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

IAEA

International Atomic Energy Agency

IAEA SAFETY RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards.

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

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

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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

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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 measures[1] 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

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

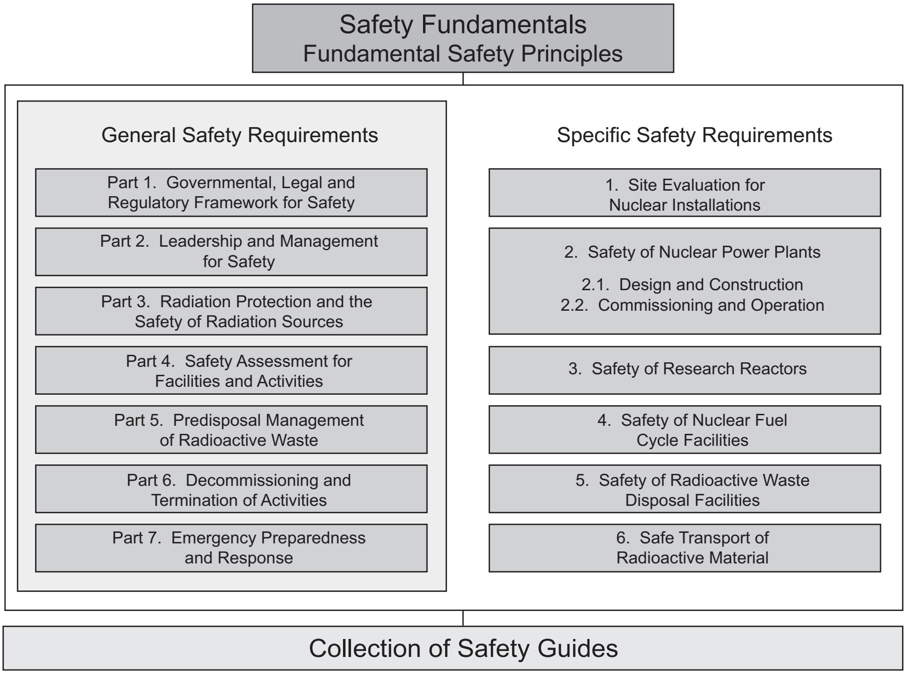

FIG. 1. The long term structure of the IAEA Safety Standards Series.

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).

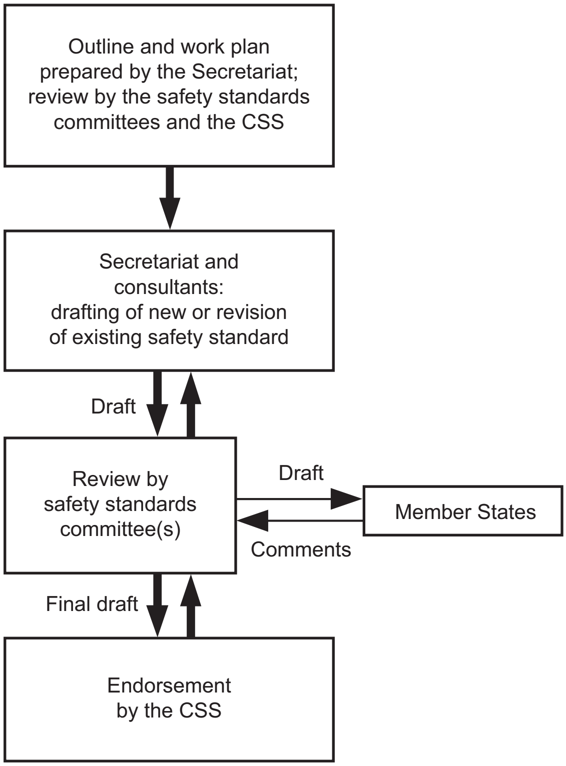

FIG. 2. The process for developing a new safety standard or revising an existing standard.

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.

CONTENTS

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) *PuO_2 (input)*.

— The ratios of the amount of (^{239}Pu + ^{241}Pu) to the total amount of plutonium, and of the amount of ^{240}Pu 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 PuO_2 density.

(b) *UO_2 (input).*

— The ratio of the amount of ^{235}U 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 UO_2 density.

(c) *MOX powder*.

— The ratios of the amount of (^{239}Pu + ^{241}Pu) to the total amount of plutonium, of the amount of ^{235}U to the total amount of uranium, and of the amount of ^{240}Pu to the total amount of plutonium (Pu isotopic specification); the ratio of PuO_2 to the total amount of oxides (the PuO_2 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 cascade of reducing absolute pressures (i.e. creating negative pressure) between the environment outside the building and the contaminated material inside.

4.17. Specific attention should be paid in the design to operations that lead to the transfer of contaminated materials outside the static containment system. Normal operations should not involve any transfer of powders outside the first barrier (with gloveboxes and tunnels linking them).

4.18. Devices for monitoring contamination should be included in the design of confinement areas.

4.19. The design of a MOX fuel fabrication facility should be such as to facilitate operation, especially maintenance and decontamination activities; consequently building compartmentalization should be considered in the design of the MOX fuel fabrication facility and a balance should be achieved between possible consequences of contamination and economic considerations.

4.20. The ventilation system normally includes filters in series to protect the workers, the public and the environment. Filters should be used when airflow crosses confinement zones and when airflow exits the facility. The filters filter the air during normal operation and ensure the continuity of the static barriers in the event of loss of ventilation.

4.21. Primary filters should be located as close to the source of contamination as practicable (e.g. near the gloveboxes) to minimize the buildup of plutonium powder or MOX powder in the ventilation ducts. Multiple primary filters in series should preferably be used since this configuration will prevent any transfer of contamination during maintenance of one of the filters.

4.22. In addition, operating fans and standby fans should be provided and should be powered such that, in the case of loss of normal power, the uninterrupted functioning of glovebox ventilation systems is ensured. Local monitoring systems and alarm systems should be installed to alert operators to system malfunctions that may result in differential pressures that are considered too high or too low.

4.23. Last stage filters are used to protect the public and the environment and are normally located close to the location at which discharges to the environment occur. Last stage filters are discussed in paras 4.30 and 4.31.

4.24. To prevent the propagation of a fire through the ventilation ducts and to maintain the integrity of firewalls, ventilation systems should be equipped with fire dampers, unless the likelihood of a fire spreading is considered to be acceptably low.

4.25. At the design stage, provision should also be made for the installation of equipment for monitoring airborne radioactive material. Monitoring points should be chosen that would correspond most accurately to the exposure of workers and would minimize the time for detection of any leakage.

Protection of workers

4.26. The first static barrier normally protects the workers. The requirements for the design of the first static barrier should be specified to ensure and to control the integrity of this barrier. The design specifications should include: welding specifications; selection of materials; leaktightness (for gloveboxes, specification of the ratio of the leak rate to the flow rate); ability to withstand seismic loads; design of equipment (internal equipment for gloveboxes); specification of penetration seals for electrical and mechanical penetrations; and the ease of carrying out maintenance work.

4.27. Gloveboxes often consist of welded stainless steel enclosures with windows, arranged either singly or in interconnected groups. Access to equipment inside the glovebox is through access holes in the glovebox window that are fitted with gloves (made out of various materials depending on the work being performed in the glovebox) which maintain the containment barrier.

4.28. The dynamic containment system is used to minimize the radiation exposure of workers and their exposure to hazardous material that could become airborne and so could be inhaled.

4.29. For normal operation, the need for the use of protective respiratory equipment should be minimized through careful design of the static and dynamic containment systems and of devices for the immediate detection of low thresholds of airborne radioactive material.

Protection of the environment

4.30. The uncontrolled dispersion of radioactive substances to the environment as a result of an accident can occur if all the containment barriers are impaired. Barriers that may provide environmental protection comprise the room and the building itself. In addition, ventilation of the containment systems, by the discharge of exhaust gases through a stack after passing through a particulate removal filter, reduces the normal environmental discharges of radioactive material to very low levels.

4.31. In addition to meeting the requirement established in para. II.14 of Appendix II of Ref. [1], the design of a MOX fuel fabrication facility should also provide measures for uninterrupted monitoring and control of the stack exhaust, for monitoring of the environment around the facility and for identification of breaches of the containment barriers.

Protection against external exposure

4.32. External exposure can be controlled by means of an appropriate combination of requirements on source reduction, distance, time and shielding. Owing to the specific activity of plutonium, the shielding provided by the vessels and/or gloveboxes of a MOX fuel fabrication facility may not be sufficient to control exposure adequately, and thus additional controls on time, distance and shielding should be considered, where necessary.

4.33. If necessary, consideration should be given to the remote operation of process equipment and the installation of equipment for powder collection to prevent any spreading of powder in gloveboxes.

4.34. Provision of shielding in material storage areas, at process gloveboxes (e.g. where powder processing or pellet processes are carried out) and in the fuel assembly area should be considered. For new MOX fuel fabrication facilities, the design of shielding should be such as to ensure compliance with targets for occupational exposure (see para. 6.4 of Ref. [1]) based on assumptions about the spread of contamination in gloveboxes, the time of occupancy and the sources of radiation.

POSTULATED INITIATING EVENTS

Internal initiating events

Fire and explosion

4.35. MOX fuel fabrication facilities, like all industrial facilities, have to be designed to control fire hazards to protect workers, the public and the environment. Fire in MOX fuel fabrication facilities may lead to the dispersion of radioactive material and/or toxic material by breaching the containment barriers or may cause a criticality accident by affecting the system or the parameters used for the control of criticality (e.g. the moderation control system or the dimensions of processing equipment).

4.36. The fire hazards that are specifically encountered in a MOX fuel fabrication facility are associated with the presence of flammable material such as electrical cabling and shielding, in particular when associated with gloveboxes.

Fire hazard analysis

4.37. As an important aspect of fire hazard analysis for a MOX fuel fabrication facility, areas of the facility that require special consideration should be identified. Special fire hazard analyses should be carried out for:

(a) Areas where fissile material is processed and stored;
(b) Gloveboxes, especially those in which nuclear material is processed as powder or powder is produced;
(c) Workshops and laboratories in which flammable liquids and/or combustible liquids, solvents and resins and reactive chemicals are used, or zirconium metal is mechanically treated (e.g. producing cuttings or shavings);
(d) Areas with high fire loads, such as waste storage areas;
(e) Waste treatment areas, especially those where incineration is carried out;
(f) Rooms housing safety related equipment, e.g. items, such as air filtering systems, and electrical switch rooms, whose degradation may lead to radiological consequences or consequences in terms of criticality that are considered to be unacceptable;
(g) Process control rooms and emergency control rooms;
(h) Evacuation routes.

4.38. Fire hazard analysis involves identification of the causes of fires, assessment of the potential consequences of a fire and, where appropriate, estimation of the frequency or probability of occurrence of fires. Fire hazard analysis is used to assess the inventory of fuels and initiation sources, and to determine the appropriateness and adequacy of measures for fire protection. Computer modelling of fires may sometimes be used in support of the fire hazard analysis.

4.39. The estimation of the likelihood of fires can be used as a basis for making decisions or for identifying weaknesses that might otherwise go undetected. Even if the estimated likelihood of fire may seem low, a fire might have significant consequences for safety, and thus certain protective measures should be undertaken, such as delineating small fire areas, to prevent fires or prevent the fire from spreading.

4.40. The analysis of fire hazards should also involve a review of the provisions made at the design stage for preventing, detecting and fighting fires.

Fire prevention, detection and mitigation

4.41. Prevention is the most important aspect of fire protection. Facilities should be designed to limit fire risks through the incorporation of measures to ensure that fires do not break out. Measures for mitigation should be put in place to minimize the consequences of a fire in the event that a fire breaks out despite preventive measures.

4.42. To accomplish the two-fold aim of fire prevention and mitigation of the consequences of a fire, a number of general and specific measures should be taken, including the following:

- — Minimization of the amount of combustible material present in gloveboxes; nevertheless it may be necessary to maintain inert atmospheres and alarms for monitoring oxygen levels to minimize the risk of a large fire.
- — Separation of the areas where non-radioactive hazardous material is stored from the process areas.
- — Minimization of the fire load of individual rooms.
- — Selection of materials, including building materials, process and glovebox components and materials for penetrations, in accordance with functional criteria and fire resistance ratings.
- — Compartmentalization of buildings and ventilation ducts as far as possible to prevent the spreading of fires. Buildings should be divided into fire zones. Measures should be put in place to prevent or severely curtail the capability of a fire to spread beyond the fire zone in which it breaks out. The higher the fire risk, the greater the number of fire zones a building should have.
- — Suppression or limitation of the number of possible ignition sources such as open flames or electrical sparks.

4.43. “Extinguishing devices, automatically or manually operated, with the use of an adequate extinguishing material shall be installed in areas where a fire is possible and where the consequences of a fire could lead to the wide dispersion of contamination outside the first static barrier. The installation of automatic devices with water sprays shall be carefully assessed for areas where uranium, plutonium and/or mixed oxide (MOX) may be present, with account taken of the risk of criticality” (Ref. [1], Appendix II, para. II.16). Extinguishing gas may be used in the event of a fire breaking out in a glovebox.

4.44. The design of ventilation systems should be given particular consideration with regard to fire prevention. Dynamic containment comprises ventilation ducts and filter units which may constitute weak points in the fire protection system unless they are of suitable design. Fire dampers should be mounted in the ventilation system unless the likelihood of widespread fires is acceptably low. The fire dampers should close automatically on receipt of a signal from the fire detection system or by means of temperature sensitive fusible links. Spark arrestors should be used to protect the filters if necessary. The required operational performance of the ventilation system should be specified so as to comply with fire protection requirements.

4.45. Lines that cross the boundaries between fire areas or fire zones (e.g. electricity, gases and process lines) should be designed to ensure that fire does not spread.

Explosions

4.46. In MOX fuel fabrication facilities, the use of hydrogen in the sintering furnaces is a potential cause of an explosion. To prevent this, one strategy is to stop oxygen from entering the furnace; a second method is to supply a quality controlled, premixed gas to the furnaces.

4.47. Hydrogen should be diluted with an inert gas (e.g. argon) before it enters the sintering furnace so that any postulated resulting explosion would result in acceptable consequences for safety. The supply of premixed gas should be automatically stopped when the concentration of hydrogen in the quality controlled premixed gas exceeds a limit.

4.48. In addition, effective gas locks should be provided between rooms with a hydrogen atmosphere and other areas of the facility. Systems for detecting hydrogen leakages should be installed in such rooms.

Flooding

4.49. Flooding in a MOX fuel fabrication facility may lead to the dispersion of radioactive material and to changes in the conditions for moderation.

4.50. Gloveboxes should not be connected to the water supply in normal operating conditions, unless the presence or leakage of water inside gloveboxes was taken into account in the criticality analysis.

4.51. For facilities where vessels and/or pipes containing water are present, the criticality analysis should take into account the presence of the maximum amount of water that could be contained within the room under consideration, as well as the maximum amount of water in any connected rooms. Such rooms or premises should be clearly identified to workers.

4.52. Walls (and floors if necessary) of rooms where flooding could occur should be capable of withstanding the water load, and safety related equipment should not be affected by flooding.

Leaks and spills

4.53. The amount of liquid present in a MOX fuel fabrication facility is limited. Water is used for cooling sintering furnaces. Possible steam explosions resulting from water entry due to a potential leak in the cooling system should have an acceptably low likelihood.

4.54. Spillages may occur outside gloveboxes from cans, drums and waste packages during transit within the MOX fuel fabrication facility and/or in storage. Appropriate mechanical protection and appropriate containment should be provided for movements of radioactive material.

Loss of support systems

4.55. To fulfil the requirement established in para. 6.28 of Ref. [1], electric power supplies to MOX fuel fabrication facilities should be of high integrity. In the event of loss of normal power (see Section 2) and depending on the status of the facility, an emergency power supply should be provided to certain structures, systems and components important to safety, including the following:

(a) Ventilation fans and glovebox monitoring systems for the confinement of radioactive material;
(b) Heat removal systems;
(c) Emergency control systems;
(d) Fire detection and alarm systems;
(e) Monitoring systems for radiation protection;
(f) Alarm systems for criticality accidents.

4.56. The loss of general supplies such as gas for instrumentation and control, cooling water for process equipment and ventilation systems, heating water, breathing air and compressed air may also have consequences for safety. In the design of a MOX fuel fabrication facility, suitable measures to ensure safety should be provided. For example:

(a) Loss of gas supply to gas actuated safety valves and dampers. In accordance with the safety analysis, valves should be used that are designed to fail to a safe position.
(b) Loss of cooling or heating water. Adequate backup capacity or a redundant supply should be provided for in the design.
(c) Loss of breathing air. Adequate backup capacity or a redundant supply should be provided to allow work in areas with airborne radioactive material to continue to be carried out.

Loss or excess of process media

4.57. Either the loss of process media such as process gas supplies (e.g. hydrogen, helium, nitrogen or argon) and additives, or any excess of these media may have consequences for safety. Some examples are the following:

(a) Excess of additives in the powder preparation process should be considered in the criticality analysis.
(b) Overpressure in the gloveboxes (containing, for example, nitrogen, argon or helium) may cause an increase in the levels of airborne contamination and/or the concentration of hazardous material in the work areas of the facility.
(c) Releases of large amounts of nitrogen, argon or helium may result in a reduction in the oxygen concentration in breathing air in the work areas of the facility.

(d) For reasons of fire protection, inert gas may be used for the atmosphere in some gloveboxes. Failure of the gas supply, therefore, would remove one protective barrier. Consideration should be given to the integrity of gas supply by providing a suitable backup supply or by ensuring diversity of supply.

Loss of means of removal of decay heat

4.58. MOX materials generate heat, and storage rooms, storage gloveboxes and larger production units in MOX fuel fabrication facilities have potentially large heat loads. Overheating may challenge the safety functions.

4.59. Ventilation systems are designed to provide cooling and so to maintain temperatures below specified values. In a MOX fuel fabrication facility, in the event of a failure of the ventilation system, the time interval before damage occurs should be adequate for repairing the failure or for taking alternative actions.

Load drops

4.60. From para. II.22 of Appendix II of Ref. [1], “Handling systems [e.g. cranes] shall be designed to reduce the frequency of occurrence of load drops. The consequences of possible load drops shall be minimized” e.g. by qualification of the containers for the drop, and by the design of floors and the provision of safe travel paths.

4.61. Mechanical or human failures during the handling of radioactive material may result in a degradation of criticality control, confinement or shielding. Mechanical or human failures during the handling of loads of non-radioactive material may also result in a degradation of the safety functions of the MOX fuel fabrication facility.

Mechanical failure

4.62. From para. II.23 of Appendix II of Ref. [1], “Measures for the industrial safety of non-nuclear-designed equipment installed in gloveboxes (e.g. mechanical guards) shall be adapted to the nuclear environment.”

4.63. Mechanical failures during the processing of nuclear material could result in damage to equipment (e.g. by crushing, bending or breakage) which may result in a degradation of criticality control, confinement or shielding. For complex or important systems (e.g. rod handling systems designed to avoid the risk of breaking a rod), a systematic method of failure analysis should be implemented.

Radiolysis

4.64. The irradiation of organic or hydrogenated substances by plutonium, or the decomposition of molecules, may lead to the generation of gas, especially the release of hydrogen. The risk of radiolysis should be taken into account in the safety analysis for:

(a) Liquid effluents and organic solvents used in the laboratory;
(b) Contaminated oils and inflammable waste;
(c) Process scraps enclosing hydrogenated additives (which should be calcinated before being placed in a sealed container);
(d) Boxes containing PuO_2.

External initiating events

Earthquakes

4.65. A MOX fuel fabrication facility should be designed for the design basis earthquake to ensure that an earthquake motion at the site would not induce a loss of confinement of plutonium or a criticality accident (i.e. a seismically induced loss of criticality safety functions such as geometry and moderation) with significant consequences for site personnel or members of the public.

4.66. To define the design basis earthquake for the facility, the main characteristics of the disturbance (intensity, magnitude and focal distance) and the distinctive geological features of the local ground should be determined. The approach should ideally evaluate the seismological factors on the basis of historical data for the site. Where historical data are inadequate or yield large uncertainties, an attempt should be made to gather palaeoseismic data to facilitate determination of the most intense earthquake affecting the site to have occurred over the period of historical record. The different approaches can be combined since the regulatory body generally takes into account the results of scenarios based on historical data and those based on palaeoseismic data in the approval of the design.

4.67. One means of specifying the design basis earthquake is to consider the historically most intense earthquake, but increased in intensity and magnitude, for the purpose of obtaining the design response spectrum (i.e. the relationship between frequencies and ground accelerations) used in designing the facility. Another way of specifying the design basis earthquake is to perform a geological review, to determine the existence of capable faults and to estimate the ground motion that such faults might cause at the location of the facility.

4.68. An adequately conservative spectrum should be used for calculating the structural response to guarantee the stability of buildings and to ensure the integrity of the ultimate means of confinement in the event of an earthquake. Certain structures, systems and components important to safety will require seismic qualification. This will apply mainly to equipment used for storage and vessels that will contain significant amounts of fissile or toxic chemical materials. Design calculations for the buildings and equipment should be made to verify that, in the event of an earthquake, no unacceptable release of fissile material to the environment would occur and the risk of a criticality accident would be very low.

External fires and explosions

4.69. Hazards from external fires and explosions could arise from various sources in the vicinity of a MOX fuel fabrication facility, such as petrochemical installations, forests, pipelines and road, rail or sea routes used for the transport of flammable material such as gas or oil.

4.70. To demonstrate that the risks associated with such external hazards are below acceptable levels, the operating organization should first identify all potential sources of hazards and then estimate the associated event sequences affecting the facility. The radiological or associated chemical consequences of any damage should be evaluated and it should be verified that they are within acceptance criteria. Toxic hazards should be assessed to verify that specific gas concentrations meet the acceptance criteria. It should be ensured that external toxic hazards would not adversely affect the control of the facility. The operating organization should carry out a survey of potentially hazardous installations and transport operations for hazardous material in the vicinity of the facility. In the case of explosions, risks should be assessed for compliance with overpressure criteria. To evaluate the possible effects of flammable liquids, falling objects (such as chimneys) and missiles resulting from explosions, their possible distance from the facility and hence their potential for causing physical damage should be assessed.

Extreme weather conditions

4.71. Typically, the extreme weather conditions assumed in the design and and in evaluation of the response of a MOX fuel fabrication facility are wind loading, tornadoes, tsunamis, etc.

4.72. The general approach is to use a deterministic, design basis value for the extreme weather condition and to assess the effects of such an event on the safety of the facility. The rules for obtaining the design basis values for use in the assessment may be specified by local regulations.

4.73. The design provisions will vary according to the type of hazard and its effects on the safety of the facility. For example, extreme wind loading is associated with rapid structural loading and thus design provisions for an event involving extreme wind loading should be the same as those for other events with potentially rapid structural loading, such as earthquakes. However, effects of extreme precipitation or extreme temperatures would take time to develop and hence there would be time for operational actions to be taken to limit the consequences of such events.

4.74. A MOX fuel fabrication facility should be protected against extreme weather conditions by means of appropriate design provisions. These should generally include:

- — The ability of structures important to safety to withstand extreme weather loads;
- — Prevention of flooding of the facility;
- — The safe shutdown of the facility in accordance with the operational limits and conditions.

Tornadoes

4.75. Measures for the protection of the facility against tornadoes will depend on the meteorological conditions for the area in which the facility is located. The design of buildings and ventilation systems should be in compliance with specific regulations relating to hazards from tornadoes.

4.76. High winds are capable of lifting and propelling objects as large as automobiles or telephone poles. The possibility of impacts of missiles such as these should be taken into consideration in the design stage for the facility, as regards both the initial impact and the effects of secondary fragments arising from collisions with and spallation of concrete walls or from other types of transfer of momentum.

Extreme temperatures

4.77. The potential duration of extreme low or high temperatures should be taken into account in the design of support system equipment to prevent unacceptable effects such as the freezing of cooling circuits or adverse effects on venting and cooling systems.

4.78. If safety limits for humidity and/or the temperature are specified in a building or a compartment, the air conditioning system should be designed to perform efficiently also under extreme hot or wet weather conditions.

Snowfall

4.79. The occurrence of snowfall and its effects should be taken into account in the design and safety analysis. Snow is generally taken into account as an additional load on the roofs of buildings. The neutron reflecting effect or the interspersed moderation effect of the snow should be considered if relevant.

Floods

4.80. Flooding should be taken into account in the design of a facility. Two approaches to dealing with flooding hazards have been put forward:

- — In some States the highest flood levels recorded over the period of historical record are taken into account and nuclear facilities are sited at specific locations above the flood level or at a sufficient elevation to avoid major damage from flooding.
- — In other States, in which the use of dams is widespread and where a dam has been built upstream of a potential or existing site for a nuclear facility, the hazard posed by a breach of the dam is taken into account. The buildings of the facility are designed to withstand the water wave arising from the breach of the dam. In such cases the equipment — especially that used for the storage of fissile material — should be designed to prevent any criticality accident.

Accidental aircraft crashes

4.81. The likelihood and possible consequences of impacts onto the facility should be calculated by assessing the number of aircraft that come close to the facility and their flight paths, and by evaluating the areas vulnerable to impacts, i.e. areas where hazardous material is processed or stored. If the risk is acceptably low no further evaluations are necessary. See also para. 5.5 (item (h)) of Ref. [1].

4.82. For evaluating the consequences of impacts or the adequacy of the design to resist aircraft impacts, only realistic crash scenarios should be considered, which may require the knowledge of such factors as the possible angle of impact or the potential for fire and explosion due to the aviation fuel load. In general, fire cannot be ruled out following an aircraft crash, and so the establishment of specific requirements for fire protection and for emergency preparedness and response will be necessary.

INSTRUMENTATION AND CONTROL (I&C)

Instrumentation

4.83. Instrumentation should be provided to monitor the variables and systems of the facility over their respective ranges for: (1) normal operation; (2) anticipated operational occurrences; and (3) design basis accidents, to ensure that adequate information can be obtained on the status of the facility and proper actions can be undertaken in accordance with operating procedures or in support of automatic systems.

4.84. Instrumentation should be provided for measuring all the main variables whose variation may affect the processes, for monitoring for safety purposes general conditions at the facility (such as radiation doses due to internal and external exposure., releases of effluents and ventilation conditions), and for obtaining any other information about the facility necessary for its reliable and safe operation. Provision should be made for the automatic measurement and recording of values of parameters that are important to safety.

Control systems

4.85. Passive and active engineering controls are more reliable than administrative controls and should be preferred for control in operational states and in accident conditions. Automatic systems should be designed to maintain process parameters within the operational limits and conditions or to bring the process to a safe state, which is generally the shutdown state.

4.86. Appropriate information should be made available to the operator for monitoring the effects of automatic actions. The layout of instrumentation and the manner of presentation of information should provide the operating personnel with an adequate impression of the status and performance of the facility. Devices should be installed that provide in an efficient manner visual and, as appropriate, audible indications of operational states that have deviated from normal conditions and that could affect safety.

Control rooms

4.87. Control rooms should be provided to centralize the main data displays, controls and alarms for general conditions at the facility. Occupational exposure should be minimized by locating the control rooms in parts of the facility where the levels of radiation are low. For specific processes, it may be useful to have dedicated control rooms to allow the remote monitoring of operations, thereby reducing exposures and risks to operators. Particular consideration should be paid to identifying those events, both internal and external to the control rooms that may pose a direct threat to the operators and to the operation of control rooms. Ergonomic factors should be taken into account in the design of control rooms.

Safety related I&C systems for normal operation

4.88. The safety related I&C systems for normal operation should include systems for:

(1) Criticality control.
    - Depending on the method of criticality control, the control parameters relating to para. II.24 of Appendix II of Ref. [1] should include mass, density, moisture content, isotopic content, fissile content, moderation and reflection of additives, and spacing between items.

(2) Process control.
    - A key safety related control system is the means of confirming the correct concentration of hydrogen in the gas supply to the sintering furnaces.

(3) Glovebox control.
   - The requirements for glovebox control are established in para. II.25 of Appendix II of Ref. [1]. For gloveboxes containing inert gas, the gas concentration should be monitored for safety and, if necessary, to verify product quality. Temperature levels should also be monitored.

(4) Control of ventilation.
   - Monitoring and control of ventilation is needed to ensure that the airflows in all areas of the MOX fuel fabrication facility are flowing in the correct direction, i.e. towards areas that are more contaminated. In working areas, the temperature and humidity levels and the level of pollutants should be controlled to ensure the comfort of workers and good levels of hygiene. In some cases, local ventilation should be used, e.g. in rooms housing backup batteries.
   - Monitoring and control of ventilation should be applied in particular in areas where sintering furnaces and pellet grinding equipment are located.

(5) Control of occupational radiation exposure.
   - External exposure. Sensitive dosimeters with real-time displays and/or alarms should be used to monitor occupational radiation doses, in particular in areas in which inspection equipment such as X ray equipment and radioactive sources are located. Portable equipment and installed equipment should be used to monitor whole body exposures and exposures of the hands to gamma radiation and neutron emissions.
   - Internal exposure. The requirements for monitoring of internal doses are established in para. II.26 of Appendix II of Ref. [1]. Owing to the specific hazards of airborne plutonium, the following provisions should be considered:
     - Continuous air monitors to detect plutonium should be installed as close as possible to the working areas to ensure the early detection of any dispersion of plutonium.
     - Devices for detecting alpha surface contamination should be installed close to the working areas and also close at least to the exits of rooms in which working areas are located.

(6) Control of liquid discharges.
   - MOX fuel fabrication facilities have low volumes of liquid discharges that can usually be monitored for control purposes by sampling and analysis and by measuring the volumes of discharges. Special arrangements should be made for effluents from laboratories, which can differ from site to site.

(7) Control of gaseous effluents.
  — From para. II.27. of Appendix II of Ref. [1], “Real time measurements shall be made to confirm that filtration systems are working effectively. Discharges shall be measured continuously.”

Safety related I&C systems for anticipated operational occurrences

4.89. In addition to the listing provided in para. 4.88, safety related I&C systems for use in anticipated operational occurrences should include the following provisions:

— Fire detection and extinguishing systems and building evacuation systems;
— Systems for the detection of surface contamination and airborne radioactive material and alarm systems;
— Gas detectors and alarm systems in areas where a leakage of gases such as hydrogen could produce an explosive atmosphere.

Safety related I&C systems for design basis accident conditions

4.90. In addition to the previous listings, the safety related I&C systems for design basis accident conditions should include:

— Criticality detection systems, alarm systems and building evacuation systems;
— Detection and alarm systems for abnormal releases of effluents.

HUMAN FACTOR CONSIDERATIONS

4.91. The requirements relating to consideration of human factors are established in paras 6.15 and 6.16 of Ref. [1].

4.92. Human factors in operation, inspection, periodic testing, and maintenance should be considered at the design stage. Human factors to be considered include:

— Possible effects on safety of unauthorized human actions (with account taken of ease of intervention by the operator and tolerance of human error);
— The potential for occupational exposure.

4.93. Design of the facility to take account of human factors is a specialist area. Experts and experienced operators should be involved from the earliest stages of design. Areas that should be considered include:

(a) Design of working conditions to ergonomic principles:
  - The operator–process interface, e.g. electronic control panels displaying all the necessary information and no more;
  - The working environment, e.g. good accessibility to, and adequate space around, equipment and suitable finishes to surfaces for ease of cleaning;

(b) Choice of location and clear labelling of equipment so as to facilitate maintenance, testing, cleaning and replacement;
(c) Provision of fail-safe equipment and automatic control systems for accident sequences for which reliable and rapid protection is required;
(d) Good task design and job organization, particularly during maintenance work, when automated control systems may be disabled;
(e) Minimization of the need to use additional means of personal radiation protection.

4.94. In the design and operation of gloveboxes, the following specific considerations should be taken into account:

(a) In the design of equipment inside gloveboxes, account should be taken of the potential for conventional industrial hazards that may result in injuries to workers, including internal radiation exposure through cuts in the gloves and/or wounds on the operator's skin, and/or the possible failure of confinement;
(b) Ease of physical access to gloveboxes and adequate space and good visibility in the areas in which gloveboxes are located;
(c) The potential for damage to gloves;
(d) Training of operators on procedures to be followed for normal and abnormal conditions.

SAFETY ANALYSIS

4.95. Safety analysis for MOX fuel fabrication facilities should be performed in two major steps:

- The assessment of occupational exposure and public exposure for operational states of the facility and comparison with authorized limits for operational states;

— Determination of the radiological and associated chemical consequences of design basis accidents (or the equivalent) for the public and verification that they are within the acceptable limits specified for accident conditions.

4.96. The results of these two steps should be reviewed for identification of the possible need for additional operational limits and conditions.

Safety analysis for operational states

Occupational radiation exposure and exposure of the public

4.97. At the design stage of a new MOX fuel fabrication facility, an assessment should be made of the external exposure of workers in all workplaces, on the basis of conservative assumptions for factors including the following:

(a) Calculations of the envelope source term on the basis of: (i) reference isotopic compositions of plutonium and traces of associated transuranic elements and fission products; and (ii) the specific activities of these radioactive materials.
(b) The licensed inventories of radioactive material present in each item of equipment, and in each glovebox and storage area.
(c) Calculations of the efficiency of shielding during normal operation on the basis of conservative assumptions regarding the performance of shielding.
(d) The maximum cumulative annual working time at each workplace for operation and anticipated maintenance work.

4.98. A best estimate approach with the use of margins may also be used in the safety analysis.

4.99. The design of equipment, the layout of equipment in, for example, gloveboxes, and the placement of shielding should be determined on the basis of adequate interaction and feedback between process and mechanical designs, safety assessment, and operational experience from similar facilities and/or facilities upstream in the process (spent fuel reprocessing or plutonium polishing facilities). Cleaning operations (e.g. elimination of heavy dust from gloveboxes) should be given special consideration in the design.

4.100. As soon as plutonium is introduced into the MOX fuel fabrication facility, the calculated doses should be compared with actual doses rates. If considered necessary, maximum permissible annual working times for specific workplaces may be included in the operational limits and conditions.

4.101. Calculations of estimated public doses should be made on the basis of maximum estimated releases of radioactive material to the air and to water and maximum depositions to the ground. Conservative models and parameters should be used to calculate the estimated doses to the public.

Releases of hazardous chemical material

4.102. This Safety Guide deals only with those chemical hazards that can give rise to radiological hazards (see para. 2.2 of Ref. [1]). Facility specific, realistic, robust (i.e. conservative), estimations of chemical hazards to workers and releases of hazardous chemicals to the environment should be performed, in accordance with the standards applied in the chemical industry.

Safety analysis for accident conditions

Methods and assumptions for safety analysis for accident conditions

4.103. There is no general agreement on the best approach to the safety analysis for design basis accidents, and the associated acceptance criteria, for MOX fuel fabrication facilities. However, there is a tendency for the following or similar criteria to be adopted for new advanced facility designs.

4.104. For a MOX fuel fabrication facility, the consequences of design basis accidents would be limited to consequences for individuals on the site and close to the location of the accident. The consequences depend on various factors such as the amount and rate of the release of radioactive material or hazardous chemicals, the distance between the individuals exposed or affected and the source of the release, pathways for the transport of material to the individuals and the exposure times.

4.105. To estimate the on-site and off-site consequences of an accident, the wide range of physical processes that could lead to a release of radioactive material to the environment should be modelled in the accident analysis and the enveloping cases encompassing the worst consequences should be determined.

4.106. The following approaches should be considered in the assessment:

(1) An approach using the enveloping case (the worst case approach), with account taken only of those safety features that mitigate the consequences of accidents and/or that reduce their likelihood. If necessary, a more realistic case can be considered that includes the use of some safety features

and some non-safety-related features beyond their originally intended range of functions to reduce the consequences of accidents (the best estimate approach).

(2) An approach using the enveloping case (the worst case approach), with no account taken of any safety feature that may reduce the consequences or the likelihood of accidents. This assessment is followed by an assessment of the possible accident sequences, with account taken of the emergency procedures and the means planned for mitigating the consequences of the accident.

Assessment of possible radiological or associated chemical consequences

4.107. Safety assessments should address the consequences associated with possible accidents. The main steps in the development and analysis of accident scenarios should include:

(a) Analysis of the actual site conditions and conditions expected in the future.
(b) Identification of workers and members of the public who could possibly be affected by accidents; i.e. a ‘critical group’ of people living in the vicinity of the facility.
(c) Specification of the accident configurations, with the corresponding operating procedures and administrative controls for operations.
(d) Identification and analysis of conditions at the facility, including internal and external initiating events that could lead to a release of material or of energy with the potential for adverse effects, the time frame for emissions and the exposure time, in accordance with reasonable scenarios.
(e) Specification of the structures, systems and components important to safety that are credited to reduce the likelihood and/or to mitigate the consequences of accidents. These structures, systems and components that are credited in the safety assessment should be qualified to perform their functions in the accident conditions.
(f) Characterization of the source term (material, mass, release rate, temperature, etc.).
(g) Identification and analysis of intra-facility transport pathways for material that is released.
(h) Identification and analysis of pathways by which material that is released could be dispersed in the environment.
(i) Quantification of the consequences for the individuals identified in the safety assessment.

4.108. Analysis of the actual conditions at the site and the conditions expected in the future involves a review of the meteorological, geological and hydrological conditions at the site that may influence facility operations or may play a part in transporting material or transferring energy that is released from the facility (see Section 5 of Ref. [1]).

4.109. Environmental transport of material should be calculated with qualified codes or using data derived from qualified codes, with account taken of the meteorological and hydrological conditions at the site that would result in the highest exposure of the public.

4.110. The identification of workers and members of the public (the critical group of maximally exposed off-site individuals) who may potentially be affected by an accident involves a review of descriptions of the facility and of demographic information.

Emergency preparedness

4.111. The operating organization of a MOX fuel fabrication facility is required to develop an emergency plan that takes into account the potential hazards at the facility (para. 9.62 of Ref. [1]). The emergency plan and the necessary equipment and provisions should be determined on the basis of selected scenarios for beyond design basis accidents (or the equivalent). The conditions under which an off-site emergency is required to be declared for a MOX fuel fabrication facility should include criticality accidents, widespread fires in the powder area explosions and earthquakes.

MANAGEMENT OF RADIOACTIVE WASTE

4.112. For economic and environmental reasons, the aim of radioactive waste management is to minimize the generation of waste [7, 8]. The main type of waste encountered in MOX fuel fabrication facilities is material contaminated with plutonium (from PuO_2 or MOX). The following aspects should be considered in the design:

(a) Generation of waste.
Paragraph II.29 of Appendix II of Ref. [1] establishes the requirement on the generation of radioactive waste for MOX fuel fabrication facilities. The waste generated in a MOX fuel fabrication facility is mainly solid waste (see para. 1.8). A record keeping system should be implemented to ensure

the proper identification, traceability and record keeping for the radioactive waste generated.

It is possible to reduce waste from gloveboxes by reducing the amount of material imported into the glovebox.

(b) Removal of waste.

From para. II.30 of Appendix II of Ref. [1]: “Filters from the gloveboxes and the ventilation system shall have engineered features” (e.g. containers).

(c) Collection of waste.

Design features for the collection and transport of waste should be such as to reduce the risk of dropping bags of waste.

For the assessment and management of waste contaminated with plutonium, provision should be made for a central waste management area. In this central area, waste should be monitored for its plutonium content and may be treated and placed in containers for interim storage.

(d) Interim storage of waste.

Subsequent treatment outside the MOX fuel fabrication facility may include conditioning, compaction and washing of the waste before its longer term storage.

MANAGEMENT OF GASEOUS AND LIQUID RELEASES

4.113. MOX fuel fabrication facilities use dry processes and generate dust, and the effluent discharges from MOX fuel fabrication facilities should be reduced by filtration, which normally consists of a number of high efficiency particulate air (HEPA) filters in series. The use of sand filters may also be considered [9].

OTHER DESIGN CONSIDERATIONS

Customer specifications on fuel characteristics

4.114. Customer specifications on fuel characteristics that have implications for safety in the design and operation of MOX fuel fabrication facilities (e.g. criticality, shielding, thermal effects) should be taken into account at an early stage in the design of the facility and equipment, especially the specifications for the plutonium content as input and the specifications for MOX fuel assemblies as output.

Gloveboxes

4.115. Gloveboxes should be designed to facilitate the use of dry methods of cleaning (e.g. with vacuum cleaners).

Radiation protection shielding

4.116. PuO_2 and MOX can generate significant dose rates depending on the isotopic composition of the material processed. MOX from higher burnup PuO_2 may give rise to significant neutron dose rates while the presence of ^{241}Am (a decay product of ^{241}Pu) may give rise to gamma radiation. UO_2 from reprocessing may also contain residual fission products and ^{232}U that give rise to beta and gamma radiation.

4.117. As there may be significant dose rates in areas of the MOX fuel fabrication facility occupied by workers, consideration should be given at the design stage to the need for neutron and gamma shielding.

4.118. Effective shielding from 60 keV gamma radiation from ^{241}Am and from neutron emissions may be applied to the faces of gloveboxes, but this can restrict visibility and thus lead to increased occupancy periods of workers by the glovebox. The type of shielding should therefore be selected on the basis of the estimated total doses due to occupational exposure during normal operation and maintenance.

Intermediate storage of MOX and PuO_2

4.119. PuO_2 may be stored in MOX fuel fabrication facilities pending its processing. MOX may be stored at intermediate stages in the process as powder, pellets, rods and assemblies. The storage capacity is determined by process buffer quantities.

Maintenance policy

4.120. The maintenance policy should cover the following aspects:

(a) Consideration of whether maintenance should be carried out by remote operation or manually by using gloves. This may vary for different stages in the process.
(b) Criticality safety conditions such as limitations on the introduction of liquids, solvents, plastics and other moderators.

(c) Prevention of contamination when replacing equipment (e.g. motors and drives may be located outside gloveboxes).
(d) Limitation and removal of dust. Gloveboxes may become dusty unless cleaned regularly. A dusty environment may reduce visibility and may increase the whole body exposure and the occupational hand exposure (when hands are placed in dusty gloves).
(e) Loss of shielding material. Shielding on gloveboxes is often provided for normal process operations and may need to be removed for access for maintenance. Ideally, it should be possible to remove the source before removing the shielding.
(f) The design should minimize sharp edges and the need for sharp equipment in gloveboxes to minimize the potential for causing wounds that could become contaminated.

Decontamination and decommissioning

4.121. To facilitate decontamination and the eventual decommissioning of the facility, surface areas of the MOX fuel fabrication facility where there may be contamination should be non-porous and easy to clean. This may be achieved by applying special coatings to surfaces and ensuring that no areas are difficult to access. In addition, all surfaces that could become contaminated should be made readily accessible to allow for periodic and incidental decontamination.

5. CONSTRUCTION

5.1. MOX fuel fabrication facilities are complex, and regulatory body authorization should be sought in several stages. Each stage may conclude with a hold point at which approval by the regulatory body is required before the subsequent stage may be commenced (para. 3.7 of Ref. [1]).

5.2. MOX fuel fabrication facilities are complex mechanically and, as such, modularized components should be used in their construction. This enables equipment to be tested and proved at manufacturers' shops before its installation at the MOX fuel fabrication facility. In addition this will also aid in the commissioning, maintenance and decommissioning of the facility. Components and cables in a MOX fuel fabrication facility should be clearly labelled, owing to the complexity of the control systems.

5.3. The construction and commissioning phases may overlap. Construction work in an environment in which radioactive material is present owing to commissioning may be significantly more difficult and time consuming than when no radioactive material is present.

6. COMMISSIONING

6.1. For a MOX fuel fabrication facility, the commissioning should be divided into three main phases:

(1) Inactive or 'cold processing' commissioning.
In this phase, the facility's systems are systematically tested, both individual items of equipment and the systems in their entirety. As much verification and testing as possible should be carried out because of the relative ease of taking corrective actions in this phase. In this phase, operators should take the opportunity to prepare the set of operational documents and to learn the details of the systems.

(2) Uranium commissioning.
Natural or depleted uranium should be used in this phase, to avoid criticality risks, to minimize doses due to occupational exposure and to limit possible needs for decontamination. This phase also provides the opportunity to initiate the control regimes that will be necessary when plutonium is introduced.
Safety tests performed during this commissioning period should mainly be devoted to confinement checking. This should include: (i) checking for airborne radioactive material; (ii) smear checks on surfaces; and (iii) checking for gaseous discharges and liquid releases. Unexpected accumulations of material should also be checked for.

(3) Plutonium or 'hot processing' commissioning.
This phase enables the process to be progressively, and cautiously, brought into full operation. The requirements for this phase are established in para. II.37 of Appendix II of Ref. [1].

6.2. The verification process, defined in para. 8.4 of Ref. [1], should be completed prior to the operation stage. The operating organization should use the commissioning stage to become familiar with the facility. The facility management should use the commissioning stage to develop a strong safety culture and good behavioural attitudes throughout the entire organization.

6.3. During commissioning and later during operation of the facility, the estimated doses to workers that were calculated should be assessed against actual dose rates. If, in operation, the actual doses are higher than the calculated doses, corrective actions should be implemented, including making any necessary changes to the licensing documentation (i.e. the safety case) or adding or changing safety features or work practices (see also Section 7).

6.4. The licence to operate the MOX fuel fabrication facility is generally issued to the operating organization just before this third phase. In this case, 'hot' processing commissioning will be performed under the responsibility, safety procedures and organization of the operating organization. It may be considered part of the operational stage of the MOX fuel fabrication facility.

6.5. Lessons learned from similar plutonium processing facilities that are in operation should be used, especially for the commissioning of a new MOX fuel fabrication facility.

7. OPERATION

CHARACTERISTICS OF MOX FUEL FABRICATION FACILITIES

7.1. The distinctive features of a MOX fuel fabrication facility that should be taken into account in meeting the safety requirements established in Ref. [1] are:

— The large inventories of plutonium and MOX powder in a finely divided and dispersible form, and the associated radiological hazards, including criticality;
— The high radiological toxicity of the radioactive plutonium and MOX.

7.2. In a MOX fuel fabrication facility, automation serves to improve productivity and to reduce occupational exposures due to plutonium and MOX.

7.3. In this section, specific recommendations are presented on good practices and on additional considerations in meeting the safety requirements for a MOX fuel fabrication facility.

QUALIFICATION AND TRAINING OF PERSONNEL

7.4. The safety requirements relating to the qualification and training of facility personnel are established in paras 9.8–9.13 and II.38 of Appendix II of Ref. [1]. Recommendations are provided in paras 4.6–4.25 of Ref. [4]. In addition, personnel should be provided periodically with basic training in radiation safety. Much of the processing performed in a MOX fuel fabrication facility is done automatically, but some processes relating to glovebox operations involve manual intervention. For this reason, "special attention shall be paid to training workers in glovebox operations, including actions to be taken if contamination occurs" (para. II.38 of Appendix II of Ref. [1]).

GENERAL RECOMMENDATIONS FOR FACILITY OPERATION

7.5. To ensure that the MOX fuel fabrication facility operates well within the operational limits and conditions under normal circumstances, a set of lower level sublimits and conditions should be defined. Such sublimits and conditions should be clear and should be made available to and well understood by the personnel operating the facility.

7.6. Operating documents should be prepared that list all the limits and conditions under which the facility is operated. Annex III gives examples of parameters that can be used for defining the operational limits and conditions in the various processing areas of the facility.

7.7. Generic limits should also be set for the facility. Examples of such limits are:

(a) The allowed ranges of the isotopic composition of PuO_2 and the content of ^{241}Am;
(b) The maximum PuO_2 content allowed for the different steps in the process;
(c) The maximum specific heat loads;
(d) The specified limits for impurities and fission products in feedstock;
(e) The maximum allowed throughputs and inventories for the facility;

(f) The maximum quantities of additives allowed at different steps in the process;
(g) The maximum concentration of hydrogen allowed in the atmosphere of sintering furnaces.

7.8. Consideration should be given to ensuring that plutonium and uranium, especially in the form of powder or pellets, are present only in areas designed for the storage or handling of plutonium and uranium. Programmes should be put in place for routine monitoring for surface contamination and airborne radioactive material, and more generally for ensuring an adequate level of housekeeping.

7.9. In a MOX fuel fabrication facility, the safe operational state of the process attained after any anticipated operational occurrence is often the shutdown state. However, some systems, such as the ventilation system used for confinement, continue to operate. Nevertheless, specific operating procedures should be used for the shutdown of certain equipment such as sintering furnaces.

7.10. Operating procedures to control process operations directly should be developed. The procedures should include directions for attaining a safe facility state from all anticipated operational occurrences and accident conditions. Procedures of this type should include the actions required to ensure criticality safety, fire protection, emergency preparedness and environmental protection.

7.11. The operating procedures for the ventilation system should be specified for fire conditions, and periodic testing of the ventilation system should be carried out and fire drills should be performed.

MAINTENANCE, CALIBRATION AND PERIODIC TESTING AND INSPECTION

7.12. When carrying out maintenance in a MOX fuel fabrication facility, particular consideration should be given to the potential for surface contamination or airborne radioactive material. The facility should not intentionally be placed in an abnormal condition to perform periodic testing.

7.13. Maintenance should follow good practices, with particular consideration given to:

(a) Work control, e.g. handover and handing back of documents, means of communication and visits to job sites, changes to the planned scope of work, suspension of work and ensuring safe access;
(b) Equipment isolation, e.g. disconnection of electrical cabling and heat and pressure piping and venting and purging of equipment;
(c) Testing and monitoring, e.g. checks before commencing work, monitoring during maintenance and checks for recommissioning;
(d) Safety precautions for work, e.g. specification of safety precautions, ensuring the availability of personal protective equipment and ensuring its use, and emergency response procedures;
(e) Reinstallation of equipment, e.g. reassembly, reconnection of pipes and cables, testing, cleaning the job site and monitoring after recommissioning.

7.14. Regular flow checks should be carried out at ventilation hoods and entrances to containment areas. Also, pressure drops across banks of air filters should be checked and recorded on a routine basis. Particular attention should be paid to gloves to ensure the detection of any degradation of glove material.

7.15. Periodic testing of fire detection and extinguishing systems for gloveboxes should be carried out.

7.16. Compliance of the operational performance of the ventilation system with the fire protection requirements (see para. 4.44) should be verified on a regular basis.

7.17. A programme of periodic inspections of the facility should be established, whose purpose is to verify that the facility is operating in accordance with the operational limits and conditions. Suitably qualified and experienced persons should carry out inspections. Particular consideration should be given to fatigue affecting equipment and to the ageing of structures.

CONTROL OF MODIFICATIONS

7.18. A standard process for any modification should be applied in a MOX fuel fabrication facility. The process should use a modification control form or equivalent management tool. The modification control form should contain a description of what the modification is and why it is being made. The main purpose of the modification control form is to provide the basis for a safety assessment of the modification, especially any changes that may affect criticality safety. The modification control form should be used to identify all the aspects of safety that may be affected by the modification and to demonstrate that adequate and sufficient safety provisions are in place to control the potential hazards For example, changes to the materials and thickness of shielding, quantities of hydrogenated and non-hydrogenated materials, and locations of equipment may affect criticality safety analyses.

7.19. Modification control forms should be scrutinized by and be subject to approval by qualified and experienced persons to verify that the arguments used to demonstrate safety are suitably robust. This should be considered particularly important if the modification could have an effect on criticality safety. The depth of the safety arguments and the degree of scrutiny to which they are subjected should be commensurate with the safety significance of the modification.

7.20. The modification control form should also specify which documentation will need to be updated as a result of the modification. Procedures for the control of documentation should be put in place to ensure that documents are changed within a reasonable time period following the modification.

7.21. The modification control form should specify the functional checks that are required before the modified system may be declared fully operational again.

7.22. The modifications made to a facility should be reviewed on a regular basis to ensure that the combined effects of a number of modifications with minor safety significance do not have hitherto unforeseen effects on the overall safety of the facility.

RADIATION PROTECTION

7.23. In a MOX fuel fabrication facility, the main radiological hazard for both the workforce and members of the public is from the inhalation of airborne PuO_2 or MOX powder. PuO_2 and MOX powders pose a particular hazard because of their long biological half-lives (and therefore effective half-lives)[1], and their typically relatively small particle size (typically a few micrometres in diameter) when encountered in MOX fuel fabrication facilities. Thus “close attention shall be

[1] The biological half-life is the time taken for the amount of a material in a specified tissue, organ or region of the body to halve as a result of biological processes. The effective half-life is the time taken for the activity of a radionuclide in a specified place to halve as a result of all relevant processes.

paid to the containment of PuO_2 and mixed oxide (MOX) powders and the control of contamination in the workplace” (para. II.42 of Appendix II of Ref. [1]).

7.24. For MOX fuel fabrication facilities, in normal operation, the main characteristic that needs to be taken into account in the development of measures for radiation protection is that the external dose rate from beta and gamma radiation and neutron emission in the operational state is relatively low. It is required to put in place emergency arrangements for criticality incidents, which are the only events in which a high external dose rate would be encountered.

7.25. Interventions for maintenance and/or modifications are activities that require justification and optimization of protective actions as specified in Ref. [5]. The procedures for intervention should include:

(a) Estimation of doses due to external exposure prior to the intervention.
(b) Preparatory activities to minimize the doses due to occupational exposure, including.
    — Identifying specifically the risks associated with the intervention.
    — Specifying in the work permit the procedures for the intervention (such as for the individual and collective means of protection, e.g. use of masks, clothing and gloves, and time limitation).
(c) Measurement of the doses due to occupational exposure during the intervention.
(d) Implementation of feedback of information for identifying possible improvements.

Control of internal exposure

7.26. Internal exposure should be controlled by the following means:

(a) Performance targets should be set for all parameters relating to internal exposure, e.g. levels of contamination.
(b) Enclosures and ventilation systems should be routinely inspected, tested and maintained to ensure that they continue to fulfil their design requirements. Regular flow checks should be carried out at ventilation hoods and entrances to containment areas. Pressure drops across air filter banks should be checked and recorded regularly.
(c) Operators should be made aware of and specially trained in the immediate actions necessary in the event of the puncture of a glove and/or a breach of containment integrity.

(d) A high standard of housekeeping should be maintained at the facility. Cleaning techniques should be used that do not give rise to airborne radioactive material, e.g. the use of vacuum cleaners with HEPA filters.
(e) Regular contamination surveys of areas of the facility and equipment should be carried out to confirm the adequacy of cleaning programmes.
(f) Contamination zones should be delineated and clearly indicated.
(g) Continuous air monitoring should be carried out to alert facility operators if levels of airborne radioactive material exceed predetermined action levels.
(h) Mobile air samplers should be used at possible sources of contamination as necessary.
(i) An investigation should be carried out promptly in response to readings of high levels of airborne radioactive material.
(j) Personnel and equipment should be checked for contamination and should undergo decontamination if necessary prior to their leaving contamination zones. Entry to and exit from the work area should be controlled to prevent the spread of contamination. In particular, changing rooms and decontamination facilities should be provided.
(k) Temporary means of ventilation and means of confinement should be used when intrusive work increases the risk of causing contamination by airborne radioactive material (e.g. during periodic testing, inspection or maintenance).
(l) Personal protective equipment (e.g. respirators, gloves and clothes) should be made available and should be used when dealing with possible releases of radioactive material from its normal means of confinement in specific operational circumstances (e.g. bag-out/bag-in operations, certain maintenance operations or changing of gloves).
(m) Personal protective equipment should be maintained in good condition, cleaned as necessary, and should be periodically inspected.
(n) Any staff having wounds should protect them with an impervious covering for work in contamination zones.

7.27. In vivo monitoring and biological sampling should be available as necessary as a complementary measure for monitoring doses due to occupational exposures. Whole body counts should also be performed periodically to check for internal exposure.

7.28. The extent of monitoring should be commensurate with the levels of airborne radioactive material and the contamination levels of workplaces.

7.29. The method for assessing doses due to internal exposure should be based on the collection of data from air sampling in the workplace, in combination with worker occupancy data. This method should be assessed, and should be reviewed as appropriate by the regulatory body.

7.30. Estimates should be regularly made, by means of monitoring data on effluents, of doses due to internal exposure received by members of the public who live in the vicinity of the site.

7.31. In carrying out the activities for periodic testing, inspection and maintenance, precautions should be taken to limit, by the use of temporary enclosures and ventilation systems, the spread of radioactive material.

7.32. On completion of maintenance work, the area concerned should be decontaminated and air sampling and smear checks should be carried out to confirm that the area can be returned to normal use.

Control of external exposure

7.33. In all process areas of a MOX fuel fabrication facility, control of external exposure is required to ensure that doses are kept below authorized limits and are as low as reasonably achievable (ALARA). External exposure due to gamma radiation from americium (and residual fission products from UO_2 where appropriate) and neutron radiation from PuO_2 can be controlled by means of an appropriate combination of requirements on time, distance and shielding. Radioactive sources are used in a MOX fuel fabrication facility to scan rods and in the laboratory.

7.34. Although most of the processes in a MOX fuel fabrication facility are automated, there are some actions that require manual work in gloveboxes. Owing to the proximity of the hands of operators to PuO_2 when work in gloveboxes is being carried out, the hands are more susceptible to exposure than other parts of the body., The dose to the hands should therefore be monitored (by extremity dosimetry).

7.35. External exposure should be controlled by:

(a) Training of personnel in radiation hazards and the use of dose monitoring equipment;
(b) Removing PuO_2 from process areas in use for extended maintenance work;
(c) Ensuring that sources are changed by suitably qualified and experienced persons;
(d) Avoiding unnecessary stays in the vicinity of gloveboxes;

(e) Using individual and temporary shielding;
(f) Performing routine surveys of radiation dose rates.

CRITICALITY CONTROL

7.36. In a MOX fuel fabrication facility, it is particularly important that the procedures for controlling criticality hazards are strictly applied (paras 9.49 and 9.50 of Ref. [1]).

7.37. Operational aspects of the control of criticality hazards in MOX fuel fabrication facilities should include:

— Anticipation of unexpected changes in conditions that could increase the risk of a criticality accident; for example, unplanned accumulation of PuO_2 or MOX powder (e.g. in gloveboxes or ventilation ducts) or hydrogenated materials;
— Management of moderating materials, particularly hydrogenated materials such as those used for the decontamination of gloveboxes, and leakages of oils from gear boxes;
— Management of mass in transfers of plutonium and uranium (procedures, mass measurement, systems and records) for which mass control is used;
— Reliable methods for detecting the onset of any of the foregoing conditions;
— Periodic calibration or testing of systems for the control of criticality hazards (e.g. control of movements of material, balances, scales, etc.);
— Evacuation drills to prepare for the occurrence of a criticality and/or the actuation of an alarm.

7.38. The tools used for the purposes of accounting for and control of nuclear material, such as the instruments used to carry out measurements of mass, volume or isotopic compositions and software used for accounting purposes, may also have application in the area of criticality safety. However, if there is any uncertainty about the characteristics of fissile material, conservative values should be used for parameters such as the plutonium content and the isotopic composition. This arises in particular in connection with floor sweepings and similar waste material.

7.39. Criticality hazards may be encountered when carrying out maintenance work. For example, "if PuO_2 or mixed oxide (MOX) powder has to be removed from equipment, only approved containers shall be used" (para. II.41 of Appendix II of Ref. [1]). Also, waste and residues arising from decontamination and maintenance activities should be collected in containers with a favourable geometry approved for the work, and should be stored in dedicated criticality safe areas.

INDUSTRIAL AND CHEMICAL SAFETY

See also para. 7.4.

7.40. The industrial and chemical hazards found in MOX fuel fabrication facilities may be summarized as follows:

(a) Asphyxiation hazards due to the presence of argon or hydrogen or mixtures thereof, or of nitrogen or carbon dioxide;
(b) Explosion of hydrogen storage bottles outside the main MOX processing building;
(c) Fire;
(d) Gas storage bottles becoming missiles;
(e) Chemical hazards in the laboratory.

7.41. A mixture of argon and hydrogen is generally used in the sintering furnaces in MOX fuel fabrication facilities. Nitrogen may be used in gloveboxes to ensure the quality of the product. Carbon dioxide may be used in automatic fire suppression systems. A leakage of any of these gases may cause asphyxiation. Additionally, there is a potential for explosion at the location outside the main processing building where the mixing of hydrogen with argon is carried out.

7.42. Gas storage bottles are used to store various gases such as carbon dioxide, hydrogen, and mixtures of argon and hydrogen. Procedures should be developed and used to ensure the proper storage and handling of gas storage bottles to prevent them from becoming missiles.

7.43. Chemicals are used mostly in the laboratory for performing product analyses. Personnel should be made aware of the potential chemical hazards. Written procedures should be developed and used to control the quantity and handling of chemicals in the laboratory to prevent explosion, fire, high toxicity, undesirable chemical interactions, etc. Chemicals should be stored in well aerated premises or in racks outside the process and laboratory area.

7.44. A health surveillance programme should be set up, in accordance with national regulations, for routinely monitoring the health of workers who may be exposed to chemicals. Monitoring of the chemical effects of uranium and of the radiological effects of plutonium, as necessary, should be considered the core part of the health surveillance programme.

MANAGEMENT OF RADIOACTIVE WASTE AND EFFLUENTS

7.45. The requirements relating to the management of radioactive waste and effluents in operation are established in paras 9.54–9.57 of Ref. [1].

7.46. Gaseous radioactive discharges should be treated, where appropriate, by means of HEPA filters or equivalent (see para. 4.122). Performance standards should be set that specify performance levels at which filters or scrubber media are to be changed. After filter changes, tests should be carried out to ensure that new filters are correctly seated and yield a removal efficiency as used in the analyses.

7.47. Chemicals should be recovered and reused where possible.

7.48. One easy way to minimize the generation of solid radioactive waste is to remove as much outer packing as possible before material is transferred to controlled areas. Processes such as incineration, metal melting and compaction may also be used to reduce the volume of waste, but such processes are beyond the scope of this publication. As far as reasonably practicable, and in accordance with national regulations, waste material should be treated to allow its further use. Cleaning methods should be adopted at the facility that minimize the generation of waste.

7.49. Information on the management of waste and effluents can also be found in Refs [7, 8].

EMERGENCY PLANNING AND PREPAREDNESS

7.50. The requirements for emergency planning and preparedness specific to MOX fuel fabrication facilities are established in paras 9.62–9.67 and paras II.44 and II.45 of Appendix II of Ref. [1].

8. DECOMMISSIONING

8.1. Requirements for the safe decommissioning of a MOX fuel fabrication facility are established in Section 10 and para. II.46 of Appendix II of Ref. [1]. Recommendations on decommissioning of nuclear fuel cycle facilities, including MOX fuel fabrication facilities, are provided in Ref. [10].

8.2. The radiological hazard associated with the decommissioning of MOX fuel fabrication facilities is mostly due to potential exposure to alpha radiation, which can be controlled by means of appropriate clothing, containment and use of respirators. Since, during the lifetime of a MOX fuel fabrication facility, the processing of nuclear material is performed inside gloveboxes, there will normally be little contamination present in areas outside the gloveboxes.

8.3. In the operational stage, gloveboxes should be routinely cleaned, in accordance with the justification provided for the cleaning interventions (the balance of cost and benefit in respect of exposure and the generation of waste).

PREPARATORY STEPS

8.4. The preparatory steps for decommissioning a MOX fuel fabrication facility should begin with the decontamination of the first containment barriers (mainly gloveboxes):

(a) Post-operational cleanout to remove all bulk amounts of PuO_2 and MOX material in gloveboxes in order to reduce the residual inventory of plutonium. The plutonium inventory should be determined on the basis of accounting data for nuclear material.
(b) Identification of parts of buildings and items of equipment that are contaminated with plutonium and their levels of contamination.
(c) Decontamination of the facility to reach the levels required by the regulatory body for cleanup operations or the lowest reasonably achievable level of residual contamination.
(d) Preparation of risk assessments and method statements for the licensing of the decommissioning process.
(e) Preparations for the dismantling of process equipment, gloveboxes and ducts upstream of the HEPA filters (or equivalent):

— Selection and justification of the dismantling methods, with account taken of all the options for waste management (pretreatment, conditioning and disposal);
— Organization and planning of the dismantling interventions;
— Assessment of the risks associated with dismantling, including emergency planning.

DECOMMISSIONING PROCESS

8.5. In the decommissioning process, particular consideration should be given to preventing the spread of contamination by means of appropriate techniques such as:

— The systematic use of enclosures to recreate both static and dynamic containment;
— Proper bagging-out of materials from gloveboxes that are being dismantled.

8.6. In addition, particular consideration should be given to:

— The appropriate handling and packaging of waste as well as planning for the appropriate disposal of radioactive waste;
— The safe storage of contaminated material and radioactive waste that cannot be decontaminated or disposed of immediately.

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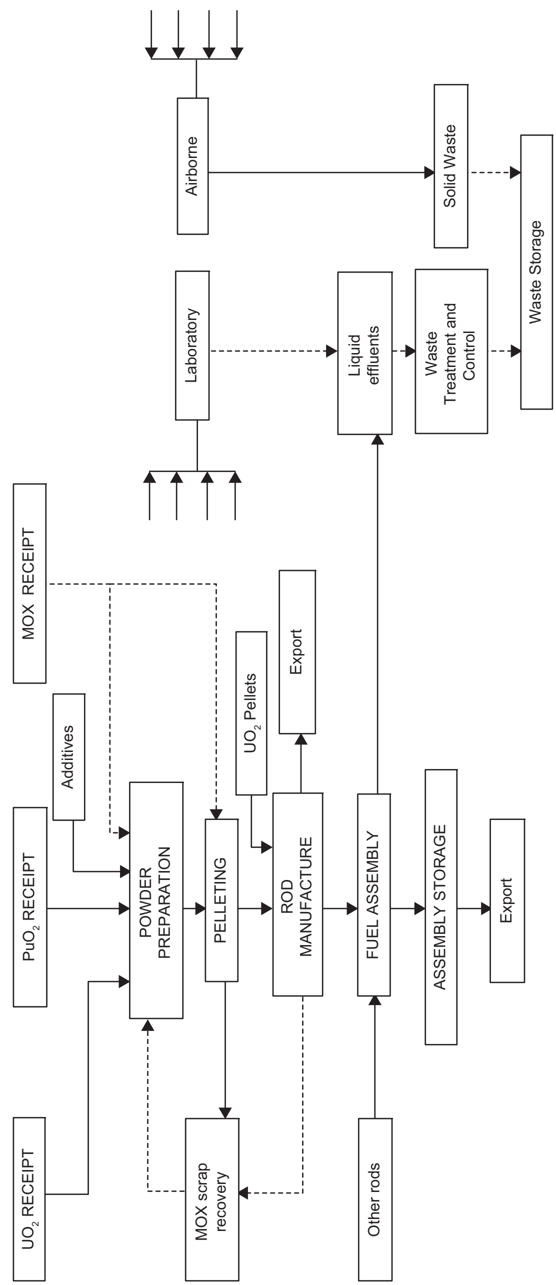
Annex I

TYPICAL PROCESS ROUTES IN A MOX FUEL FABRICATION FACILITY



Annex II

STRUCTURES, SYSTEMS AND COMPONENTS IMPORTANT TO SAFETY AND POSSIBLE CHALLENGES TO SAFETY FUNCTIONS FOR MOX FUEL FABRICATION FACILITIES

Safety function: (1) Criticality prevention;
(2) Confinement of radioactive material;
(3) Protection against external exposure.

Process area	Structures, systems and components important to safety	Events	Safety function initially challenged
Receipt of PuO_2 and MOX	Equipment for non-destructive analysis or destructive analysis of PuO_2 for isotopic characterization[a]	Degradation of criticality safety margin (material out of specification)	1
Receipt of UO_2	Equipment for non-destructive analysis or destructive analysis of UO_2 for isotopic and stoichiometric characterization[a]	Degradation of criticality safety margin (material out of specification) Fire (spontaneous ignition of UO_2 in air owing to stoichiometry being out of specification)	1, 2
Powder preparation	Equipment for powder metering (dosing) and weighing	Degradation of criticality safety margin (mass)	1
	Additive metering device	Degradation of criticality safety margin (moderation)	1
	Homogenizer mixer	Degradation of criticality safety margin (mass) Radiolysis due to hydrogenated additives	1 2

Process area	Structures, systems and components important to safety	Events	Safety function initially challenged
	Gloveboxes	Release of radioactive material (glovebox leak, glove rupture)	2
	Shielding	Increase in dose rate to hands and body	3
Pellet manufacture	Pellet press design (oil volume limit)	Degradation of criticality safety margin (moderation — oil leak) Fire (oil leak)	1, 2
	Sintering furnace design (gas mixture control, leaktightness, airlocks)	Release of radioactive material (explosion in sintering furnace)	2
	Gloveboxes	Release of radioactive material (glovebox leak, glove rupture)	2
	Shielding	Increase in dose rate to hands and body	3
	Grinding dust cleaning system	Increase in dose rate (if system fails and dust accumulates in glovebox)	3
Pellet storage	Pellet storage rack structure	Degradation of criticality safety margin (geometry)	1
	Ventilation and air cooling device	Degradation of neutron absorber (due to heating of reprocessed plutonium)	1
Fuel rod manufacture	Gloveboxes	Release of radioactive material (glovebox leak, glove rupture)	2
	Glovebox fire protection systems	Fire (zirconium particles)	2

Process area	Structures, systems and components important to safety	Events	Safety function initially challenged
	Shielding	Increase in dose rate to hands and body	3
Fuel rod inspection	Rod testing equipment for leaktightness	Release of radioactive material	2
	Shielding	Increase in dose rate to hands and body	3
	Rod X ray scanner	External exposure	3
	Rod transfer machines	Breakage	2
Fuel rod storage	Fuel rod structure	Degradation of criticality safety margin (geometry)	1
	Ventilation and air cooling devices	Degradation of neutron absorber (due to heating of plutonium)	1
Fuel rod assembly manufacture	Handling machines on assembly lines	Degradation of criticality safety margin (geometry, neutron absorber, moderation) Rod breakage (release of radioactive material) External hazard (time and/or proximity to rods)	1 2 3
	Fire protection systems	Fire (zirconium particles)	2, 3
	Cranes	Dropped assembly	1, 2
	Washing unit	Degradation of criticality safety margin (geometry, moderation, reflection)	1
Fuel assembly storage	Fuel assembly storage structure	Degradation of criticality safety margin (geometry)	1
	Ventilation and air cooling devices	Degradation of neutron absorber (due to heating of plutonium)	1
	Shielding	Increase in dose rate	3

Process area	Structures, systems and components important to safety	Events	Safety function initially challenged
MOX scrap recovery	Gloveboxes	Release of radioactive material	2
	Shielding	Increase in dose rate to hands and body	3
	Characterizing devices for plutonium content and moderation	Degradation of criticality safety margin (mass, moderation) Radiolysis due to hydrogenated additives	1 2
Laboratory	Gloveboxes Storage of samples Use of chemicals	Release of radioactive material Increase of dose rate Chemical reactions including fire Radiolysis	2 1 2 2
Waste handling	Measuring devices for plutonium content	Degradation of criticality safety margin (mass)	1
	Fire protection systems in the radioactive waste storage area	Fire	2
All process areas	Building structure, including wall penetrations and doors between fire areas and between confinement areas	Loss of integrity	2
	Ventilation systems and controls	Loss of dynamic confinement with release of radioactive material into the work place	2
	Filters inside the process areas	Fire Degradation of criticality safety margin (mass)	2 1

Process area	Structures, systems and components important to safety	Events	Safety function initially challenged
	Process gas in ventilation ducts	Degradation of criticality safety margin (mass — accumulation of material)	1
	Measurement devices for activity in waste air	Release of radioactive material	2
	Emergency power supply system	Release of radioactive material (loss of dynamic confinement — ventilation system shutdown) Loss of instrumentation and control	2 2
	Fire protection systems	Fire	2

[a] If the quality assurance by the supplier and the MOX fuel fabrication facility is considered adequate, the measurements carried out on PuO_2 or MOX before their transfer to the facility may be sufficient.

Annex III

EXAMPLES OF PARAMETERS FOR DEFINING OPERATIONAL LIMITS AND CONDITIONS FOR MOX FUEL FABRICATION FACILITIES

Safety function: (1) Criticality prevention;
(2) Confinement of radioactive material;
(3) Protection against external exposure.

Process area (including storage areas)	Safety function	Control parameter for operational limits and conditions
Area for receipt of PuO_2 and MOX	1	Isotopic composition (fissile isotopes and minimum value of ^{240}Pu)
	1	Limited moderation (moisture)
	1	PuO_2 content in MOX
	2	Specific heat of PuO_2
	2	Total amount of plutonium allowed on the site
	3	Isotopic composition, for neutron and gamma exposure (americium, etc.)
Area for receipt of UO_2	1	Enrichment in ^{235}U (if >1%, then criticality concern)
	1	Limited moderation
Intermediate storage of PuO_2 powder	1	Mass per container
Intermediate storage of UO_2 powder (only if ^{235}U >1%)	1	Total mass or mass per container
Powder preparation	1	Total mass of fissile material in each process unit to correspond with the criticality analysis
	1	Content of PuO_2 in each process unit to correspond with the criticality analysis
	1	Limited moderation (moisture, additives)

Process area (including storage areas)	Safety function	Control parameter for operational limits and conditions
	1	Operational controls to ensure homogeneity of MOX mixture before pellet manufacture
	3	Content of americium in the MOX
	2	Surface contamination of radioactive sources
Pellet manufacture	1	Total mass of fissile material in each process unit to correspond with the criticality analysis
	1	Limited moderation (moisture)
	1	Size of pellets is within the limits of the criticality analysis
	1	For pellets received from other facilities, enrichment of uranium in the uranium pellets is within the limits of the criticality analysis
	2	Composition of atmosphere in sintering furnace (gas mixture)
	2	Temperature of sintering furnace
	2	Surface contamination of radioactive sources
Fuel rod manufacturing and fuel rod inspection	1	Total mass of fissile material or number of rods in each process unit or manual rod transport container, to correspond with the criticality analysis
	1	Limited moderation (moisture)
	1	Fissile length of fuel pellets in rods and diameter of rods are within limits of criticality analysis
	1	For rods received from other facilities, isotopic content, PuO_2 content and enrichment of uranium in the uranium rods are within the limits of the criticality analysis
	2, 3	Surface contamination of rods
	2	Surface contamination of radioactive sources

Process area (including storage areas)	Safety function	Control parameter for operational limits and conditions
Fuel assembly manufacturing	1	Operational controls to ensure that the types of rods are correct and the rods are in the correct locations in the assembly
	1	Operational controls to ensure that all rods have been installed into the assembly
	2	Surface contamination of radioactive sources
MOX scrap recovery	1	Total mass of fissile material in each process unit to correspond with the criticality analysis
	2	Surface contamination of radioactive sources
Laboratory	1	Mass of plutonium
	2	Surface contamination of radioactive sources
Radioactive waste treatment	1	Mass of PuO_2 in containers and maximum number of containers in storage
	2	Surface contamination of radioactive sources
Ventilation system	2	Stages of pressure in the building
	2	Efficiency of last stage filters
	2	Minimum number of exhaust fans that are operational at any given time
	2, 3	Limits on radiation levels in flow going out to the environment
	2	Maximum pressure differential across filters
Gloveboxes	1	Total mass of fissile materials in each process unit (which can comprise one or more gloveboxes) to correspond with the criticality analysis
	2	Overpressure and underpressure values
	2	Detection limits or alarm level for detecting room contamination caused by glovebox leakage

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