uncertainties to the extent possible.

2.25. The following major factors should be taken into account in the safety analysis for the reactor core:

- (a) Initial operating conditions (e.g. global and local thermohydraulic conditions, power levels, power distributions and time in the reloading cycle);
- (b) Reactivity feedback;

- (c) Rate of change of the concentration of soluble absorber in the moderator and the coolant;
- (d) Position or rate of insertion of positive (or negative) reactivity regulated by the reactivity control device(s), or caused by changes in process parameters;
- (e) Rate of insertion of negative reactivity associated with a reactor trip;
- (f) The response of individual channels to transients in relation to the average thermal power of the core (for boiling water reactors);
- (g) Performance characteristics of safety system equipment, including the changeover from one mode of operation to another (e.g. from the injection mode for emergency core cooling to the recirculation mode);
- (h) The decay of xenon and other neutron absorbers in the analysis of the long term behaviour of the core;
- (i) The activity inventory of the core.

Appropriate provisions or margins should be included in the above factors such that the safety analysis remains valid for specific loading patterns or fuel designs. Recommendations on methods of safety analysis are provided in SSG-2 (Rev. 1) [6].

2.26. Safety analysis for the reactor core should be performed to verify that fuel design limits are not exceeded in all applicable plant states. For accident conditions, the effect of fuel behaviour on core cooling should be included in the safety analysis (e.g. ballooning and rupture of the cladding, exothermic metal–water reactions, distortions of fuel rods and fuel assemblies). The effects of hydrogen accumulation (as a result of a metal–water reaction between the zirconium based alloy cladding and water at high temperature) on the boundary of the reactor coolant system should be evaluated.

2.27. Systematic, complete, qualified and up to date documentation of the state of the SSCs of the plant and the reactor core should be maintained to ensure that the safety analysis is performed using the actual plant and core configuration.

3. SPECIFIC SAFETY CONSIDERATIONS IN THE DESIGN OF THE REACTOR CORE

GENERAL

3.1. This section addresses specific design aspects for the SSCs of the reactor core for meeting Requirements 43–46 established in SSR-2/1 (Rev. 1) [1]. It also addresses the interface with core management, which strongly influences the core design with regard to the performance of fuel rods and fuel assemblies. Specific guidance is provided in IAEA Safety Standards Series No. NS-G-2.5, Core Management and Fuel Handling for Nuclear Power Plants [12].

3.2. The design of the reactor core, in combination with the design of reactor cooling systems, and the reactor control and reactor protection systems, should enable the fulfilment, at all times, of the fundamental safety functions (para. 2.2) for all applicable plant states (i.e. normal operation, anticipated operational occurrences, design basis accidents and design extension conditions without significant fuel degradation).

3.3. The reactor core and associated control and protection systems should be designed with adequate margins to ensure that fuel design limits are not exceeded for all applicable plant states. Fuel design limits are described in paras 3.65–3.76.

Fuel type

3.4. Fuel rods contain fissile materials (e.g. ^{235}U , ^{239}Pu) that are highly reactive with thermal neutrons. In selecting the fuel pellet materials, the following properties should be optimized (examples of pellet materials are provided in Annex I):

- (a) Reactivity with thermal neutrons;
- (b) Impurities with low thermal neutron absorption properties;
- (c) Thermal performance (e.g. high thermal conductivity is desirable for operational states while high thermal diffusivity is desirable for accident conditions);
- (d) Dimensional stability;
- (e) Fission gas retention;
- (f) Resistance to pellet–cladding interaction.

3.5. Cladding materials should be selected with consideration of the following properties (examples of cladding materials are provided in Annex I):

- (a) Low absorption cross-section for thermal neutrons;
- (b) High resistance to irradiation conditions;
- (c) High thermal conductivity and high melting point;
- (d) High corrosion resistance and low hydrogen pick-up;
- (e) Low oxidation and low hydriding in high temperature conditions;
- (f) Adequate resistance to breakaway oxidation at high integrated-time temperature conditions;
- (g) Adequate mechanical properties (e.g. high strength, high ductility, low creep rate in normal operation, high relaxation rate in transients);
- (h) Low susceptibility to stress corrosion cracking;
- (i) Adequate resistance to hydrogen assisted cracking and hydride related cracking in normal operation and for fuel storage.

Coolant

3.6. In light water reactors, the coolant also acts as the moderator. The choice of coolant should take into account interactions between the coolant and fuel and core components in all chemical conditions (see Annex I for supplementary information). For pressurized heavy water reactors, the coolant and the moderator are separated; typically, chemicals are not added to the coolant for controlling reactivity.

3.7. The coolant should be physically and chemically stable with respect both to high temperatures and to irradiation in order to fulfil its primary function, namely the continuous removal of heat from the core.

3.8. The reactor core should be designed to prevent or control flow instabilities and the resultant fluctuations in core reactivity or power.

3.9. The reactor fuel and core design should include the following safety considerations associated with the coolant:

- (a) Ensuring that the coolant system is free of foreign materials prior to the initial startup of the reactor and following refuelling and maintenance outages, for the operating lifetime of the plant;
- (b) Maintaining the radionuclide activity in the coolant as low as reasonably achievable by means of purification systems, corrosion product minimization or removal of defective fuel as appropriate;