

IAEA Safety Standards

for protecting people and the environment

Safety of Uranium and Plutonium Mixed Oxide Fuel Fabrication Facilities

Specific Safety Guide

No. SSG-7



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SAFETY OF URANIUM AND
PLUTONIUM MIXED OXIDE
FUEL FABRICATION FACILITIES

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

IAEA SAFETY STANDARDS SERIES No. SSG-7

SAFETY OF URANIUM AND PLUTONIUM MIXED OXIDE FUEL FABRICATION FACILITIES

SPECIFIC SAFETY GUIDE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2010

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FOREWORD

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.

THE IAEA SAFETY STANDARDS

BACKGROUND

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

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

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

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

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

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

THE IAEA SAFETY STANDARDS

The status of the IAEA safety standards derives from the IAEA's Statute, which authorizes the IAEA to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection

of health and minimization of danger to life and property, and to provide for their application.

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

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

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

Safety Fundamentals

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

Safety Requirements

An integrated and consistent set of Safety Requirements establishes the requirements that must be met to ensure the protection of people and the environment, both now and in the future. The requirements are governed by the objective and principles of the Safety Fundamentals. If the requirements are not met, measures must be taken to reach or restore the required level of safety. The format and style of the requirements facilitate their use for the establishment, in a harmonized manner, of a national regulatory framework. The safety requirements use ‘shall’ statements together with statements of

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

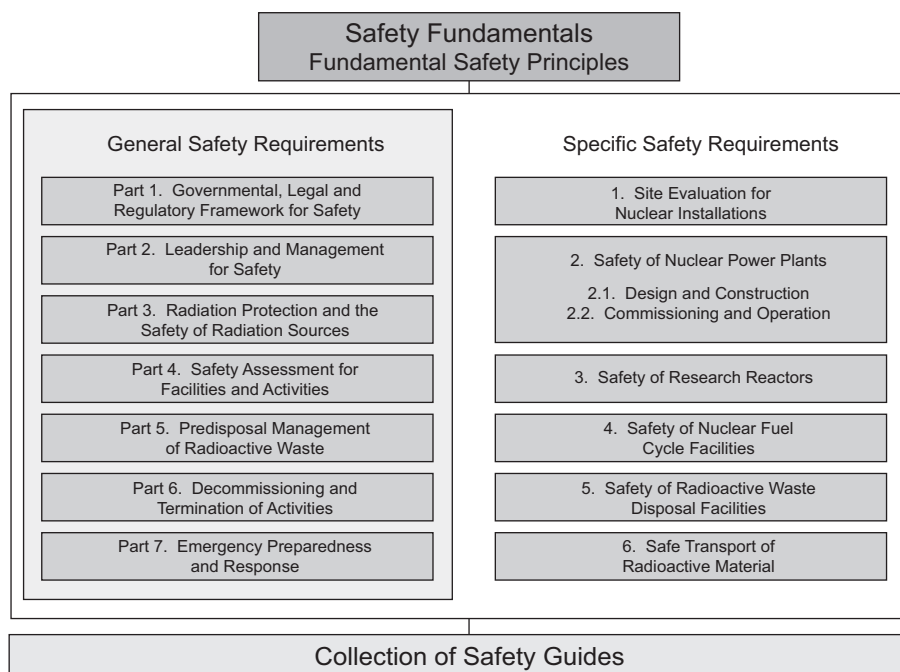


FIG. 1. The long term structure of the IAEA Safety Standards Series.

associated conditions to be met. Many requirements are not addressed to a specific party, the implication being that the appropriate parties are responsible for fulfilling them.

Safety Guides

Safety Guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus that it is necessary to take the measures recommended (or equivalent alternative measures). The Safety Guides present international good practices, and increasingly they reflect best practices, to help users striving to achieve high levels of safety. The recommendations provided in Safety Guides are expressed as ‘should’ statements.

APPLICATION OF THE IAEA SAFETY STANDARDS

The principal users of safety standards in IAEA Member States are regulatory bodies and other relevant national authorities. The IAEA safety

standards are also used by co-sponsoring organizations and by many organizations that design, construct and operate nuclear facilities, as well as organizations involved in the use of radiation and radioactive sources.

The IAEA safety standards are applicable, as relevant, throughout the entire lifetime of all facilities and activities — existing and new — utilized for peaceful purposes and to protective actions to reduce existing radiation risks. They can be used by States as a reference for their national regulations in respect of facilities and activities.

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

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

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

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

DEVELOPMENT PROCESS FOR THE IAEA SAFETY STANDARDS

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

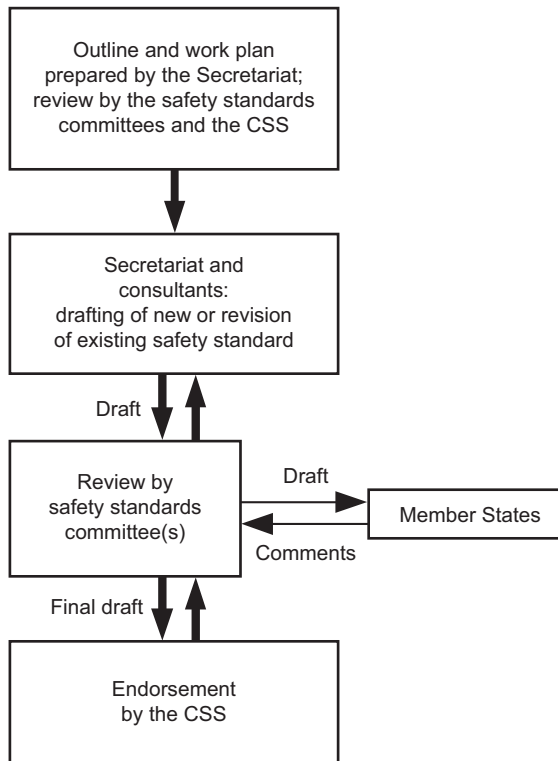


FIG. 2. The process for developing a new safety standard or revising an existing standard.

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

A management system has been established for the processes of planning, developing, reviewing, revising and establishing the IAEA safety standards. It articulates the mandate of the IAEA, the vision for the future application of the safety standards, policies and strategies, and corresponding functions and responsibilities.

INTERACTION WITH OTHER INTERNATIONAL ORGANIZATIONS

The findings of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the recommendations of international

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

INTERPRETATION OF THE TEXT

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

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

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

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

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1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide on the Safety of Uranium and Plutonium Mixed Oxide Fuel Fabrication Facilities recommends how to meet the safety requirements established in the Safety Requirements publication on the Safety of Nuclear Fuel Cycle Facilities [1] and supplements and elaborates on those requirements.

1.2. The safety of uranium and plutonium mixed oxide (MOX) fuel fabrication facilities is ensured by means of their proper siting, design, construction, commissioning, and operation, including management, and decommissioning. This Safety Guide addresses all of these stages in the lifetime of MOX fuel fabrication facilities on an industrial scale only, with emphasis placed on the safety of their design and operation.

1.3. Plutonium is a valuable energy resource that arises from the civil and military industries in a number of States. When plutonium is mixed with uranium oxide, the resulting mixed oxide can be manufactured into fuel suitable for loading into water reactors and fast breeder reactors, thereby utilizing this energy resource.

1.4. The toxicity of plutonium is high and therefore it is important that best practice be employed at all stages of the manufacture of MOX fuel, and that plutonium and all waste from MOX fuel fabrication facilities be handled, processed, treated and stored safely. The goal is to maintain the lowest possible levels of discharges to the environment and limit the impact of accident conditions on workers, the public and the environment.

OBJECTIVE

1.5. The objective of this Safety Guide is to provide recommendations that, in the light of experience in States and the present state of technology, should be followed to ensure safety for all stages in the lifetime of a MOX fuel fabrication facility. These recommendations specify actions, conditions or procedures necessary for meeting the requirements established in Ref. [1]. This Safety Guide is intended to be of use to designers, operating organizations and regulators for ensuring the safety of MOX fuel fabrication facilities.

SCOPE

1.6. The safety requirements applicable to fuel cycle facilities (i.e. facilities for uranium ore processing and refining, conversion, enrichment, fabrication of fuel including MOX fuel, storage and reprocessing of spent fuel, associated conditioning and storage of waste, and for related research and development) are established in Ref. [1]. The requirements applicable specifically to MOX fuel fabrication facilities are established in Appendix II of Ref. [1]. This Safety Guide provides recommendations on meeting the requirements established in Sections 5–10 and in Appendix II of Ref. [1].

1.7. This Safety Guide deals with the handling, processing and storage of: (1) plutonium oxide; (2) depleted, natural or reprocessed uranium oxide; (3) MOX manufactured from plutonium oxide and uranium oxide for use as a feed material to form MOX fuel rods and assemblies in water reactors and fast breeder reactors.

1.8. The fuel fabrication processes covered by this Safety Guide are dry processes; pre-processing, or polishing, of oxide powders is not addressed.

1.9. This Safety Guide is limited to the safety of MOX fuel fabrication facilities; it does not deal with any impact that the manufactured fuel assemblies may have on safety for the reactors in which they are to be used.

1.10. The implementation of other safety requirements such as those on the legal and governmental framework and regulatory supervision (e.g. requirements for the authorization process, regulatory inspection and regulatory enforcement) as established in Ref. [2], and those on the management system and the verification of safety (e.g. requirements for the management system and for safety culture) as established in Ref. [3], are not addressed in this Safety Guide. Recommendations on meeting the requirements for the management system and for the verification of safety are provided in Ref. [4].

1.11. Sections 3–8 of this publication provide recommendations on radiation protection measures for meeting the safety requirements established in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources [5]. The recommendations in the present Safety Guide supplement the recommendations on occupational radiation protection provided in Ref. [6].

1.12. The typical process routes of MOX fuel fabrication facilities are shown in a schematic diagram in Annex I.

STRUCTURE

1.13. This Safety Guide consists of eight sections and three annexes. Section 2 provides general safety recommendations for a MOX fuel fabrication facility. Section 3 describes the safety aspects to be considered in the evaluation and selection of a site to avoid or minimize any environmental impact of operations. Section 4 deals with safety in the design stage: it provides recommendations on safety analysis for operational states and accident conditions and discusses the safety aspects of radioactive waste management in the MOX fuel fabrication facility and other design considerations. Section 5 addresses the safety aspects in the construction stage. Section 6 discusses safety considerations in commissioning. Section 7 deals with safety in the stage of operation of the facility: it provides recommendations on the management of operation, maintenance and periodic testing, control of modifications, criticality control, radiation protection, industrial safety, the management of waste and effluents, and emergency planning and preparedness. Section 8 provides recommendations on meeting the safety requirements for the decommissioning of a MOX fuel fabrication facility. Annex I shows the typical process routes for a MOX fuel fabrication facility. Annex II provides examples of structures, systems and components important to safety in MOX fuel fabrication facilities, grouped in accordance with process areas. Annex III provides examples of parameters for defining the operational limits and conditions for a MOX fuel fabrication facility.

2. GENERAL SAFETY RECOMMENDATIONS

2.1. In MOX fuel fabrication facilities, large amounts of fissile material and radioactive material are present in a dispersible form. This is particularly so in the early stages of the fuel fabrication process, when the material is in powder form. In addition, the radioactive materials encountered exist in diverse physical forms. Thus, in MOX fuel fabrication facilities the main hazards are potential criticality, loss of confinement and radiation exposure (both internal and external), from which workers, the public, and the environment must be protected by means of

adequate design, siting, construction, commissioning and safe operation, and decommissioning.

2.2. In MOX fuel fabrication facilities, both plutonium oxide (PuO_2) and uranium oxide (UO_2) are processed. The factors affecting the safety of a MOX fuel fabrication facility include the following:

- While the radiological toxicity of uranium is low, this is not the case for plutonium, and thus any potential off-site radiological consequences following an accident might be expected to be high;
- The dry process fabrication method has a potential for the dispersion of radioactive material;
- The isotopic characteristics of the plutonium used in MOX fuel fabrication facilities have an effect on the potential for criticality, external exposure and thermal effects.

2.3. External exposure is due to neutron emission from ^{238}Pu and ^{240}Pu isotopes and gamma radiation from ^{241}Am , which is formed through the radioactive decay of ^{241}Pu during storage. Thermal hazards come mainly from the decay heat of ^{238}Pu .

2.4. A MOX fuel fabrication facility does not store or process significant quantities of hazardous chemicals. Thus, in MOX fuel fabrication facilities, chemical hazards that could lead to radiological consequences are low compared with those for wet processes used in other fuel cycle facilities.

2.5. The wide variety of hazards posed by MOX fuel fabrication facilities has determined the various safety measures employed in such facilities. The main safety objectives in a MOX fuel fabrication facility are the prevention of criticality, confinement of radioactive material and protection against radiation exposure.

2.6. Thus, it is important to perform a safety analysis in which potential accidents are analysed to ensure that they are adequately prevented, detected and, if they do occur, mitigated. The safety requirements are to be applied by means of a graded approach, as stated in Section 1 of Ref. [1].

2.7. For the application of the requirement that the concept of defence in depth be applied at the facility (see Section 2 of Ref. [1]), the first two levels of defence in depth are the most important, as risks can be reduced to insignificant levels by means of design and appropriate operating procedures (see Sections 4 and 7).

2.8. With respect to the hazard of potential criticality, MOX fuel fabrication facilities reach a safe state when the process of fuel fabrication is brought to a stop (i.e. there is no movement or transfer of material).

2.9. There are, however, some systems of the facility that should continue to operate to maintain the facility in a safe state, such as the following:

- Heat removal systems in storage areas to remove decay heat from reactor grade plutonium (however, the buildup of heat is not immediate);
- Although static barriers ensure a certain degree of confinement of radioactive material, dynamic containment systems should continue to operate to prevent leakage of radioactive material from the facility;
- Inert gas feed systems of sintering furnaces or gloveboxes.

3. SITE EVALUATION

3.1. The site evaluation process for a MOX fuel fabrication facility will depend on a large number of criteria, some of which are more important than others. At the earliest stage of planning a facility, a list of these criteria should be prepared and considered in accordance with their safety significance. In most cases, it is unlikely that all the desirable criteria can be met, and the risks posed by possible safety significant external initiating events (e.g. earthquakes, aircraft crashes, fires and extreme weather conditions) will probably dominate in the site evaluation process.

3.2. For a MOX fuel fabrication facility, liquid discharges of hazardous materials are generally negligible owing to the dry process used to manufacture fuel. Appropriate design and operation can ensure that gaseous releases are negligible under normal operating conditions. The major hazard in accident conditions is the potential release of plutonium (as plutonium oxide or MOX) as particles to the atmosphere.

3.3. A MOX fuel fabrication facility should be considered to be a facility with a high hazard potential. The characteristics of the site that should be considered to ensure the safety of the facility include the following:

- *Legal requirements.* In some States, the licensing process for a MOX fuel fabrication facility is facilitated by using a site for which regulatory consent to process plutonium has already been granted.
- *Transport links.* In principle, the aim should be to minimize the extent to which fissile material needs to be transported. Export of MOX fuel will require ready access to safe and effective transport networks, e.g. ports (for overseas transport), roads and railways.

3.4. However, the following characteristics of MOX fuel fabrication facilities tend to diminish some of the constraints that usually apply to the siting of nuclear facilities:

- MOX fuel fabrication facilities do not require the availability of large volumes of water for their processes, for cooling purposes or for diluting discharges of liquid effluents.
- MOX fuel fabrication facilities do not require tall structures such as chimneys or cooling towers.
- The main hazards are flooding, which could result in criticality issues, and earthquakes, which could result in loss of confinement, and potential criticality events due to loss of safe geometry. However, the consequences of these hazards can be minimized by means of proper design.
- The need for land (the environmental ‘footprint’ of the buildings and the surrounding site area) is relatively small compared with that for other fuel cycle facilities.

3.5. The density of population in the vicinity of the MOX fuel fabrication facility and the direction of the prevailing wind at the site should be considered in the site evaluation process to minimize any possible health consequences for people in the event of a release of radioactive material.

3.6. A full record should be kept of the decisions taken on the selection of a site for a MOX fuel fabrication facility and the reasons behind those decisions.

4. DESIGN

GENERAL

Safety functions for MOX fuel fabrication facilities

4.1. Safety functions (see Ref. [1], Appendix II, para. II.1), i.e. those functions the loss of which may lead to releases of radioactive material having possible radiological consequences for workers, the public or the environment, are those designed for:

- (1) Prevention of criticality;
- (2) Confinement of radioactive material, including removal of decay heat;
- (3) Protection against external exposure.

Specific engineering design requirements

4.2. The following requirements apply:

- (1) The requirements on prevention of criticality as established in paras 6.43–6.51 and II.3–II.8 of Appendix II of Ref. [1].
- (2) The requirements on confinement of radioactive materials as established in paras 6.37–6.39, 6.52 and II.9–II.14 of Appendix II of Ref. [1].
- (3) The requirements on protection against external exposure are established in paras 6.40–6.42 of Ref. [1]. Owing to the radiation fields associated with plutonium (neutron emissions and gamma radiation), an appropriate combination of requirements on source limitation, distance, time and shielding is necessary for the protection of workers in respect of whole body exposures and exposures of the hands. For neutron emissions, a general design principle is to place the shielding as close as possible to the source. In some cases, remote operation should be considered if necessary.

Design basis accidents and safety analysis

4.3. The definition of a design basis accident in the context of fuel cycle facilities can be found in para. III-10 of Annex III of Ref. [1]. The safety requirements relating to design basis accidents are established in paras 6.4–6.9 of Ref. [1].

4.4. The specification of a design basis accident (or equivalent) will depend on the facility design and national criteria. However, particular consideration should be given to the following hazards in the specification of design basis accidents for MOX fuel fabrication facilities:

- (a) A nuclear criticality accident;
- (b) A hydrogen explosion;
- (c) A fire;
- (d) Natural phenomena such as earthquakes, flooding or tornadoes;
- (e) An aircraft crash.

4.5. The first two events might result primarily in radiological consequences for on-site workers. The last three events might have both on-site and off-site consequences.

4.6. The events listed in para. 4.4 may occur as a consequence of a postulated initiating event (PIE). Selected PIEs are listed in Annex I of Ref. [1].

Structures, systems and components important to safety

4.7. The likelihood of design basis accidents (or equivalent) should be minimized, and any associated radiological consequences should be controlled by means of structures, systems and components important to safety (see paras 6.5–6.9 and Annex III of Ref. [1]). Annex II of this Safety Guide presents examples of structures, systems and components and representative events that may challenge the associated safety functions.

SAFETY FUNCTIONS

Prevention of criticality

4.8. “For the prevention of criticality by means of design, the double contingency principle shall be the preferred approach” (Ref. [1], para 6.45). Paragraph II.5 of Appendix II of Ref. [1] establishes requirements for the control of system parameters for the prevention of criticality. Some examples of the parameters subject to control are listed in the following.

- (a) *PuO₂ (input)*.
 - The ratios of the amount of (²³⁹Pu + ²⁴¹Pu) to the total amount of plutonium, and of the amount of ²⁴⁰Pu to the total amount of plutonium (the isotopic composition of the plutonium); and the amount of moisture (degree of moderation), for control of criticality by means of mass and geometry;
 - The presence of appropriate neutron absorbers, in, for example, the materials used for the construction of storage equipment, cans for powder and shipment containers;
 - The upper bounded PuO₂ density.
- (b) *UO₂ (input)*.
 - The ratio of the amount of ²³⁵U to the total amount of uranium (the isotopic composition of the uranium; if this ratio is less than 1%, there may be considered to be no criticality hazard); and the amount of moisture (degree of moderation), for control of criticality by means of mass and geometry.
 - The upper bounded UO₂ density.
- (c) *MOX powder*.
 - The ratios of the amount of (²³⁹Pu + ²⁴¹Pu) to the total amount of plutonium, of the amount of ²³⁵U to the total amount of uranium, and of the amount of ²⁴⁰Pu to the total amount of plutonium (Pu isotopic specification); the ratio of PuO₂ to the total amount of oxides (the PuO₂ concentration); and the level of moisture and the amount of additives (the degree of moderation), for assessment of the criticality hazard at each stage of the process;
 - The presence of non-homogeneous distributions of moderators, if considered necessary.

4.9. The aim of the criticality analysis, as required in para. II.7 of Appendix II of Ref. [1], is to demonstrate that the design of equipment is such that the values of controlled parameters are always maintained in the subcritical range. One method to accomplish this is by determining the effective multiplication factor (k_{eff}), which mainly depends on the mass, heterogeneity of the material and the moderation, geometry, density, reflection and nuclear properties of the fissionable material. The calculated value of k_{eff} is then compared with the value specified by the design limit.

4.10. The methods of calculation vary widely in basis and form, and each has its place in the broad range of situations encountered in the field of nuclear criticality safety. The criticality analysis should involve:

- The use of a conservative approach, with account taken of:
 - Uncertainties in physical parameters, the physical possibility of worst case moderation conditions and the presence of non-homogeneous distributions of moderators;
 - Plausible operational occurrences and their combinations if they cannot be shown to be independent;
 - Operational states that may result from external hazards.
- The use of appropriate and qualified computer codes (i.e. those that have been compared with benchmarks to determine the uncertainties in the code in respect of the calculated effective multiplication factor k_{eff}) within their applicable range and of appropriate data libraries of nuclear reaction cross-sections.

4.11. Another method of calculation is to specify the ‘safe mass’ as a factor of the critical mass, and demonstrating that the system inventory will always be less than this safe mass under all normal and abnormal conditions.

4.12. The following are recommendations for conducting a criticality analysis for a MOX fuel fabrication facility to meet the safety requirements established in Ref. [1], Appendix II, para. II.7:

- *Mass*. “Criticality safety shall be assessed with significant margins” (Ref. [1], para. II.7(b)). The mass margin should be sufficient to compensate for possible over-batching of PuO_2 or MOX or under-batching of UO_2 .
- *Density and forms of materials*. “A conservative approach shall be taken” (Ref. [1], para. II.7(d)). The analysis should cover a range of densities and moderators for different forms of MOX (e.g. powder, green and sintered pellets, and rods) to determine the most reactive conditions that could occur.
- *Concentration and density (in an analytical laboratory and in liquid effluent units)*. “A conservative approach shall be taken” (Ref. [1], para. II.7(e)). The analysis should cover a range of: (i) plutonium and uranium concentrations for solutions; and (ii) powder and pellet densities for solids, to determine the most reactive conditions that could occur.
- *Moderation*. “The analysis shall consider a range of moderation to determine the most reactive conditions that could occur” (Ref. [1], para. II.7(f)). Water, oil and other hydrogenous substances are common moderators that are present in MOX fuel fabrication facilities or that may be present in accident conditions (e.g. water from firefighting). Special consideration should be given to cases of inhomogeneous moderation.

- *Reflection*. “A conservative assumption concerning reflection shall be made in the criticality analysis” (Ref. [1], para. II.7(g)). The most conservative margin should be retained of those resulting from different assumptions such as: (i) a hypothetical thickness of water around the processing unit; and (ii) consideration of the actual neutron reflection effect due, for example, to the presence of human beings, organic materials, shielding materials, or the concrete or steel of the container in or around the processing unit.
- *Neutron absorbers*. “When taken into account in the safety analysis, and if there is a risk of degradation, the presence and integrity of neutron absorbers shall be verifiable during periodic testing. Uncertainties in absorber parameters (e.g. mass and density) shall be considered in the criticality calculations” (Ref. [1], para. II.7 (i)). The neutron absorbers that may be used in MOX fuel fabrication facilities include cadmium and boron and the safety analysis should incorporate their effect as neutron absorbers; however, ignoring their effects would yield conservative results. The use of mobile neutron absorbers should be avoided.

4.13. For processes in which radioactive material is handled in a discontinuous manner (batch processing), the process and the related equipment should be designed to ensure that radioactive material is transferred only when the limits defined for the next process are satisfied.

Confinement of radioactive material

4.14. The requirements for confinement are established in para. II.9 of Ref. [1]: “Confinement shall be the primary method for protection against the spreading of powder contamination” (e.g. in areas where significant quantities of plutonium powder are held). “Confinement shall be provided by two complementary containment systems — static and dynamic.”

4.15. The first static barrier normally consists of gloveboxes, fuel claddings or material containers. The second static barrier normally consists of rooms around the gloveboxes and/or the walls of the building. In the design of the static containment system account should be taken of typical openings between different confinement zones (e.g. doors, penetrations).

4.16. To complement the effectiveness of the static barriers, a “dynamic containment system shall be used to create airflow towards equipment that is more contaminated” (normally the gloveboxes). Such airflow will establish a