

IAEA Safety Standards

for protecting people and the environment

Safety of Conversion Facilities and Uranium Enrichment Facilities

Specific Safety Guide

No. SSG-5



IAEA

International Atomic Energy Agency



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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.

The publications by means of which the IAEA establishes standards are issued in the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety and waste safety. The publication categories in the series are **Safety Fundamentals**, **Safety Requirements** and **Safety Guides**.

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SAFETY OF
CONVERSION FACILITIES AND
URANIUM ENRICHMENT FACILITIES

Safety standards survey

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

IAEA SAFETY STANDARDS SERIES No. SSG-5

SAFETY OF CONVERSION FACILITIES AND URANIUM ENRICHMENT FACILITIES

SPECIFIC SAFETY GUIDE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2010



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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
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FOREWORD

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

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

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

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

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

THE IAEA SAFETY STANDARDS

BACKGROUND

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

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

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

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

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

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

THE IAEA SAFETY STANDARDS

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

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

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

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

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

Safety Fundamentals

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

Safety Requirements

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

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

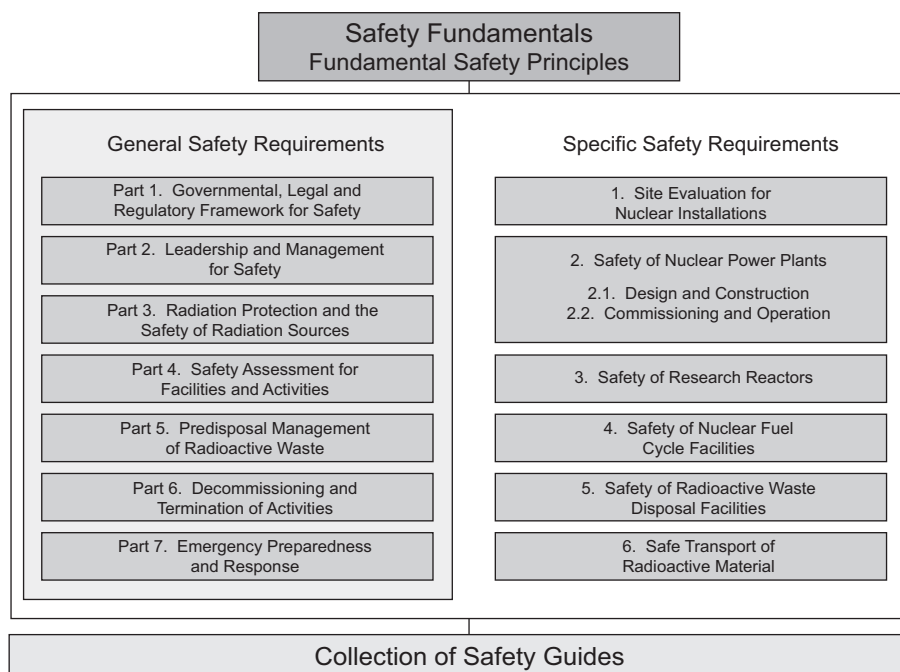


FIG. 1. The long term structure of the IAEA Safety Standards Series.

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

Safety Guides

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

APPLICATION OF THE IAEA SAFETY STANDARDS

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

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

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

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

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

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

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

DEVELOPMENT PROCESS FOR THE IAEA SAFETY STANDARDS

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

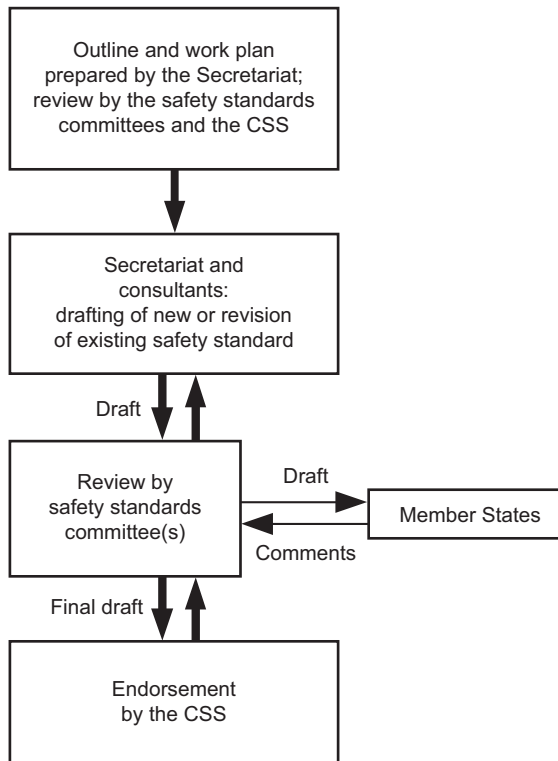


FIG. 2. The process for developing a new safety standard or revising an existing standard.

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

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

INTERACTION WITH OTHER INTERNATIONAL ORGANIZATIONS

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

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

INTERPRETATION OF THE TEXT

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

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

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

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

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1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide on the Safety of Conversion Facilities and Uranium Enrichment Facilities makes recommendations on how to meet the 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 conversion facilities and uranium enrichment facilities is ensured by means of their proper siting, design, construction, commissioning, operation including management, and decommissioning. This Safety Guide addresses all these stages in the lifetime of a conversion facility or an enrichment facility, with emphasis placed on design and operation.

1.3. Uranium and waste generated in conversion facilities and enrichment facilities are handled, processed, treated and stored throughout the entire facility. Conversion facilities and enrichment facilities may process or use large amounts of hazardous chemicals, which can be toxic, corrosive, combustible and/or explosive. The conversion process and the enrichment process rely to a large extent on operator intervention and administrative controls to ensure safety, in addition to active and passive engineered safety measures. A significant potential hazard associated with these facilities is a loss of the means of confinement resulting in a release of uranium hexafluoride (UF_6) and hazardous chemicals such as hydrofluoric acid (HF) and fluorine (F_2). In addition, for enrichment facilities and conversion facilities that process uranium with a ^{235}U concentration of more than 1%, criticality can also be a significant hazard.

OBJECTIVE

1.4. 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 conversion facility or a uranium enrichment 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 conversion facilities and enrichment facilities.

SCOPE

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

1.6. This Safety Guide deals specifically with the handling, processing and storage of depleted, natural and low enriched uranium (LEU) that has a ^{235}U concentration of no more than 6%, which could be derived from natural, high enriched, depleted or reprocessed uranium. In conversion facilities for the conversion of uranium concentrate to UF_6 , several different conversion processes are currently used throughout the world on a large industrial scale. At present enrichment facilities use either the gaseous diffusion process or the gas centrifuge process.

1.7. 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], is 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].

1.8. 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 (Ref. [5]). The recommendations in the present Safety Guide supplement the recommendations on occupational radiation protection provided in Ref. [6].

1.9. The typical process routes of conversion facilities and enrichment facilities are shown in schematic diagrams in Annexes I and II (see also Ref. [7]).

STRUCTURE

1.10. This Safety Guide consists of eight sections and four annexes. Section 2 provides the general safety recommendations for a conversion facility or an enrichment 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 conversion facility or enrichment 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 conversion facility or an enrichment facility. Annexes I and II show the typical process routes for a conversion facility and an enrichment facility. Annexes III and IV provide examples of structures, systems and components important to safety and operational limits and conditions grouped in accordance with process areas, for conversion facilities and enrichment facilities, respectively.

2. GENERAL SAFETY RECOMMENDATIONS

2.1. In conversion facilities and enrichment facilities, large amounts of uranium compounds are present in a dispersible form:

- In conversion facilities, uranium exists in diverse chemical and physical forms and is used in conjunction with flammable or chemically reactive substances as part of the process.
- In enrichment facilities, most of the uranium is in the chemical form UF_6 . The physical form of UF_6 could be the gaseous, liquid or solid state.

2.2. In conversion facilities and enrichment facilities, the main hazards are HF and UF_6 . In addition, where uranium is processed that has a ^{235}U concentration of more than 1%, criticality may be a significant hazard. Workers, the public and the

environment must be protected from these hazards during commissioning, operation and decommissioning.

2.3. Generally, in a conversion facility or an enrichment facility, only natural uranium or LEU that has a ^{235}U concentration of no more than 6% is processed. The radiotoxicity of this uranium is low, and any potential off-site radiological consequences following an accident would be expected to be limited. However, the radiological consequences of an accidental release of reprocessed uranium would be likely to be greater, and this should be taken into account in the safety assessment if the licence held by the facility permits the processing of reprocessed uranium.

2.4. The chemical toxicity of uranium in a soluble form such as UF_6 is more significant than its radiotoxicity. Along with UF_6 , large quantities of hazardous chemicals such as HF are present. Also, when UF_6 is released, it reacts with the moisture in the air to produce HF and soluble uranyl fluoride (UO_2F_2), which present additional safety hazards. Therefore, safety analyses for conversion facilities and enrichment facilities should also address the potential hazards resulting from these chemicals.

2.5. Conversion facilities and enrichment facilities do not pose a potential radiation hazard with the capacity to cause an accident with a significant off-site release of radioactive material (in amounts equivalent to a release to the atmosphere of ^{131}I with an activity of the order of thousands of terabecquerels). However, deviations in processes may develop rapidly into dangerous situations involving hazardous chemicals.

2.6. 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).

3. SITE EVALUATION

3.1. The site evaluation process for a conversion facility or an enrichment 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. These risks should be compensated for by means of adequate design provisions and constraints on processes and operations as well as possible economic arrangements.

3.2. The density of population in the vicinity of a conversion facility or an enrichment 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 hazardous chemicals.

3.3. A full record should be kept of the decisions taken on the selection of a site for a conversion facility or an enrichment facility and the reasons behind those decisions.

4. DESIGN

GENERAL

Safety functions for conversion facilities and enrichment facilities

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

- (1) Prevention of criticality;
- (2) Confinement for the prevention of releases that might lead to internal exposure and for the prevention of chemical releases;
- (3) Protection against external exposure.

4.2. For conversion facilities:

- The main hazard is the potential release of chemicals, especially HF and UF_6 . Controls to address this hazard will adequately protect also against internal radiation exposure.
- A criticality hazard exists only if the conversion facility processes uranium with a ^{235}U concentration greater than 1%.
- External exposure is a concern for the handling of residues containing thorium and its daughter products produced in fluorination reactors. External exposure is also a concern in the handling of recently emptied cylinders, especially those used as containers for reprocessed uranium, where there is a buildup of ^{232}U .

4.3. For enrichment facilities:

- The main hazard is a potential release of UF_6 ;
- A criticality hazard exists since the concentration of ^{235}U present in enrichment facilities is greater than 1%;
- External exposure is a concern in the handling of recently emptied cylinders, especially those used as containers for reprocessed uranium, with buildup of ^{232}U .

Specific engineering design requirements

4.4. The following requirements apply:

- (1) The requirements on prevention of criticality are established in paras 6.43–6.51 and III.3–III.7 of Appendix III of Ref. [1];
- (2) The requirements on confinement for the prevention of releases that might lead to internal exposure and chemical hazards are established in paras 6.37–6.39, 6.54–6.55 and paras III.8 and III.9 of Appendix III of Ref. [1];
- (3) The requirements on protection against external exposure are established in paras 6.40–6.42 of Ref. [1]. Shielding should be considered for processes or areas that could involve sources of high levels of external gamma radiation, such as reprocessed uranium or newly emptied cylinders (e.g. exposure to daughter products of ^{232}U and ^{238}U).

Design basis accidents and safety analysis

4.5. 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].

Conversion facilities

4.6. 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 conversion facilities:

- (a) A release of HF or ammonia (NH_3) due to the rupture of a storage tank;
- (b) A release of UF_6 due to the rupture of a storage tank, piping or a hot cylinder;
- (c) A large fire originating from H_2 or solvents;
- (d) An explosion of a reduction furnace (release of H_2);
- (e) Natural phenomena such as earthquakes, flooding or tornadoes¹;
- (f) An aircraft crash;
- (g) Nuclear criticality accidents, e.g. in a wet process area with a ^{235}U content of more than 1% (reprocessed uranium or unirradiated LEU).

4.7. The first four types of events ((a)–(d)) are of major safety significance as they might result in chemical and radiological consequences for on-site workers and may also result in some adverse off-site consequences for people or the environment. The last type of accident on the list would generally be expected to result in few or no off-site consequences unless the facility is very close to occupied areas.

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

4.9. The potential occurrence of a criticality accident should be considered for facilities that process uranium with a ^{235}U concentration of more than 1%. Particular consideration should be given to the potential occurrence of a

¹ For some facilities of older design, natural phenomena were not given consideration. These phenomena should be taken into account for the design of new conversion and enrichment facilities.

criticality accident for facilities treating various feed products including reprocessed uranium.

Enrichment facilities

4.10. 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 enrichment facilities:

- (a) The rupture of an overfilled cylinder during heating (input area);
- (b) The rupture of a cylinder containing liquid UF_6 or the rupture of piping containing liquid UF_6 (depending on the facility design for product take-off);
- (c) A large fire, especially for diffusion facilities;
- (d) Natural phenomena such as earthquakes, flooding or tornadoes (see footnote 1);
- (e) An aircraft crash;
- (f) A nuclear criticality accident.

4.11. These hazards would result primarily in radiological consequences for on-site workers, but might also result in some adverse off-site consequences for people or the environment. The last type of hazard on the list would generally be expected to result in few or no off-site consequences unless the facility is very close to populated areas.

4.12. The hazards listed in para. 4.10 may occur as a consequence of a PIE. Selected PIEs are listed in Annex I of Ref. [1].

Structures, systems and components important to safety

4.13. The likelihood of design basis accidents (or equivalent) should be minimized, and any radiological and associated chemical consequences should be controlled by means of structures, systems and components important to safety and appropriate administrative measures (operational limits and conditions). Annexes III and IV contain examples of structures, systems and components and representative events that may challenge the associated safety functions.

SAFETY FUNCTIONS

Prevention of criticality

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

- The mass and degree of enrichment of fissile material present in a process: for conversion facilities, in vessels or mobile transfer tanks, or analytical laboratories; for enrichment facilities, in effluent treatment units or analytical laboratories;
- Geometry and/or interaction (limitation of the dimensions or shape) of processing equipment, e.g. by means of safe diameters for storage vessels, control of slabs and appropriate distances in and between storage vessels;
- Concentration of fissile material in solutions, e.g. in the wet process for recovering uranium or decontamination;
- Presence of appropriate neutron absorbers, e.g. neutron poisoning of cooling water in gaseous diffusion enrichment facilities;
- Degree of moderation, e.g. by means of control of the ratio of hydrogen to ^{235}U in UF_6 cylinders and in diffusion cascades.

4.15. Paragraph III.4 of Appendix III of Ref. [1] requires that preference be given to achieving criticality safety by design rather than by means of administrative measures. As an example, to the extent practicable, vessels which could contain fissile material should be made geometrically safe.

4.16. Several methods can be used to perform the criticality analysis, such as the use of experimental data, reference books or consensus standards, hand calculations and calculations by means of deterministic or probabilistic computer codes. Calculations should be suitably verified and validated and performed under a quality management system.

4.17. The aim of the criticality analysis is to demonstrate that the design of equipment is such that the values of controlled parameters are always maintained in the subcritical range. This is generally achieved by determining the effective multiplication factor (k_{eff}), which depends on the mass, the distribution and the nuclear properties of uranium and all other materials with which it is associated.

The calculated value of k_{eff} is then compared with the value specified by the design limit.

4.18. 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 and of the physical possibility of worst case moderation conditions);
- The use of appropriate and qualified computer codes that are validated within their applicable range and of appropriate data libraries of nuclear reaction cross-sections.

4.19. The following are recommendations for conducting a criticality analysis for a conversion facility or an enrichment facility to meet the safety requirements established in para. III.6 of Appendix III of Ref. [1]:

- *Mass*. The mass margin should be 100% of the maximum value attained in normal operation (to compensate for possible ‘double batching’, i.e. the transfer of two batches of fissile material instead of one batch in a fuel fabrication process) or equal to the maximum physical mass that could be present in the equipment.
- *Geometry of processing equipment*. “The potential for changes in dimensions during operation shall be considered” (e.g. bulging of slab tanks or slab hoppers).
- *Neutron interaction*. Preference should be given to engineered spacing over spacing achieved by administrative means.
- *Moderation*. Hydrogenous substances (e.g. water and oil) are common moderators that are present in conversion facilities and enrichment facilities or that may be present in accident conditions (e.g. water from firefighting); the subcriticality of a UF_6 cylinder should rely only on moderation control.
- *Reflection*. Full water reflection should be assumed in the criticality analysis unless it is demonstrated that the worst case conditions relating to neutron reflection (e.g. by human beings, organic materials, wood, concrete, steel of the container) result in a lower degree of reflection. The degree of reflection in interacting arrays should be carefully considered since the assumption of full water reflection may provide a degree of neutronic isolation from interacting items. Moderation control should ensure criticality safety for an individual UF_6 cylinder or an array of UF_6 cylinders for any conditions of reflection.

- *Neutron absorbers.* “When taken into account in the safety analysis, and if there is a risk of degradation, the presence and the integrity of neutron absorbers shall be verifiable during periodic testing. Uncertainties in absorber parameters shall be considered in the criticality calculations.” The neutron absorbers that may be used in conversion facilities and enrichment facilities include cadmium, gadolinium or boron in annular storage vessels or transfer vessels for liquids. Absorber parameters include thickness, density and isotopic concentration.

Confinement to protect against internal exposure and chemical hazards

4.20. As far as possible, the following parameters should be minimized:

- The amount of liquid UF_6 in process areas, e.g. by limiting the size of crystallization (desublimation) vessels in both conversion and enrichment facilities;
- The amount of nuclear material unaccounted for in the process vessels;
- The duration of operation when UF_6 is at a pressure above atmospheric pressure;
- The capacity for storage of HF , NH_3 and H_2 .

4.21. Conversion facilities and enrichment facilities should be designed to minimize, to the extent practicable, contamination of the facility and releases of radioactive material to the environment, and to facilitate decontamination and eventual decommissioning. Especially in the working areas where liquid UF_6 is processed, two static barriers should be installed. Particular consideration should also be given to minimizing the use of flexible hoses and to ensuring their maintenance and periodic checking.

4.22. Use of an appropriate containment system should be the primary method for protection against the spreading of dust contamination from areas where significant quantities of either powder of uranium compounds or hazardous substances in a gaseous form are held. To improve the effectiveness of static containment, a dynamic containment system providing negative pressure should be used when practicable, through the creation of airflow towards the more contaminated parts of equipment or an area. The speed of the airflow should be sufficient to prevent the migration of radioactive material back to areas that are less contaminated. A cascade of reducing absolute pressures can thus be established between the environment outside the building and the hazardous material inside.

4.23. In the design of the ventilation and containment systems for areas that may contain elevated levels of airborne radioactive material during operation, account should be taken of criteria such as: (i) the desired pressure difference between different parts of the premises; (ii) the air replacement ratio in the facility; (iii) the types of filters to be used; (iv) the maximum differential pressure across filters; (v) the appropriate flow velocity at the openings in the ventilation and containment systems (e.g. the acceptable range of air speeds at the opening of a hood); and (vi) the dose rate at the filters.

Protection of workers

4.24. The ventilation system should be used as one of the means of minimizing the radiation exposure of workers and exposure to hazardous material that could become airborne and so could be inhaled by workers. Conversion facilities and enrichment facilities should be designed with appropriately sized ventilation and containment systems in areas of the facility identified as having potential for giving rise to significant concentrations of airborne radioactive material and other hazardous material. Wherever possible, the layout of ventilation equipment should be such that the flow of air is from the operation gallery towards the equipment.

4.25. The need for the use of protective respiratory equipment should be minimized through careful design of the containment and ventilation systems. For example, a glovebox, hood or special device should be used to ensure the continuity of the first containment barrier when changing a valve to remove the need for respiratory protection.

4.26. In areas that may contain airborne uranium in particulate form, primary filters should be located as close to the source of contamination as practicable unless it can be shown that the design of the ventilation ducts and the air velocity are sufficient to prevent unwanted deposition of uranium powder in the ducts. Multiple filters in series should be used to avoid reliance on a single filter. In addition, duty and standby filters and/or fans should be provided to ensure the continuous functioning of ventilation systems. If this is not the case, it should be ensured that failure of the duty fan or filter will result in the safe shutdown of equipment in the affected area.

4.27. Monitoring equipment such as differential pressure gauges (on filters, between rooms or between a glovebox and the room in which it is located) and devices for measuring uranium or gas concentrations in ventilation systems should be installed as necessary. Alarm systems should be installed to alert

operators to fan failure or high or low differential pressures. At the design stage, provision should also be made for the installation of equipment for monitoring airborne radioactive material and/or gas monitoring equipment. 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 (see para. 6.39 of Ref. [1]).

4.28. To prevent the propagation of a fire through ventilation ducts and to maintain the integrity of firewalls, and as practicable in view of the potential of corrosion by HF, ventilation systems should be equipped with fire dampers and should be constructed from non-flammable materials.

4.29. If fume hoods and gloveboxes are used (e.g. in laboratories), their design should be commensurate with the specific local hazards in the conversion facility or enrichment facility.

4.30. To facilitate decontamination and the eventual decommissioning of the facility, the walls, floors and ceilings in areas of the conversion facilities and enrichment facilities where contamination is likely to exist should be made non-porous and easy to clean. This may be done by applying special coatings, such as epoxy, to such 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 decontamination as necessary.

Protection of the environment

4.31. The uncontrolled dispersion of radioactive or chemical substances to the environment as a result of an accident can occur if all the containment barriers are impaired. Barriers may comprise the process equipment itself, or the room or building structure. The number of physical barriers for containment should be adapted to the safety significance of the hazard. The minimum number of barriers is two, in accordance with the principle of redundancy (see para. II-1 of Annex II of Ref. [1]). The optimum number of barriers is often three. In addition, ventilation of the containment systems, by the discharge of exhaust gases through a stack via gas cleaning mechanisms such as wet scrubbers in conversion facilities, or cold traps and dry chemical absorbers in enrichment facilities, reduces the normal environmental discharges of radioactive or chemical (mainly HF) material to very low levels. In such cases, the ventilation system may also be regarded as a containment barrier. The design should also provide for the monitoring of the environment around the facility and the identification of breaches to the containment barriers.

Protection against external exposure

4.32. External exposure can be controlled by means of an appropriate combination of requirements on distance, time and shielding. Owing to the low specific activity of naturally sourced material, the shielding provided by the vessels and pipe work of a conversion facility or an enrichment facility will normally be sufficient to control adequately occupational exposure. However, in areas that are in close proximity to newly emptied UF₆ cylinders or bulk storage areas, installation of shielding or restrictions on occupancy should be considered. Additional shielding or automation may also be required for the handling of reprocessed uranium.

4.33. When reprocessed uranium is processed, shielding should be strengthened for protection of the workers, because of the higher gamma dose rates from ²³²U daughters and fission products.

4.34. In selecting the areas for storage of tailings, requirements on distance, occupancy time and shielding should be considered to minimize the direct exposure of members of the public to gamma and neutron radiation. In estimating the exposure, ‘sky shine’ (scattered gamma radiation in air) should also be taken into account.

POSTULATED INITIATING EVENTS

Internal initiating events

Fire and explosion

4.35. Conversion facilities and enrichment facilities, like all industrial facilities, have to be designed to control fire hazards in order to protect workers, the public and the environment. Fire in conversion facilities and enrichment facilities can 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 of 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 conversion facility such as from anhydrous ammonia (explosive and flammable), nitric acid (ignition if organic materials) and hydrogen should be given due consideration.