

IAEA Safety Standards

for protecting people and the environment

Design of the Reactor Core for Nuclear Power Plants

Safety Guide
No. NS-G-1.12



IAEA

International Atomic Energy Agency

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The publications by means of which the IAEA establishes standards are issued in the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety and waste safety, and also general safety (i.e. all these areas of safety). The publication categories in the series are **Safety Fundamentals**, **Safety Requirements** and **Safety Guides**.

Safety standards are coded according to their coverage: nuclear safety (NS), radiation safety (RS), transport safety (TS), waste safety (WS) and general safety (GS).

Information on the IAEA's safety standards programme is available at the IAEA Internet site

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The site provides the texts in English of published and draft safety standards. The texts of safety standards issued in Arabic, Chinese, French, Russian and Spanish, the IAEA Safety Glossary and a status report for safety standards under development are also available. For further information, please contact the IAEA at P.O. Box 100, A-1400 Vienna, Austria.

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Safety related publications are also issued in the **Technical Reports Series**, the **IAEA-TECDOC Series**, the **Training Course Series** and the **IAEA Services Series**, and as **Practical Radiation Safety Manuals** and **Practical Radiation Technical Manuals**. Security related publications are issued in the **IAEA Nuclear Security Series**.

DESIGN OF THE REACTOR CORE FOR NUCLEAR POWER PLANTS

Safety standards survey

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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. NS-G-1.12

DESIGN OF THE REACTOR CORE FOR NUCLEAR POWER PLANTS

SAFETY GUIDE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2005

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Sales and Promotion Unit, Publishing Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna
Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
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FOREWORD

by Mohamed ElBaradei
Director General

The IAEA's Statute authorizes the Agency to establish safety standards to protect health and minimize danger to life and property — standards which the IAEA must use in its own operations, and which a State can apply by means of its regulatory provisions for nuclear and radiation safety. A comprehensive body of safety standards under regular review, together with the IAEA's assistance in their application, has become a key element in a global safety regime.

In the mid-1990s, a major overhaul of the IAEA's safety standards programme was initiated, with a revised oversight committee structure and a systematic approach to updating the entire corpus of standards. The new standards that have resulted are of a high calibre and reflect best practices in Member States. With the assistance of the Commission on Safety Standards, the IAEA is working to promote the global acceptance and use of its safety standards.

Safety standards are only effective, however, if they are properly applied in practice. The IAEA's safety services — which range in scope from engineering safety, operational safety, and radiation, transport and waste safety to regulatory matters and safety culture in organizations — assist Member States in applying the standards and appraise their effectiveness. These safety services enable valuable insights to be shared and I continue to urge all Member States to make use of them.

Regulating nuclear and radiation safety is a national responsibility, and many Member States have decided to adopt the IAEA's safety standards for use in their national regulations. For the Contracting 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 designers, manufacturers and operators around the world to enhance nuclear and radiation safety in power generation, medicine, industry, agriculture, research and education.

The IAEA takes seriously the enduring challenge for users and regulators everywhere: that of ensuring a high level of safety in the use of nuclear materials and radiation sources around the world. Their continuing utilization for the benefit of humankind must be managed in a safe manner, and the IAEA safety standards are designed to facilitate the achievement of that goal.

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IAEA SAFETY STANDARDS

SAFETY THROUGH INTERNATIONAL STANDARDS

While safety is a national responsibility, international standards and approaches to safety promote consistency, help to provide assurance that nuclear and radiation related technologies are used safely, and facilitate international technical cooperation and trade.

The standards also provide support for States in meeting their international obligations. One general international obligation is that a State must not pursue activities that cause damage in another State. More specific obligations on Contracting States are set out in international safety related conventions. The internationally agreed IAEA safety standards provide the basis for States to demonstrate that they are meeting these obligations.

THE IAEA STANDARDS

The IAEA safety standards have a status derived from the IAEA's Statute, which authorizes the Agency to establish standards of safety for nuclear and radiation related facilities and activities and to provide for their application.

The safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment.

They are issued in the IAEA Safety Standards Series, which has three categories:

Safety Fundamentals

- Presenting the objectives, concepts and principles of protection and safety and providing the basis for the safety requirements.

Safety Requirements

- Establishing the requirements that must be met to ensure the protection of people and the environment, both now and in the future. The requirements, which are expressed as 'shall' statements, are governed by the objectives, concepts and principles of the Safety Fundamentals. If they are not met, measures must be taken to reach or restore the required level of safety. The Safety Requirements use regulatory language to enable them to be incorporated into national laws and regulations.

Safety Guides

- Providing recommendations and guidance on how to comply with the Safety Requirements. Recommendations in the Safety Guides are expressed as 'should' statements. It is recommended to take the measures stated 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. Each Safety Requirements publication is supplemented by a number of Safety Guides, which can be used in developing national regulatory guides.

The IAEA safety standards need to be complemented by industry standards and must be implemented within appropriate national regulatory infrastructures to be fully effective. The IAEA produces a wide range of technical publications to help States in developing these national standards and infrastructures.

MAIN USERS OF THE STANDARDS

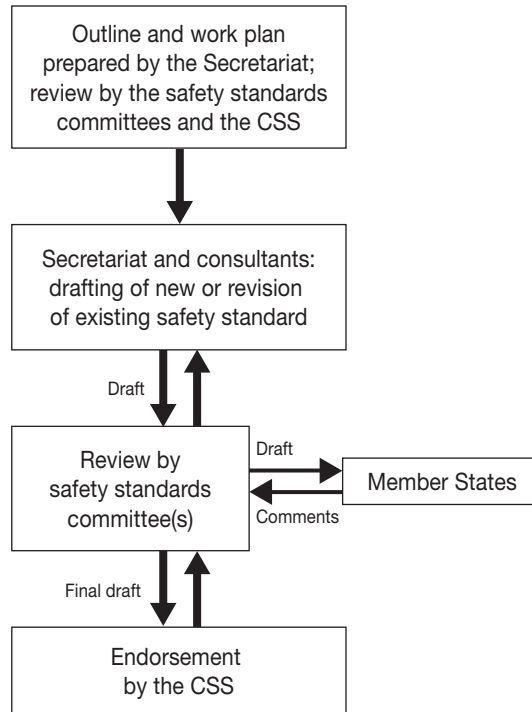
As well as by regulatory bodies and governmental departments, authorities and agencies, the standards are used by authorities and operating organizations in the nuclear industry; by organizations that design, manufacture and apply nuclear and radiation related technologies, including operating organizations of facilities of various types; by users and others involved with radiation and radioactive material in medicine, industry, agriculture, research and education; and by engineers, scientists, technicians and other specialists. The standards are used by the IAEA itself in its safety reviews and for developing education and training courses.

DEVELOPMENT PROCESS FOR THE STANDARDS

The preparation and review of safety standards involves the IAEA Secretariat and four safety standards committees for safety in the areas of 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 entire safety standards programme. All IAEA Member States may nominate experts for the safety standards committees and may provide comments on draft standards. The membership of the CSS is appointed by the Director General and includes senior government officials having responsibility for establishing national standards.

For Safety Fundamentals and Safety Requirements, the drafts endorsed by the Commission are submitted to the IAEA Board of Governors for approval for publication. Safety Guides are published on the approval of the Director General.

Through this process the standards come to represent a consensus view of the IAEA's Member States. 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 standards. Some 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 International



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

Labour Organization, the OECD Nuclear Energy Agency, the Pan American Health Organization and the World Health Organization.

The safety standards are kept up to date: five years after publication they are reviewed to determine whether revision is necessary.

APPLICATION AND SCOPE OF THE STANDARDS

The IAEA Statute makes the safety standards 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 concerning any form of Agency assistance is required to comply with the requirements of the safety standards that pertain to the activities covered by the agreement.

International conventions also contain similar requirements to those in the safety standards, and make them binding on contracting parties. The Safety Fundamentals were used as the basis for the development of the Convention on Nuclear Safety and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. The Safety

Requirements on Preparedness and Response for a Nuclear or Radiological Emergency reflect the obligations on States under the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency.

The safety standards, incorporated into national legislation and regulations and supplemented by international conventions and detailed national requirements, establish a basis for protecting people and the environment. However, there will also be special aspects of safety that need to be assessed case by case at the national level. For example, many of the safety standards, particularly those addressing planning or design aspects of safety, are intended to apply primarily to new facilities and activities. The requirements and recommendations specified in the IAEA safety standards might not be fully met at some facilities built to earlier standards. The way in which the safety standards are to be applied to such facilities is a decision for individual States.

INTERPRETATION OF THE TEXT

The safety standards use the form 'shall' in establishing international consensus requirements, responsibilities and obligations. Many requirements are not addressed to a specific party, the implication being that the appropriate party or parties should be responsible for fulfilling them. Recommendations are expressed as 'should' statements, indicating an international consensus that it is necessary to take the measures recommended (or equivalent alternative measures) for complying with the requirements.

Safety related terms are to be interpreted as stated in the IAEA Safety Glossary (<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 within the 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 main text (e.g. material that is subsidiary to or separate from the main text, is included in support of statements in the main text, or describes methods of calculation, experimental 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 standard. Material in an appendix has the same status as the main 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. An annex is not an integral part of the main text. Annex material published by the IAEA is not necessarily issued under its authorship; material published in standards that is under other authorship may be presented in annexes. 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 was prepared under the IAEA programme for establishing safety standards for nuclear power plants. The basic requirements for the design of safety systems for nuclear power plants are provided in the Safety Requirements publication, Safety Standards Series No. NS-R-1: Safety of Nuclear Power Plants: Design [1], which it supplements. This Safety Guide recommends how to meet the requirements for the design of the reactor core for nuclear power plants.

1.2. The publication is a revision of a previous Safety Guide on Design for Reactor Core Safety in Nuclear Power Plants, issued in 1986 as Safety Series No. 50-SG-D14, which is superseded by the present Safety Guide. This revision takes account of developments in the design of the reactor core since the earlier Safety Guide was issued and includes recommendations and guidance on general and specific design considerations.

OBJECTIVE

1.3. The objective of this Safety Guide is to make recommendations concerning safety features for incorporation into the design of the reactor core for a nuclear power plant. The Safety Requirements publication on Safety of Nuclear Power Plants: Design establishes general safety requirements for design. The present Safety Guide provides recommendations and guidance on the interpretation and implementation of these requirements. It should be noted that nuclear safety is achieved through a combination of proper design, manufacture, construction and operation. For operational aspects, reference should be made to the Safety Requirements publication on Safety of Nuclear Power Plants: Operation [2] and its associated Safety Guides.

SCOPE

1.4. In Safety of Nuclear Power Plants: Design [1] it is stated that:

“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 production applications (such as district heating or desalination). It is recognized that in the case of other reactor types, including innovative developments in future systems, some of the requirements may not be applicable, or may need some judgement in their interpretation.”

1.5. This Safety Guide covers the neutronic, thermal, hydraulic, mechanical, chemical and irradiation considerations that are important for the safe design of the core of a nuclear power reactor. This Safety Guide further deals with the individual systems and components that make up the core, the equipment associated with the core and the design provisions for the safe operation of the core. The safe handling of the fuel and other core components is discussed in Ref. [3].

1.6. This Safety Guide covers the internals of the reactor vessel and the devices¹ mounted on the reactor vessel for reactivity control and shutdown. Interactions of these internals and devices with the reactor coolant and the reactor coolant system components, including its pressure boundary (i.e. including the pressure vessel or the pressure tubes), are considered only to the extent necessary to clarify the interface with the Safety Guide on the Design of the Reactor Coolant System and Associated Systems in Nuclear Power Plants [4] and other Safety Guides. The guidance in relation to instrumentation and control systems is limited mainly to functional considerations.

1.7. The following structures, systems and components in the reactor vessel are considered in this Safety Guide:

- The *fuel assemblies* and those structures that hold the fuel assemblies and other components in a predetermined geometrical configuration. The moderator and the coolant within the core are also considered.
- The *components and structures* used for reactivity control and shutdown, comprising the neutron absorbers (solid or liquid), the associated structure and drive mechanism, and related components of the fluid system.

¹ In this Safety Guide the term ‘device’ (e.g. shutdown device or reactivity control device) is used to designate a part (regardless of its shape, material or purpose) that is inserted into the core (e.g. a control rod or a tube containing fluid for reactivity control). The term ‘device’ may include the drive mechanism for the parts. By contrast, the term ‘means’ (e.g. means of shutdown or means of reactivity control) is used to denote more broadly the functional aspect of the component or system.

- The *support structures* that provide the foundation for the core within the reactor vessel, the structure for guiding the flow, such as the core barrel or the pressure tubes of a pressurized heavy water reactor (PHWR, pressure tube type), and guide tubes for reactivity control devices.
- Other *reactor vessel internals* such as instrumentation tubes, in-core instrumentation for core monitoring, steam separators and neutron sources. These are dealt with to a limited extent only in this Safety Guide.

STRUCTURE

1.8. Section 2 describes basic considerations for safe core design in addition to the requirements established in Ref. [1]. Section 3 discusses detailed considerations in safe design for each reactor core component and the related design for safe operation. Section 4 describes qualification and testing. Section 5 addresses quality assurance in design. Some specific technical aspects are discussed in Appendices I to V.

2. GENERAL SAFETY CONSIDERATIONS IN DESIGN

GENERAL

2.1. The safety objectives and concepts, as presented in Ref. [5] and reproduced in Ref. [1], Section 2, are as follows:

“General Nuclear Safety Objective: To protect individuals, society and the environment from harm by establishing and maintaining in nuclear installations effective defences against radiological hazards.

“Radiation Protection Objective: To ensure that in all operational states radiation exposure within the installation or due to any planned release of radioactive material from the installation is kept below prescribed limits and as low as reasonably achievable, and to ensure mitigation of the radiological consequences of any accidents.

“Technical Safety Objective: To take all reasonably practicable measures to prevent accidents in nuclear installations and to mitigate their consequences

should they occur; to ensure with a high level of confidence that, for all possible accidents taken into account in the design of the installation, including those of very low probability, any radiological consequences would be minor and below prescribed limits; and to ensure that the likelihood of accidents with serious radiological consequences is extremely low.

“Safety Objectives require that nuclear installations are designed and operated so as to keep all sources of radiation exposure under strict technical and administrative control. However, the Radiation Protection Objective does not preclude limited exposure of people or the release of legally authorized quantities of radioactive materials to the environment from installations in operational states. Such exposures and releases, however, must be strictly controlled and must be in compliance with operational limits and radiation protection standards.”

The requirements for the safety concept of defence in depth are also established in Ref. [1] (para. 4.1). In summary, application of the concept of defence in depth in the design of a nuclear power plant results in a number of levels of defence (inherent features, equipment and procedures) aimed at preventing accidents and ensuring appropriate protection in the event that prevention fails.

2.2. Three types of event are required to be prevented to the extent practicable in the design of the core (Ref. [1], para. 4.2) to ensure that defence in depth is maintained:

- “(1) challenges to the integrity of physical barriers;
- (2) failure of a barrier when challenged;
- (3) failure of a barrier as a consequence of failure of another barrier.”

For example, the plant should be designed in such a way that: the fuel pellets do not release an inordinate amount of radioactive fission products; the fuel does not challenge the integrity of the fuel cladding; the integrity of the fuel cladding is maintained under all operating conditions and under transient conditions as far as practicable; and failure of fuel cladding does not propagate and result in failure of the reactor vessel or of pressure tubes. Any resulting effects of core behaviour on other barriers should also be considered to ensure that the core design fully meets the intent of the requirements [1].

2.3. The three fundamental safety functions should be considered in the design of the core, for operational states and a wide range of accident conditions:

- (1) Control of the reactivity;
- (2) Removal of heat from the core;
- (3) Confinement of radioactive material and control of operational discharges, as well as limitation of accidental radioactive releases.

The performance of these functions should be ensured by means of appropriate design of the core and its associated systems to ensure that they are capable and robust (Ref. [1], para. 4.6).

2.4. The core design should be such as to minimize the adverse effects of a wide range of postulated initiating events (see para. 4.7 and Appendix I of Ref. [1]; see also under the heading Safety Analysis in Section 3 of this Safety Guide).

2.5. In summary, the following should be taken into account in considering general design features: appropriate safety margins; safety standards on radiation protection [6–8]; static and dynamic loadings; the maximum rate and amount of addition of reactivity; post-accident recriticality; and inspection and testing throughout the plant's operating lifetime (Ref. [1], paras 6.1–6.5).

2.6. Structures, systems and components of the core should be designed, fabricated, erected, constructed, tested and inspected in accordance with appropriate national or international engineering codes and standards or practices (Ref. [1], para. 3.6).

2.7. The core design needs to be reviewed and, if necessary, modified accordingly when a significant configuration change occurs during the plant's operating lifetime, as a result of, for example:

- The use of mixed uranium oxide and plutonium oxide (mixed oxide) fuel;
- An increase in burnup for a discharged fuel assembly;
- An increase in the duration of a fuel cycle;
- An increase in the rated power of the plant.

2.8. For operational states (normal operation and anticipated operational occurrences), it is required to maintain the integrity of fuel elements; for design basis accidents it is required to ensure that any damage to fuel elements is kept to a minimum (Ref. [1], paras 6.1 and 6.35). Components of the reactor core and its associated structures should be designed with account taken of the safety functions to be achieved during and following design basis accidents (e.g. shutdown of the reactor, emergency core cooling, long term stable cooling and

reactivity control, and confinement of radioactive material). The approach to mitigating beyond design basis accidents is outlined in Ref. [1], para. 5.31.

2.9. Suitable provision is required to be made in the design and layout of the structures, systems and components of the reactor core to ensure that radiation doses to the public and to site personnel in all operational states, including maintenance, testing and inspection and decommissioning, do not exceed authorized limits and are as low as reasonably achievable [1, 5–7].

2.10. Additional requirements for core design are given in Ref. [1], paras 6.6–6.20 under the headings fuel elements and assemblies, control of the reactor core and reactor shutdown. The following paragraphs give related guidance on design.

NEUTRONIC DESIGN

2.11. The design of the reactor core should be such that the feedback characteristics of the core rapidly compensate for an increase in reactivity. The reactor power should be controlled by a combination of the inherent neutronic characteristics of the reactor core, its thermal-hydraulic characteristics and the capability of the control and shutdown systems to actuate for all operational states and in design basis accident conditions. When rapid acting control or shutdown systems are necessary, their capabilities (e.g. speed and reliability) should be fully justified. (Further information on inherent neutronic characteristics and reactivity coefficients is given in Appendix I.)

2.12. In accordance with para. 4.6 of Ref. [1], the maximum insertion rate for positive reactivity in operational states and in design basis accidents should be limited in such a way that the means of reduction of reactor power described in para. 2.11 are effective in maintaining core coolability, minimizing damage to the core and preventing failure of the pressure boundary for the reactor coolant. The design basis for fuel elements should be adequate to prevent undesired consequences of reactivity initiated accidents (e.g. by means of limits on maximum fuel enthalpy or rise in fuel enthalpy).

2.13. At least two independent and diverse shutdown systems should be provided (see paras 6.3–6.20 of Ref. [1] and the discussion in Section 3 on means of reactor shutdown for further information).

2.14. Calculation of the core power distribution should be performed in the design for representative operational states to provide information for use in determining: (a) operational limits and conditions; (b) action set points for safety protection systems; (c) operating procedures that will ensure compliance with design limits, including core design parameters, throughout the service life of the reactor core.

2.15. Reactivity control devices should be used to maintain the reactor in a subcritical condition, with account taken of possible design basis accidents and their consequences. Adequate provision should be made in the design to maintain subcriticality for plant states in which normal shutdown, fuel cooling or the integrity of the primary cooling system is temporarily disabled, for example when the reactor vessel is open for maintenance or refuelling.

2.16. The shutdown systems should be testable, as far as practicable, during operation in order to provide assurance that the systems are available on demand.

THERMAL-HYDRAULIC DESIGN

2.17. Thermal-hydraulic design limits on parameters such as the maximum linear heat generation rate, the minimum critical power ratio, the minimum departure from nucleate boiling ratio, the peak fuel temperature and the cladding temperature should be set in such a way that there are sufficient margins in operational states to keep the failure rates of fuel elements under design basis accident conditions to an acceptably low level.

2.18. Suitable means of instrumentation and control should be provided so that parameters indicative of the core conditions (e.g. the rate of coolant flow, the coolant temperature and the neutron flux) can be monitored and adjusted safely to ensure that the design limits are not exceeded for all operational states, including refuelling.

2.19. Suitable instrumentation for monitoring is required to be provided for assessing the status of the core and associated features under accident conditions (see Ref. [1], para. 6.68).

MECHANICAL DESIGN

2.20. The fuel elements, control devices, burnable poisons and fuel assemblies should be designed to ensure that the cladding remains leaktight for all operational states throughout its lifetime.

2.21. In the design of the fuel elements, control devices, burnable poisons and fuel assemblies, account should be taken of the effects of temperature, pressure, irradiation, fission products, static and dynamic mechanical loads, including seismic loads, flow induced vibration and changes in the chemical characteristics of the constituent materials.

2.22. Means should be provided for safe handling of core components such as the fuel assemblies, control and shutdown devices and core support structures to ensure their integrity in transport, storage, installation and refuelling operations (see Ref. [3]).

2.23. The structural integrity of the core should be ensured so that the core can be safely controlled, shut down and cooled under operational states and in design basis accident conditions. Static and dynamic mechanical loads, including thermal stress, acting in operational states and in design basis accident conditions should be considered.

2.24. The fuel assembly, other reactor vessel internals and the reactor cooling system should be designed to minimize the chance of any obstruction of the coolant flow due to the release of loose parts, so as to prevent core damage in any operational state and in design basis accident conditions.

2.25. The core and its associated components should be designed to be compatible under the effects of irradiation and chemical and physical processes.

2.26. The uncontrolled movement of reactivity control devices should be prevented.

SAFETY CLASSIFICATION ASPECTS OF CORE DESIGN

2.27. In the light of the Safety Requirements (Ref. [1], paras 5.1–5.3), and the central importance of the reactor core to safety, it is expected that all

components of the reactor core and its associated structures should be classified appropriately according to their importance to safety.

2.28. Two safety barriers (the fuel itself and its cladding) are located inside the core, and the performance of two fundamental safety functions (reactivity control and core cooling) depends on the maintenance of the correct core configuration and the accessibility of devices. Furthermore, if an accident that is disruptive of the core occurred, it would have the potential to challenge the containment barrier. Proper safety classification and consequently appropriate analysis, judgement and verification should therefore be performed to ensure the integrity of the core and to maintain the performance of the fundamental safety functions of reactivity control and core cooling.

2.29. The consequences of the failure of each system and component, including the consequences of its possible effects on other systems and components, should be analysed carefully to determine an appropriate classification.

3. SPECIFIC SAFETY CONSIDERATIONS IN DESIGN

GENERAL

3.1. This section addresses further design considerations for the core components in meeting the objectives and requirements for design mentioned in Section 2. It also covers core management, which strongly influences the core design with regard to the integrity of fuel elements as well as the fuel economy.

3.2. Some devices in a core may also perform safety functions that are within the scope of other Safety Guides. In the design of such hardware, account should be taken of the recommendations and guidance of the present Safety Guide and other relevant Safety Guides, such as Refs [3, 4, 9].

FUEL ELEMENTS AND ASSEMBLIES

3.3. Considerations in this subsection apply to both uranium fuel and mixed oxide fuel.
