

IAEA Safety Standards

for protecting people and the environment

Radiation Protection Aspects of Design for Nuclear Power Plants

Safety Guide

No. NS-G-1.13



IAEA

International Atomic Energy Agency



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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**.

RADIATION PROTECTION ASPECTS OF DESIGN 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. NS-G-1.13

RADIATION PROTECTION ASPECTS OF DESIGN FOR NUCLEAR POWER PLANTS

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2005

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<http://www.iaea.org/books>

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Printed by the IAEA in Austria
November 2005
STI/PUB/1233

IAEA Library Cataloguing in Publication Data

Radiation protection aspects in the design of nuclear power plants. —
Vienna : International Atomic Energy Agency, 2005.
p. ; 24 cm. — (IAEA Safety standards series, ISSN 1020-525X ;
no. NS-G-1.13)
STI/PUB/1233
ISBN 92-0-107905-2
Includes bibliographical references.

1. Nuclear power plants — Design and construction. 2. Nuclear
power plants — Safety measures. 3. Radiation — Safety measures.
I. International Atomic Energy Agency. II. Series: Safety standards
series ; NS-G-1.13.

IAEAL

05-00419

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.

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

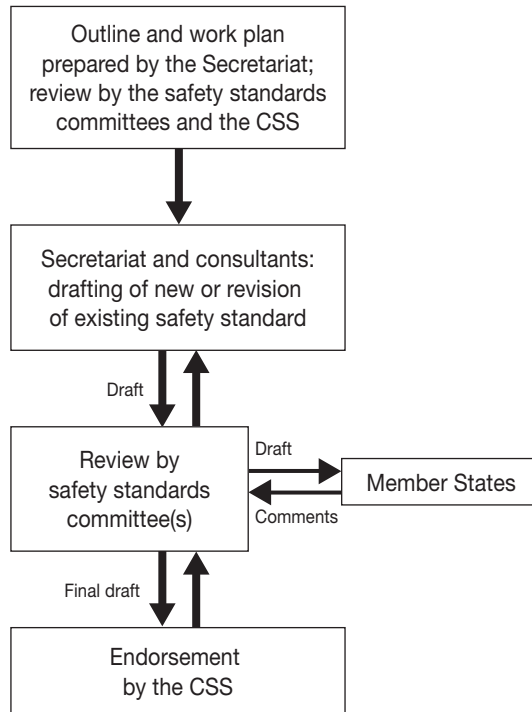
As well as by regulatory bodies and governmental departments, authorities and agencies, the standards are used by authorities and operating organizations in the nuclear industry; by organizations that design, manufacture and apply nuclear and radiation related technologies, including operating organizations 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 has been prepared as a part of the IAEA programme on safety standards for nuclear power plants.

1.2. This Safety Guide includes recommendations on how to satisfy the requirements established in paras 4.9–4.13, 5.61, 6.32, 6.87, 6.92–6.94 and 6.99–6.106 of the Safety Requirements publication on the Safety of Nuclear Power Plants: Design [1]. It addresses the provisions that should be made in the design of nuclear power plants in order to protect site personnel, the public and the environment against radiological hazards for operational states, decommissioning and accident conditions.

1.3. The recommendations on radiation protection provided in this Safety Guide are consistent with the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [2], which were jointly sponsored by the Food and Agriculture Organization of the United Nations (FAO), the IAEA, the International Labour Organisation (ILO), the OECD Nuclear Energy Agency (OECD/NEA), the Pan American Health Organization (PAHO) and the World Health Organization (WHO).

1.4. This Safety Guide supersedes Safety Series No. 50-SG-D9, Design Aspects of Radiation Protection for Nuclear Power Plants, published in 1985.

1.5. Effective radiation protection is a combination of good design, high quality construction and proper operation. Procedures that address the radiation protection aspects of operation are covered in the Safety Guide on Radiation Protection and Radioactive Waste Management in the Operation of Nuclear Power Plants [3].

OBJECTIVE

1.6. The purpose of this Safety Guide is to provide recommendations for ensuring radiation protection in (1) the design of new nuclear power plants, (2) design modifications to operating plants, and (3) safety reviews of operating plants. They are provided to assist in meeting the requirements established in

Ref. [1] for which the first of three fundamental safety objectives is to protect individuals, society and the environment from harm by establishing and maintaining in nuclear installations effective defences against radiological hazards. This Safety Guide is for use by regulatory bodies¹ and by personnel of operating organizations and contractor organizations, including plant operators who are involved in planning, managing and carrying out the design and design modification of nuclear power plants. It can also be used for conducting safety reviews of operating plants.

SCOPE

1.7. This Safety Guide:

- (1) Describes the applicable requirements of the system of dose limitation and optimization as a basis for the radiation protection measures that should be implemented in the design of nuclear power plants;
- (2) Describes the measures to be taken in the design for the radiation protection of site personnel and the public;
- (3) Outlines the methods that are used to calculate on-site and off-site radiation levels and to verify that the design provides an adequate level of radiation protection;
- (4) Describes in annexes the important sources of radiation and contamination against which protection for site personnel, the public and the environment has to be provided in the design.

1.8. In addition to the measures that are required to protect site personnel and members of the public when the plant is in operational states and during decommissioning, this Safety Guide also deals with accident conditions, including severe accidents.²

¹ Throughout this publication, the term ‘regulatory body’ is used to mean an authority or a system of authorities designated by the government of a State as having legal authority for conducting the regulatory process, including issuing authorizations, and thereby regulating nuclear, radiation, radioactive waste and transport safety. Earlier safety standards used the term ‘Regulatory Authority’

² This Safety Guide does not address the design measures that are necessary to reduce the probability of the occurrence and to prevent the development of accidents. These aspects are considered in the Safety Requirements for Design [1] and in other Safety Guides.

1.9. Although the majority of the new designs for nuclear power plants are for water cooled reactors, this Safety Guide also deals with other types of operating reactors, and it is relevant to design issues associated with modifications to existing plants and their decommissioning.

1.10. This Safety Guide addresses radiation protection aspects of the handling, treatment and storage of radioactive waste. It does not specifically deal with the safety aspects of waste treatment relating to the form or quality of the waste product with regard to its longer term storage or disposal. These aspects are considered in a number of other safety standards [4–6].

STRUCTURE

1.11. Section 2 of the Safety Guide introduces the relevant requirements, such as those in respect of dose limits, the application of the principle of optimization of protection and the setting of design targets. Design approaches for operational states, decommissioning and accident conditions are described in Section 3, while Section 4 deals with the design features that protect site personnel in operational states and decommissioning. Section 5 covers discharge criteria, source reduction and systems for protecting the public in operational states and decommissioning. Sections 6 and 7 provide guidance on estimating radiation dose rates and on monitoring for the purposes of radiation protection under the same conditions. Guidance on radiation monitoring for processes and on auxiliary facilities is given in Sections 8 and 9. Section 10 deals with the principles of design for the protection of personnel at the site from radiation that might result from accident conditions and Section 11 covers radiation protection of the public under accident conditions. Guidance on the radiation monitoring system for accident conditions is given in Section 12.

1.12. Annexes I–III provide information on sources of radiation during normal operation and decommissioning as well as under accident conditions, while Annex IV deals with the determination of source terms for operational states and decommissioning. Annex V gives examples of zoning that may be used for design purposes.

2. SAFETY OBJECTIVES, DOSE LIMITATION AND OPTIMIZATION

SAFETY OBJECTIVES

2.1. In accordance with the principles of radiation protection, provisions are required to be made in the design to comply with the Radiation Protection Objective as given in para. 2.4 of Safety of Nuclear Power Plants: Design [1]:

“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”.

Furthermore, provisions are required to be made in the design to comply with the following part of the Technical Safety Objective as outlined in para. 2.5 of Ref. [1]:

“To take all reasonably practicable measures... 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...”

AUTHORIZED DOSE LIMITS AND DOSE CONSTRAINTS³ FOR OPERATIONAL STATES AND DECOMMISSIONING

2.2. The design of the nuclear power plant should be such as to ensure that authorized dose limits⁴ and dose constraints for site personnel and the public will not be exceeded over specified periods (e.g. monthly, quarterly or annually) in operational states (normal operation and anticipated operational

³ For internal exposures, such as those that result from the inhalation and ingestion of radioactive substances, the dose limits apply to the committed dose.

⁴ An authorized dose limit or dose constraint is one that has been established or formally accepted by a regulatory body.

occurrences) and decommissioning. In order to comply with the requirements of the BSS [2], the authorized dose limits and dose constraints should not exceed the values of the dose limits established in the BSS. For workers who do not enter the designated areas (supervised areas and controlled areas), the authorized dose constraints should be set at the same level as the individual dose limit for members of the public [7].

2.3. The authorized annual dose constraints for members of the public apply to the average dose to the critical groups of the population; that is, groups of persons that are reasonably homogeneous with respect to their exposure for a given radiation source and given exposure pathway, and are representative of individuals who receive the highest dose as a result of the nuclear operations that are being undertaken [8]. A critical group may be specific with respect to age or gender [9]. Pre-operational studies should be carried out to identify the critical groups and critical pathways for the exposure of such groups. Discharge limits for specific radionuclides in liquid and gaseous effluents (e.g. annual, quarterly, monthly, daily — the shorter periods permit increased release rates over short time periods and thus increased operational flexibility) should be derived from the application of the authorized dose constraints for members of the critical groups using the approved critical exposure pathways for all relevant nuclear operations. The discharge limits should ensure that the maximum individual dose for a critical group does not exceed the dose constraint.

APPLICATION OF THE OPTIMIZATION PRINCIPLE

2.4. To keep all exposures within authorized dose limits and dose constraints and as low as reasonably achievable, economic and social factors being taken into account:

- The radiation exposure should be reduced by means of radiation protection measures to values such that further expenditure for design, construction and operation would not be warranted (economic factors) by the associated reduction in radiation exposure.
- Issues such as reducing major disparities in the occupational doses received by workers of different types who work within the controlled area and avoiding arduous working conditions in radiation areas (social factors) should be taken into account in the design. The types of worker who could potentially receive the highest doses include maintenance and inspection personnel and health physics staff.

2.5. In general the optimization of radiation protection implies a choice from a set of protective measures such as shielding, remote operation and tooling to minimize radiation exposure time. To this end, feasible options should be identified, criteria for comparison and appropriate values for them should be determined and, finally, the options should be evaluated and compared. Details of different structured approaches to making decisions are given in Annex I.

2.6. The concept of optimization should also apply to design features whose purpose is to prevent or mitigate the consequences of accidents at the plant that could lead to the exposure of site personnel and/or the public. However, the techniques that are needed to take account of the probabilities of such events and their consequences are not yet well developed.

DESIGN TARGETS FOR OPERATIONAL STATES

2.7. To ensure that a design both reduces doses to levels that are as low as reasonably achievable and represents best practice, design targets should be set for the individual dose and collective dose to workers and for the individual dose to those members of the public who will receive the greatest doses. The setting of design targets for individual doses to site personnel and members of the public is consistent with the concept of dose constraints, which is discussed in paras 2.24 and 2.26 of the BSS [2]. The design targets should be set at an appropriate fraction of the dose limits.⁵ The term ‘target’ or ‘target dose’ is used throughout this Safety Guide in respect of both individual and collective doses.

2.8. In order to focus the design efforts on those aspects of the design that contribute most to the collective and individual doses to the workforce, it is useful to set design targets for the collective dose to the groups of workers that are likely to receive the greatest doses, such as maintenance workers and health physics staff. It is also useful to set design targets for the collective dose for each category of work, such as maintenance of the major components, in-service inspection, refuelling and waste management. These, combined with dose assessments at the key stages of the design, can be used to monitor the major

⁵ It should be recognized that design targets are not limits. They are useful design tools in the optimization process. However, provided that any excess can be justified, they may be exceeded. Also, achieving a design target does not, in itself, demonstrate that a design satisfies the optimization principle. A dose should be reduced below a target if this can be done at a cost that is justifiable.

contributions to the dose and to identify aspects that contribute more to the dose than was envisaged initially.

2.9. The design target for the long term collective dose should preferably be expressed in terms of man Sv/unit of electricity generation, indicating the ratio of the radiation detriment to the benefit (the energy produced).

DESIGN TARGETS FOR ACCIDENTS

2.10. The adequacy of the design provisions for the protection of the site personnel and public under postulated accident conditions should be judged by means of the comparison of calculated doses with the specified dose criteria that constitute the design targets for accidents. In general, the higher the probability of the accident condition, the lower the specified design target should be. The regulatory body may recognize this principle by setting different design targets for accidents with different probabilities of occurrence. In addition, the regulatory body may define design targets by specifying frequency criteria for all accidents in specified dose bands. For design basis accidents, it is required that there is only a minor radiological impact outside the site boundary or the exclusion area, depending on the national regulatory requirements. The definition of minor radiological impact may be specified by the regulatory body. Typically it corresponds to very restrictive dose levels so as to preclude the need for evacuation.

2.11. It is beneficial to address separately:

- Design basis accidents (DBAs);
- Beyond DBAs (including severe accidents).

For severe accidents, the regulatory body may specify a risk criterion or a criterion associated with specified releases of radioactive substances.

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3. RADIATION PROTECTION ASPECTS IN DESIGN

SOURCES OF RADIATION

3.1. The magnitudes and locations of the sources of radiation in operational states and during decommissioning should be determined in the design phase. Annex II briefly describes the main sources that cause radiation exposure in normal operation and during decommissioning. They are: the reactor core and vessel; the reactor coolant and fluid moderator system; the steam and turbine system; the waste treatment systems; irradiated fuel; the storage of new fuel; decontamination facilities; and miscellaneous sources such as sealed sources that are used for non-destructive testing. The largest sources are the reactor core, irradiated fuel and spent resins, and the design should therefore be such as to ensure that personnel are not exposed to direct radiation from these sources.

3.2. The magnitudes, locations, possible transport mechanisms and transport routes of the sources of potential radiation exposure under accident conditions should also be determined in the design phase of the plant. Guidance on the safety analysis to be carried out during the development of the design and for the final assessment is given in Ref. [10].

3.3. The main source of radiation under accident conditions for which precautionary design measures should be adopted consists of radioactive fission products. These are released either from the fuel elements or from the various systems and equipment in which they are normally retained. In Annex III examples of methods for assessing radiation sources for selected accidents are described. The scenarios are selected for illustrative purposes and cover all the major categories of designs for nuclear power plants with LWRs, CO₂ cooled reactors with UO₂ metal clad fuel, HWRs and reactors with on-load refuelling.

DESIGN APPROACH FOR OPERATIONAL STATES AND DECOMMISSIONING

Human resources

3.4. The design team should be fully aware of the radiological protection measures that should be incorporated into the design.⁶ A key issue is that design organizations should invite experts from relevant operating organizations to participate in activities in relation to the design of new plants and design modifications to an existing plant, to assist in ensuring that the requirements for radiation protection and waste management are met. Moreover, the applicable operating experience should be transferred to the design organization. In this way the interrelation between design aspects and operational procedures can be properly taken into account.

3.5. The optimization of protection and safety should be carried out at all stages of the lifetime of equipment and installations, from design and construction to operation and decommissioning. A structured approach should be taken to the radiation protection programme and the radioactive waste management programme to ensure the coherent application of the optimization principle in the operational stage of the plant [3].

3.6. In order to implement this structured approach, the design organization should have an optimization culture⁷ in which the importance of radiation protection is recognized at each stage of the design. An optimization culture is established by ensuring that all participants in a project are aware of the general requirements for ensuring radiation protection and of the direct and indirect impact of their individual activities or functions on the provision of radiation protection for site personnel and members of the public.

3.7. More specifically, an optimization culture should be established on the basis of:

⁶ There are various ways of ensuring that the design team is fully aware of the radiological protection measures that should be incorporated into the design, such as by having experts in radiological protection document the requirements and provide training. It may be appropriate to include an experienced operator in the design team.

⁷ An optimization culture may be explained as a system of shared knowledge, common objectives and attitudes that ensures that the management of occupational exposure and the exposure of members of the public benefit from the cooperation of all personnel involved in a project.

- Knowledge of the practices that result in the occupational exposure of site personnel and members of the public;
- Achieving good feedback of operating experience to the design team;
- Familiarity with the main factors that influence individual and collective doses;
- Familiarity with the analytical methods that are available to assist in the optimization of the design;
- Recognition that specialists in radiation protection are to be consulted whenever necessary to ensure that aspects that will have implications for radiation protection are properly evaluated and taken into account in the design.

3.8. Specialists in radiation protection should be closely involved in the design process because of their:

- Expertise in all areas that affect the production of radioactive material and its transport on the plant and its transport in the environment;
- Ability to evaluate the different sources of radiation in the plant and the resulting doses using the best available analytical methods and data from relevant operating experience;
- Familiarity with the relevant regulations, guidance and best practices;
- Familiarity with maintenance, in-service inspection and other work in high radiation areas that make a major contribution to the radiation exposure of site personnel.

3.9. Because chemical parameters are very important in controlling the radioactive sources in the plant, specialists in radiochemistry should also be involved in the design process. Materials specialists should be involved in controlling the source term due to corrosion products.

Organizational aspects

3.10. The requirement to achieve an adequate level of radiation protection affects a wide range of issues associated with the design. It is necessary therefore to ensure that for all design related decisions that may affect exposures the recommendations of radiation protection specialists have been recorded. However, the design process should be planned so that the implementation of these recommendations is not on the critical path. A means should be provided of ensuring that the design engineers take into account the required radiation protection measures at every stage of the design process. Such means could include:

- Rules or prescriptions for the layout and design of the plant;
- Written policies on such issues as the optimum use of respiratory protection;
- Checklists for use by engineers that can be reviewed by radiation protection specialists.

3.11. The project should be organized to enable the following:

- Radiation protection specialists within the design organization should be consulted at the early stages of the design when options for the major aspects of the design are being evaluated. It may also be appropriate to consult with specialists from external organizations.
- The design should incorporate good engineering practices that operating experience has shown to be effective in reducing exposure; deviations from such practices should be accepted only when a net benefit has been demonstrated.
- Radiation protection specialists should review all decisions that may have a major influence on exposures.
- There should be an appropriate forum for proposing improvements and resolving disputes that may occur between design engineers and radiation protection specialists.

3.12. A systematic and structured quality assurance (QA) programme should be applied in the entire design process as required by Ref. [11].⁸

3.13. A strong management commitment should be made to ensure that an optimization procedure is effective. In some organizations, this commitment includes the appointment of a manager for optimization who is directly responsible to the senior manager of the design project and thereby is involved in the decision making process.

⁸ The IAEA is revising the requirements and guidance in the area of quality assurance as established in Safety Series No. 50-C/SG-Q (1996) in new safety standards on management systems for the safety of nuclear facilities and activities involving the use of ionizing radiation. The term ‘management system’ has been adopted in the revised standards instead of the terms ‘quality assurance’ and ‘quality assurance programme’. The new standards will integrate all aspects of managing a nuclear facility, including the safety, health, environmental and quality requirements, into one coherent system.

Design strategy

General approach

3.14. As discussed in paras 2.7–2.8, design targets should be set at the start of the design process, and should include:

- Annual collective dose targets and individual dose targets for site personnel;
- Annual individual dose targets for members of the public.

The methods used for calculating doses should be subject to the approval of the regulatory body.

3.15. In practice, these design targets can be addressed independently, although in principle any enhancement of waste treatment systems to reduce the releases of radioactive substances to the environment may result in additional work being carried out by site personnel with a consequent increase in their exposures. In providing the best practicable means for reducing releases, the implications for the exposures of site personnel should be monitored to ensure that there is no undue increase.

3.16. In setting these design targets, account should be taken of experience at relevant plants that have a good operating record in terms of radiation protection, and the targets should be subject to the approval of the regulatory body. Account should be taken of any differences in the design, operations or policies between these reference plants and the plant under design. Such changes might include the power level, the materials that are used for the primary circuit, the type of fuel, the burnup, the extent of load following, the extent to which the reactor may operate with failed fuel and the extent to which on-load access to the containment is planned for.

3.17. A simple illustration of the use of design targets is given in Fig. 1 for the design of a plant that is a development of an earlier design(s). In the initial stages of the design process, design changes are introduced to ensure that the design targets will be achieved. However, achieving the design targets does not ensure that doses will be reduced to levels that are as low as reasonably achievable, and further development of the design may be necessary to ensure that radiation protection is optimized.

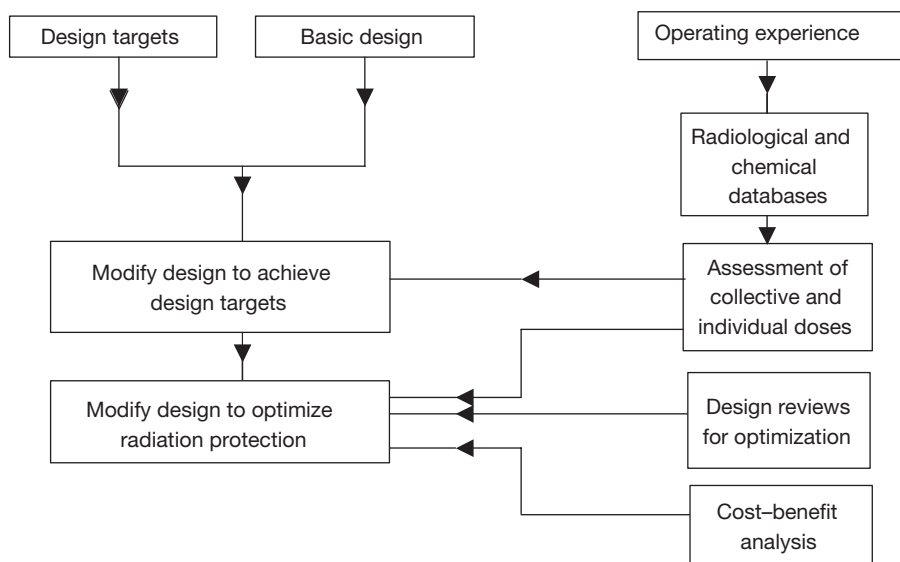


FIG. 1. Strategy for the optimization of radiation protection in the design of a nuclear facility.

Radiation protection design for site personnel

3.18. The following procedure should be adopted for developing the design to ensure the radiation protection of site personnel:

- (1) A strategy for controlling exposures should be developed so that the most important aspects are considered early in the design and in a logical order. For example, in many types of reactor design, two areas in which there is a major potential for reducing exposures are scheduled and unscheduled maintenance. In some designs of PWRs, two of the plant items that are important contributors to exposures are the steam generators and valves. These should therefore be considered first and it should be ensured that the reliability of the design has been proven. This will reduce exposures to levels that are as low as reasonably achievable and will also help to improve the efficiency and therefore the economic performance of the plant.

The second area that should be considered is design features that minimize the production and buildup of radionuclides, since reducing these will reduce radiation and contamination levels throughout the

plant, whereas a local solution, such as increasing the shielding or improving ventilation, will have only a local benefit. Subsequently, local plant features should be considered, such as the plant layout, the shielding and the design of systems and components. An example of a simplified strategy for a PWR is shown in Fig. 2.

- (2) The general requirements for the plant should be developed and documented. These should include the principles on which the layout of the plant will be based and restrictions on the use of specific materials in the design of the plant. These documents form part of the QA process for the design [11].
- (3) A logical layout for the plant should be developed that is divided into zones based on predicted dose rates and contamination levels, access requirements and specific requirements such as the need to separate safety trains.⁹ The dose rates may be calculated by using the source terms that are the basis for the radiation protection aspects of design (see Annexes II and IV), or they may be based on operating experience from similar plants provided that any changes in the relevant design and operating parameters are not significant. The zoning should be consistent with national legislation and regulatory requirements. It may be adequate to use the same definition of the zones as will be used when the plant is operational but it is found in many cases that a more specific definition of the zones is necessary for design purposes. Examples are given in Annex V.
- (4) The maintenance programme and operational tasks should be defined, preferably on the basis of well established concepts. The number of staff for each task should be based only on the operational requirements and should not be artificially increased to comply with the regulatory requirements or the dose constraints. For tasks for which doses are predicted to be relatively minor, the work can be expressed generically in terms of the number of person-hours that will be spent in each radiation zone. The type of worker who will perform each task is also identified. Types of worker include maintenance personnel, in-service inspection personnel, electrical staff, support staff (e.g. scaffolders), decontamination staff and health physics staff.

⁹ The term 'safety train' refers to a set of plant components that perform a safety function, such as an emergency core cooling pump and its associated equipment and source of water.

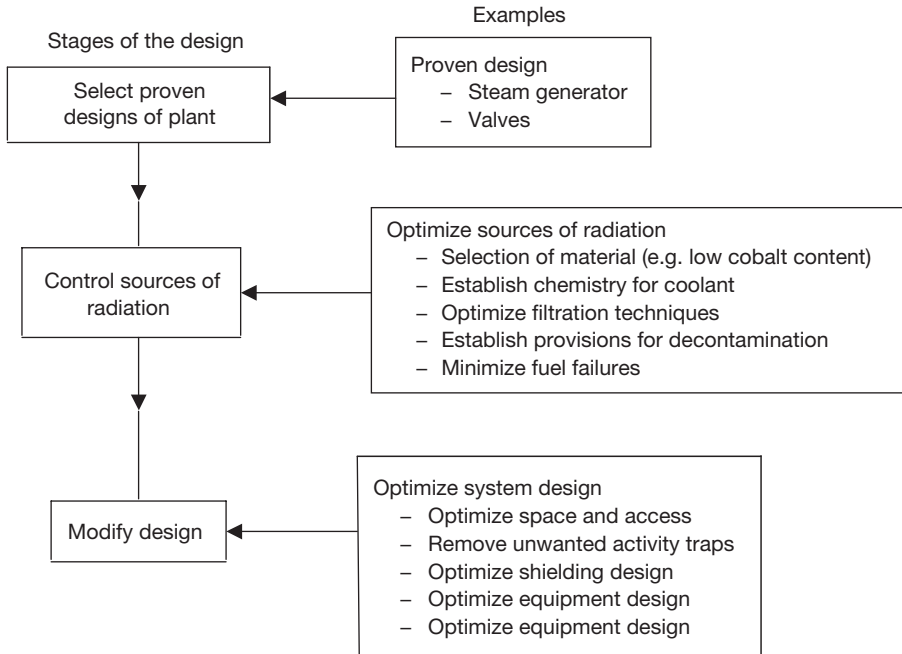


FIG. 2. A simplified strategy for the reduction of exposures in the (dashed of a PWR).

- (5) Collective and individual doses should be evaluated by combining the results of steps 3 and 4. The use of a database is recommended. The maximum use should be made of relevant operational experience, where available, particularly for work that is difficult to predict such as unplanned maintenance.
- (6) The proposed procedure is shown in the schematic flow chart of the factors that determine individual and collective doses in Fig. 3. This procedure is repeated at each significant stage of the design, and the level of detail should increase as the design is developed. At each stage, the doses that are evaluated should be compared with the design targets for each type of work.
- (7) At each step in Fig. 3, where there are options for the design, optimization studies should be performed. This is particularly important in cases for which it is predicted that the design targets will be exceeded.

3.19. Thus, the procedure is iterative, as is illustrated in Table 1.

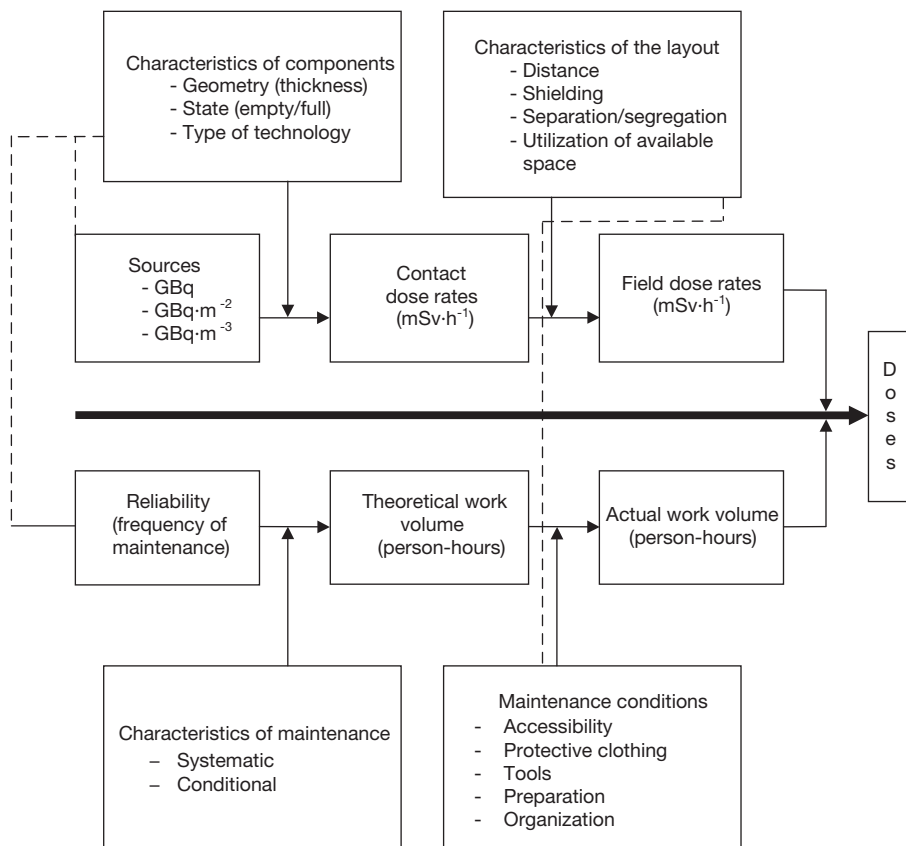


FIG. 3. Schematic flow chart of the origin of doses at a plant (dashed lines indicate the possible impact of certain blocks on others).

3.20. In PHWRs, for which an important contributor to exposures is the inhalation of airborne tritium, a logical layout of the plant should be developed that is divided into zones on the basis of levels of airborne radionuclides.

3.21. An auditable record should be kept of all the decisions made in the course of the design process and the reasons for those decisions, so that each aspect of the design that affects exposure to radiation is justified. This is part of the QA process for the design.

3.22. A preliminary decommissioning plan should be developed to ensure that the design includes the necessary features to reduce and control exposures

TABLE 1. AN EXAMPLE OF THE PRACTICAL IMPLEMENTATION OF THE STRATEGY FOR THE DESIGN PROCESS

Step ^a ↓	Design targets		Optimization process	Dose rates		Individual and collective doses
Item ^b ⇒	Individual dose target	Collective dose target	Studies to be performed	Zoning	CDR ^c	EWV ^d
Step 1 ^e	Average for all workers	Total for facility	Description of advantages/drawbacks of options	(Not relevant)	(Not relevant)	Estimation of EWV with options
Step 2	Update step 1 value	Update step 1 value	Evaluate main options	Establish approximate zoning	(Not relevant)	Programme definition EWV estimation
Step 3	Definitive value for the average for all workers	Evolution with decisions of step 2	Limited to important points	Evaluate using DST/RST/AST ^f	Calculate CDRs	Estimation of EWV
Step 4	Values for each craft type ^g	Evolution	Detailed by tasks	Verification/precision	Verification/precision	Detailed evaluation of EWV

^a Steps: The design of a complex project for which studies extend for several years is commonly divided into steps. The level of detail in the studies increases with the step number.

^b Item: The line of the table indicates the main parameters that are to be considered.

^c CDR: contact dose rate.

^d EWV: exposed work volume.

^e The information given in this line of the table is as follows: during step 1, an average dose constraint will be set (all craft/trade types included) as well as a collective dose target, including a margin; the optimization studies will result in a list of advantages and drawbacks of options; no zoning will be performed or contact dose rate calculations made; the exposed work volume will be estimated, with account taken of different options (the work is performed by workers or by robots).

^f AST: accident source term; DST: design source term; RST: realistic source term.

^g 'Craft' may be termed 'trade' in some States.

during decommissioning. In many cases, these features are the same as those necessary for operational states, but some additional special features may be necessary for decommissioning. If these are major, the necessary features for operational states and those for decommissioning should be optimized.

3.23. The design should be such as to facilitate achievement of the targets for occupational doses — both individual doses and collective doses — by adopting some or all of the following measures:

- (1) Reduction of dose rates in working areas by:
 - Reduction of sources (e.g. by the appropriate selection of materials; decontamination measures; the control of corrosion, water chemistry, filtration and purification; and the exclusion of foreign material from the primary systems);
 - Improvement of shielding;
 - Increase in the distance between workers and sources (e.g. by the use of remote handling);
 - Improvement of ventilation in PHWRs.
- (2) Reduction of occupancy times in radiation fields by:
 - Specifying high standards of equipment to ensure very low failure rates;
 - Ensuring ease of maintenance and removal of equipment;
 - Removing the necessity for some operational tasks by, for example, providing built-in auxiliary equipment and making provision in the design for permanent access;
 - Ensuring ease of access and good lighting.

Design for radiation protection for members of the public

3.24. As indicated in para. 2.7, design targets should be set at the start of the design process for annual individual doses to members of the public. Developments in the area surrounding the site and likely future population distributions should be taken into account as necessary.

3.25. The design targets should be achieved in the following way:

- Site specific features that affect the doses to members of the public should be identified at an early stage of the design process and taken into account in the design [12]. This should include the identification of the critical groups and the exposure pathways for these groups, which should be subject to the approval of the regulatory body.

- One possible approach would be to set targets for radioactive releases for which account is taken of operational experience and the use of best practicable means in the design of the treatment systems for radioactive effluents.
- The resulting doses to the critical groups should be evaluated to ensure achievement of the target.
- If the target is not met, other options should be evaluated.

3.26. The design should be such as to ensure that the contamination of material that leaves the plant can be adequately monitored.

Commissioning

3.27. The measures that are included in the design to provide an optimized level of radiation protection for operational states will be more than adequate for addressing the requirements for the commissioning phase (in which radiation levels are generally lower because of the lower power levels and the low buildup of radioactive material in the plant's components).

3.28. Measures should be taken during the early commissioning phase to identify any design deficiencies, such as the shielding being inadequate to prevent streaming, so that these can be rectified before the reactor reaches full power operation.

APPROACH TO DESIGN FOR ACCIDENT CONDITIONS

3.29. The principal design measures that are taken to protect the public against the possible radiological consequences of accidents are required to have the objectives of reducing the probability that accidents will occur (prevention of accidents) and reducing the source term and releases (mitigation of consequences) associated with accidents if they do occur [1]. Accident prevention is not explicitly addressed in this Safety Guide, but reference should be made to the available relevant information [13, 14].

3.30. The design objectives for accident conditions are to limit to acceptable levels: (1) the risks to the public from possible releases of radioactive material from the nuclear power plant; and (2) the risks to site personnel from these releases and from direct radiation exposure. These design objectives should be achieved by means of high quality design and special features, such as safety systems and protection systems, that are incorporated into the design of the

plant. Achievement of the design objectives should be confirmed by means of a safety analysis. Deterministic safety analyses and the associated dose assessments and probabilistic safety assessments for demonstrating compliance with the radiation dose limits should be based on conservative assumptions for the analysis of design basis accidents and realistic or best estimate assumptions for the analysis of severe accidents. These issues are discussed in Sections 10 and 11 of this Safety Guide and in Refs [1, 10].

3.31. To achieve the design objectives mentioned, the necessary design provisions and procedures (e.g. for access to the control room, maintenance of essential equipment or process sampling) should be such as to enable the plant operators to manage the situation adequately in an accident. Recommendations on how to protect site personnel under accident conditions are provided in Section 10.

3.32. Practices that are similar to those used for operational states should also be used to ensure that proper plant design is achieved to provide adequate radiation protection for site personnel and the public under accident conditions. A safety culture should be established to ensure that safety matters are given the highest priority and that regulatory requirements on releases of radioactive material under accident conditions are met with adequate margins.

3.33. The proper design of plant systems and components for radiation protection under accident conditions should be achieved by means of consultation with experts in radiation protection, plant operations, plant design and accident analysis, and regulatory matters. There should be continuous interactions among these groups throughout the design process to arrive at a design that provides radiation protection under accident conditions which is acceptable to the regulatory body. The design should also ensure that effective procedures for accident management can be implemented.

4. PROTECTION OF SITE PERSONNEL IN OPERATIONAL STATES AND DURING DECOMMISSIONING

OBJECTIVES

4.1. In this section, consideration is given to the design features for protecting site personnel from the radiation that results in operational states and during the decommissioning of a nuclear power plant, and the means of implementing the system of dose limitation as described in Appendix I of the BSS [2] and in Ref. [7]. Guidance given in Ref. [15] is also taken into account here.

CONTROL OF SOURCES OF RADIATION

General

4.2. As discussed in Section 3, one of the early tasks for the designer should be to optimize the protection against the sources of radiation in the plant since these affect the radiation levels throughout the plant, while most of the other aspects of the design affect the radiation levels in local areas only. For many reactor designs, the major sources of radiation are activated corrosion products, although fission products may also be significant if there are significant amounts of failed fuel cladding. These sources originate in the reactor core. The radioactive materials are then transported by the reactor coolant and by the moderator in liquid moderated reactors. Any practicable means should be employed by which the strength of sources or the transport of radioactive material can be reduced without excessive cost or reduction of the reliability of components. Leaktightness should be ensured as far as possible and leakage detection features should be provided, particularly for HWRs, for which the hazard due to tritium should be addressed. If seals are used, it should be ensured that these contain no antimony. Details are given in Annex II.

4.3. It should be recognized that, while consideration is given to decommissioning at the design stage, there will be significant and ongoing changes in conditions during decommissioning. Measures should be taken in the design to reduce the significance of these changes, but this factor should also be recognized in the operational arrangements. Equally, access will be necessary during decommissioning to areas that are not normally accessed. Consideration should be given to this factor in the design of facilities and equipment.

Corrosion products

4.4. Corrosion products contained in the coolant are activated as a result of temporary deposition in the core and during the normal passage of the coolant through the core. They are deposited in other parts of the primary circuit such as external pipe work and heat exchangers. This source should be minimized by the following means: (a) reducing the corrosion and erosion rate of circuit materials by the proper selection of materials and the control of the coolant chemistry; (b) selection of materials to minimize the concentration of nuclides (particularly of cobalt in steel) that are known from experience to become major sources of radiation; (c) providing removal systems (such as particulate filters and ion exchange resins); (d) minimizing the concentration in feedwater of nuclides that can be activated in the core.

4.5. The presence of materials with a high cobalt content, such as stellite, which are used for valve seats and bearings because of their hardness, in the primary coolant circuit and chemical control circuits, in the turbine systems of BWRs and in directly connected circuits should be reduced by applying the optimization principle. This is particularly important for components within the reactor core. In the case of direct cycle reactors, the use of materials with a high cobalt content should be minimized in components of the feedwater system that are situated after the condensate purification plant. For direct cycle, light water cooled, pressure tube reactors, for which the pressure tube and fuel cladding are made of zirconium or zirconium alloys of high purity and low activation cross-section, another important source of corrosion products (crud) is the feedwater circuit following the condensate polishing plant. Special attention should be paid to the choice of heater material for the feedwater, and consideration should be given to the possible installation of filters in the feedwater or core coolant return circuit close to the core inlet.

4.6. Special attention should also be paid to the selection of materials and to the coolant chemistry, which also make an important contribution to the reliability of the steam supply system for the nuclear plant. The compatibility of materials and coolant, which is of the utmost importance to minimizing the amount of maintenance, repair and statutory inspection necessary for primary circuit components, should be given careful consideration. Only those materials should be used that have been shown to be compatible with the coolant under the conditions (of temperature of coolant and material and coolant composition) that will prevail in the reactor. A specific concern is the possible occurrence of intergranular stress corrosion cracking.

4.7. In water cooled reactors, corrosion products are removed by treating the water with ion exchange resins to remove soluble species and by the installation of particulate filters. Their capacities should be adequate to cope with the enhanced release of corrosion products ('crud bursts') and fission products ('spiking') that occurs during the startup and cooldown phases.

4.8. Systems to remove corrosion products, both radioactive and non-radioactive, should be provided for the primary coolant for both water cooled and gas cooled reactors (GCRs). These systems are particularly important for gas cooled reactors with stainless steel clad fuel, such as advanced gas cooled reactors (AGRs), to minimize the amount of radioactive material available for deposition in the coolant circuit. In an AGR, active corrosion products arise in the coolant circuit primarily from the oxidation of fuel cladding. The oxides are released from the core surface in the form of particles when the fuel experiences a thermal shock as a result of reactor trip. Channel filters should be provided to remove this active oxide from the coolant so as to reduce deposition in the boilers and in other areas of the coolant circuit to which access for inspection and maintenance is required. Consideration should be given to treating the fuel cladding (e.g. by plating) to reduce spalling.

Fission products

4.9. Defects in the fuel cladding may result in the release of fission products to the coolant, which can add significantly to the activity of the coolant and contamination of the coolant circuit. Defective fuel elements should be removed as soon as possible after a failure occurs to reduce the exposure of site personnel from this source. Where refuelling is not on-load, means should be provided for detecting failed cladding, appropriate limits should be set for the coolant activity and the plant should be shut down within a prescribed time interval if these are exceeded.

Activity in pond water

4.10. Water in the fuel storage pond should be maintained at a low activity level by means of a cleanup system consisting of particulate filters and ion exchange resins. Where modifications are made to the fuel storage pond of a reactor in which there have been major fuel failures, the design should provide a means for containing any radioactive material that might otherwise leak into the pond water by bottling the fuel or some equivalent handling.

PLANT LAYOUT

4.11. In the design, a careful assessment should be made of the access requirements for operation, inspection, maintenance, repair, replacement and decommissioning of equipment. The layout of the plant should be designed to facilitate these tasks and to limit the exposure of site personnel.

Classification of areas and zones

4.12. The requirements for the classification of areas as controlled areas and supervised areas are established in the BSS, Appendix I, paras I.21–I.25 [2]. Each controlled area should have a minimum number of access and exit points for personnel and for materials and equipment.

4.13. Provision should be made for controlling the exit(s) from the controlled areas and for monitoring persons and equipment leaving the controlled areas.

4.14. Controlled areas should be divided into zones on the basis of the anticipated radiation levels and radioactive contamination levels (i.e. dose rates and activity concentrations for surface or airborne radionuclides; see Annex V). The greater the radiation or contamination related risks of a zone, the greater is the need to control access to that zone for the purpose of ensuring compliance with individual annual dose limits and taking account of dose constraints.

4.15. In the plant design stage, all rooms should be classified into planning zones on the basis of their likely dose rates, surface contamination levels and concentrations of airborne radionuclides. These zones constitute the controlled areas. The general practice is to divide the controlled areas of a nuclear power plant into three or more radiation and contamination zones, including zones that may not be accessible during operation.

4.16. Consideration should be given to the possibility that it may be necessary during operation or planned maintenance to reclassify certain areas temporarily or permanently. In this regard, particular attention should be paid to the planning of access routes. Under such conditions the zones and the controlled areas should be re-evaluated.