Safety Reports Series

No. 36

Safety Considerations in the Transition from Operation to Decommissioning of Nuclear Facilities

IAEA
International Atomic Energy Agency

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SAFETY CONSIDERATIONS IN THE TRANSITION FROM OPERATION TO DECOMMISSIONING OF NUCLEAR FACILITIES

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FOREWORD

The decommissioning of nuclear facilities is a topic of great interest to many Member States of the International Atomic Energy Agency. A growing number of nuclear facilities around the world are being shut down for various reasons. The final phase, decommissioning, is a complex process. The transition period between operation and the implementation of the decommissioning strategy includes some routine operations and others that may be specific to the transition stage. In this period, a number of modifications, both technical and organizational, are required to adjust the facility to new objectives and requirements. Some important operations that are required to achieve safe storage, which are independent of the chosen decommissioning strategy, should be carried out promptly after shutdown to achieve a large reduction in radiological hazards to workers and to the public.

In cases where the decommissioning strategy has not yet been decided at the time of permanent shutdown, transitional operations need to be accomplished to provide assurance that conditions at the facility are not a potential threat to human health and safety or to the environment.

The main safety requirements for the transition period for nuclear facilities are presented in two IAEA Safety Requirements publications: Safety of Nuclear Power Plants: Operation (No. NS-R-2) and Predisposal Management of Radioactive Waste, Including Decommissioning (No. WS-R-2). Three Safety Guides outline the safety aspects to be considered during the decommissioning of various nuclear facilities: Decommissioning of Nuclear Power Plants and Research Reactors (No. WS-G-2.1), Decommissioning of Nuclear Fuel Cycle Facilities (No. WS-G-2.4) and Decommissioning of Medical, Industrial and Research Facilities (No. WS-G-2.2). The present Safety Report provides information to support and extend the recommendations given in these Safety Guides.

Experience shows that many of the operations in the transition phase are routine. However, some transitional operations may never have been performed before or are so infrequently performed that special procedures and regulatory approvals may be necessary. This Safety Report provides information regarding the safety concerns associated with the transition period and suggests solutions for managing them. It addresses issues that are generically applicable to any nuclear facility and those that are specific to various types of nuclear facility.

This Safety Report has been developed through three consultancies. The IAEA wishes to express its gratitude to all those who assisted in its drafting and review. The technical officer responsible for preparation of this report was L. Jova Sed of the Division of Radiation and Waste Safety.

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1. INTRODUCTION

1.1. BACKGROUND

The stages in the lifetime of nuclear facilities are: siting, design, construction, commissioning, operation and decommissioning. The final phase, decommissioning, is a complex process involving operations such as detailed radiological surveys, decontamination and dismantling of plant equipment and systems, demolition of buildings and structures and processing of the resulting radioactive and non-radioactive waste. The number of existing nuclear power plants in the world exceeds 500. Of these, 108 are in the shutdown phase or are undergoing decommissioning. Only 13 nuclear power plants have been fully decommissioned so far. A considerable amount of experience has already been gained from the decommissioning of nuclear power plants by various Member States, but the experience achieved on the transition from operation to decommissioning of nuclear facilities is concentrated in only a few Member States. This report intends to transmit the experience gained by these to other Member States.

The transition period between operation and the implementation of decommissioning involves some routine operations along with others that may be specific to the transition stage based on the type of facility. This period can be confusing and stressful to plant workers and, in addition, operational safety may be compromised. During this period a number of plant, system and organizational modifications will be necessary to meet the objectives and requirements associated with decommissioning. A change of thinking within the management and workforce is also needed to respond to these new objectives and to the different management and working practices.

A number of IAEA Safety Standards apply to the decommissioning of nuclear facilities [1–7]. In these publications the term decommissioning refers to the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a nuclear facility (except for a repository, for which the term closure and not decommissioning is used). These actions are carried out to achieve a progressive and systematic reduction in radiological hazards and are taken on the basis of preplanning and assessment to ensure safety during decommissioning operations.

IAEA Safety Standards acknowledge that there is a large range of possible decommissioning strategies, but the standards focus on three main options. These are: immediate dismantling, when decommissioning is carried out in one continuous operation following shutdown; safe enclosure or the deferred dismantling option, which consists of a minimum degree of early

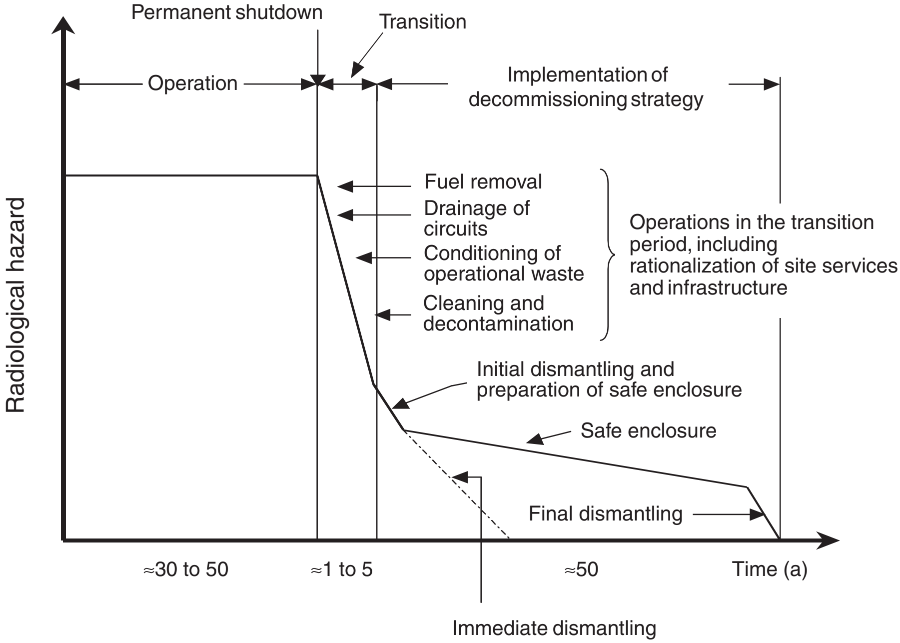

FIG. 1. Transitional decommissioning operations and typical durations for the 'safe enclosure' option (the chain line shows the 'immediate dismantling' option).

dismantling and conversion of the plant to a safe storage condition for a defined period of time before final dismantling; and entombment, when the resulting facility becomes, essentially, a waste repository.

There are some important operations that are independent of the decommissioning strategy and that need to be carried out promptly after shutdown as part of the operational phase of the facility in order to achieve a large reduction in radiological hazards. Examples of these transitional operations are: removal of fuel, drainage of circuits, cleaning and decontamination, conditioning of operational waste, and rationalization of site services and infrastructure that may no longer be required during the decommissioning phase (Fig. 1).

These transitional operations are undertaken following procedures authorized by the regulatory body. Even in cases where the decommissioning strategy has not yet been decided at the time of permanent shutdown, shutdown and transitional operations need to be accomplished safely to provide assurance that conditions at the facility are not a potential threat to human health and safety or to protection of the environment. These operations would involve utilization of key operational staff, whose experience and knowledge of the plant are invaluable for these operations, before inevitable staff reductions occur.

1.2. OBJECTIVE

The objective of this Safety Report is to provide information to Member States to help in ensuring safe management of the transition from the operational phase to the beginning of implementation of the decommissioning strategy for nuclear facilities. The transition period may be defined as the time from when a facility is permanently shut down until the decommissioning strategy begins to be implemented. This period is normally considered to be part of the operational phase.

The goal during the transition period is to achieve a significant reduction in radiological hazards through the safe termination of operational activities and removal of radioactive material, and to place the facility in a stable and safe condition until the decommissioning strategy is implemented. During this period, control of any remaining spent fuel, other radioactive material or non-radioactive hazardous material should be maintained, and the safety of the workers and the public, and protection of the environment, should be ensured.

1.3. SCOPE

This Safety Report is issued in support of the recommendations and guidance provided in three IAEA Safety Guides that address decommissioning of nuclear installations [5–7]. The emphasis is on the safety issues involved in the main operations and activities needed in the transition from the operational phase to the implementation of the decommissioning strategy when considering and planning for permanent shutdown. This report covers issues applicable to any facility (such as power plants, research reactors and fuel cycle facilities). Application will require the information to be tailored to meet the size and nature of the specific facility. This Safety Report provides information that can be used in the application of safety standards, describes good practices and gives practical examples.

Organizational, strategic and administrative activities and the technologies associated with the transition period are addressed in more detail in a companion IAEA Technical Report [8]. Safety related information on safe enclosure during deferred dismantling is provided in Ref. [9].

1.4. STRUCTURE

Section 2 summarizes the organizational, strategic and administrative activities to be performed at the latest during the transition period. These include appropriate changes to the operator's organizational structure and preparation of the final decommissioning plan. Section 3 deals with licensing during the transition period. Depending upon the requirements of the regulatory body, transitional operations may be undertaken under the operating licence, a specific licence, an overall decommissioning licence, or under direct control by the regulatory body. Section 4 describes the operations to be undertaken during the transition period. For each operation, specific safety concerns are identified, mitigating actions suggested and good practices specified. Lessons learned from operations in facilities and plants that underwent transition periods in the past are also included.

2. ORGANIZATIONAL AND ADMINISTRATIVE ACTIVITIES

There are important organizational and administrative activities to be performed prior to final shutdown or at the latest during the transition period in preparation for implementation of the decommissioning strategy. These activities include:

(a) Appropriate changes to the structure of the licensee's organization, with the establishment of a decommissioning project team, responsible and accountable for decommissioning planning and operations. The team may report initially to the facility manager but, as decommissioning subsequently progresses, the decommissioning process should be managed under the executive control of a decommissioning project manager.
(b) Establishment of clear interfaces with stakeholders, including the general public, and of adequate information exchange mechanisms to build confidence in, and acceptance of, the selected decommissioning strategy.
(c) Preparation of the final decommissioning plan with all related documents.
(d) Collection and retention of important records and establishment of an efficient record keeping system.
(e) Definition of a programme of development work on techniques and equipment required for dismantling, if necessary.

Specific information on these activities is provided in the companion IAEA Technical Report [8].

Of particular importance is the establishment of the final decommissioning plan. IAEA safety standards require that decommissioning should be addressed initially at the design stage of a nuclear facility through an initial decommissioning plan [4]. It is important that such a plan be regularly updated and further developed in the later phases of the facility lifetime (i.e. construction, commissioning and operation), so that, at the end of operation, a detailed decommissioning plan is available. If this is not the case, the transition period is the last opportunity for the licensee to prepare, finalize and submit the decommissioning plan for regulatory approval, in order that the selected and approved decommissioning strategy can be implemented. Recommendations and guidance for the establishment and contents of the decommissioning plan and related documents are provided in Refs [5–8].

3. LICENSING DURING THE TRANSITION PERIOD

Licensing during the transition from facility operation to implementation of the decommissioning strategy is dependent on the processes and requirements established by the regulatory body within the particular Member State. Regulatory authorization may be given in several stages and, therefore, specific licensing requirements are needed for the various phases of facility lifetime, from construction to operation to decommissioning [2, 3]. Specific requirements are established to provide adequate assurance of safety for particular periods within these phases. These periods could include, but are not limited to, subcritical operation, full power operation, long term safe storage; dismantling and decontamination; and final verification of radiological conditions prior to removal of regulatory control. Finally, regulatory requirements may be established for specific support activities, such as: fuel storage in dry and wet configurations; fuel transport; reactor vessel transport; and radioactive waste treatment, transport and disposal.

While a facility is operating, it is required to have an operating licence. If there is a requirement for the implementation of the decommissioning strategy to begin at the facility, the operator has to submit an application for authorization to decommission the facility, together with the proposed final decommissioning plan [4]. This decommissioning licence is written for site and facility activities after the facility ceases power operation or utilization activities involving radioactive material. The decommissioning licence can therefore provide the minimum requirements (in conjunction with the rules and regulations of the Member State concerned) necessary to provide assurance that the radiological and non-radiological activities conducted at the facility will pose no threat to public health, safety or the environment.

IAEA safety standards require pre-review and pre-approval of decommissioning activities performed during the transition period [4–7]. This can take the form of a decommissioning licence and decommissioning plan. Regardless of which particular action is required, this regulatory process may take up to several years. Therefore, the preparatory work for decommissioning of a facility may have to commence years before final shutdown in order to prevent any delay in the implementation of the decommissioning strategy.

A decommissioning plan typically lists decommissioning activities and discusses why they have been proposed. These activities will include managerial, organizational and programme changes and the proposed methods, techniques and processes to be utilized for the actual dismantling and decontamination of the facility. Information provided typically includes cost projections, scheduling information and lists of activities to be accomplished.

Techniques to reduce radiation doses to as low as reasonably achievable will also be described. These efforts could include chemical and mechanical decontamination methods to reduce the exposure of workers and the public, and to minimize the volume of waste and/or to facilitate disposal. Similarly, radiological survey techniques, statistically based dose analyses, dismantling, storage and disposal methods, and transport and packaging controls are generally included in decommissioning plans.

This facility specific decommissioning information is often augmented or supplemented by evaluations demonstrating the effects of decommissioning on the environment. These environmental studies or evaluations not only assess the impact of decommissioning and of transport and disposal of radioactive waste outside the facility premises but may also evaluate the impact on flora, fauna and terrestrial elements. These assessments also include the impact of residual radioactive material or non-radiological hazards left at the facility following completion of the decommissioning activities.

Decommissioning plans can be submitted to the regulatory body to cover various phases of decommissioning, such as a plan detailing the operation to the decommissioning transition or a dismantling and decontamination phase, or a plan describing final site activities that conclusively demonstrates that radiological and non-radiological hazards are reduced to within levels set by the regulatory body of the State. The contents of a typical decommissioning plan are given in Refs [5–7].

From a safety perspective, it is advisable to have a nuclear facility either operating or permanently shut down, for example a defuelled nuclear power facility or research reactor. Studies conducted in some States have demonstrated significant levels of risk associated with decommissioning activities being conducted while a reactor is shut down but not defuelled. With all the fuel in the core or with the core partially loaded, safety concerns related to nuclear reactor criticality and chemistry, reactor vessel water level, pressure and temperature and heat removal must be carefully managed to provide assurance that significant radiological accidents will not occur.

The same control needs to be applied to the spent fuel pool (SFP). In many cases, the majority of spent fuel operations would need to be conducted during the transition period. More information on core management and fuel handling for nuclear power plants can be found in Ref. [10].

A decommissioning licence and/or the rules and regulations associated with decommissioning are generally a subset of those required for operating nuclear facilities. For example, a permanently shut down reactor plant does not present the same safety concerns as an operating (fuelled) reactor. Most reactors that are permanently shut down no longer give rise to the high temperatures and pressures associated with reactor operation. Therefore, the motive force to rupture containment and confinement systems and spread radioactive material no longer exists.

Similarly, if all nuclear material is removed from the reactor vessel or processing systems and placed in a storage system or other engineered system designed for nuclear material, then criticality, exothermic heat generation or chemical stability may no longer represent a significant safety concern because the storage or holding systems are designed to prevent transient or accident conditions. However, this does not mean that additional plant, system or control requirements may not be necessary, for it is possible that some decommissioning activities may not be covered by the existing 'operating' requirements and guidance [3, 4, 10].

Regardless of the specific regulatory processes within each country concerning decommissioning of a nuclear facility, providing assurance (through legislation, regulations and licences) that decommissioning can be conducted safely without adverse radiological consequences or unacceptable impact on humans or the environment is a significant safety consideration. This can be accomplished in a number of ways: through the careful application of 'operating' requirements during decommissioning; through development of specific requirements for decommissioning; or through a combination of both.

4. OPERATIONS DURING THE TRANSITION PERIOD

This section identifies and discusses safety concerns and considerations associated with facility activities during the transition period. Facility and plant operations conducted during the transition period could include:

— Handling and temporary storage of nuclear fuel (Section 4.3);
— Drainage of systems (Section 4.4);
— Cleaning and decontamination (Section 4.5);
— Estimates of the inventory of radioactive material at shutdown (Section 4.6);
— Conditioning and removal of operational waste (Section 4.7);
— Retirement, reconfiguration and planning for the provision of new systems (Section 4.8);
— Changes to confinement barriers (Section 4.9).

Within each of these sections, safety considerations and concerns are presented in an effort to assist in the safe conduct of activities throughout the transition period. These considerations and concerns are based on decommissioning experience gained in Member States and have been shown to contribute to the safety of the plant and personnel and to protection of the environment.

Also included in Section 4 is a discussion of administrative and plant controls (Section 4.1) and social and economic aspects (Section 4.2) during the transition period. Section 4.1 is generally applicable to all the activities that an operator of a nuclear facility may implement during the transition period. Section 4.2 presents probable safety concerns which may develop due to reductions in staff at the facility. Without appropriate consideration and evaluation of these and other items, safety problems can arise.

4.1. ADMINISTRATIVE AND PLANT CONTROLS

All operators of nuclear facilities will have to plan and conduct facility and site activities to release the site from regulatory control. For each activity, it is important to ensure that appropriate plans, procedures and programmes are developed and implemented so that the workforce can conduct the activities properly and safely. This will not only contribute to schedules being met but also help in reducing the overall cost of decommissioning. This philosophy has to be applied equally to activities requiring regulatory approval and to those that do not.

Many of the operations may be routine; however, some transition operations may never have been performed before or are so infrequently performed that special procedures and approvals may be necessary. Specific regulatory approvals (as discussed in Section 3) may be needed, for example, for changes to radiological effluent release concentrations, shipments of large components (e.g. old steam generators or process vessels) or interim dry storage of spent fuel. Also of high importance are the transition operations that may adversely impact the environment or those that may not have been previously reviewed and approved, such as:

— Generation of dust from the demolition of large concrete structures;
— On-site interim storage or disposal of operational and future decommissioning waste, both radioactive and non-radioactive;
— Retirement of radioactive retention pools, tanks and piping;
— Retirement of sewage disposal areas;
— Removal of underground services (e.g. electrical services).

The specific regulatory approvals for each facility or site need to be identified and procedures developed prior to conducting the activity, in order to facilitate efficient and effective decommissioning.

Many site activities that do not require regulatory approval may still require similar administrative controls in the form of procedures and programmes. Of course, if the procedures and programmes used during facility operation were revised, in part, to reflect the shutdown status of the equipment or facility, then these could also be acceptable and be applied to the decommissioning plan with proper safety evaluation and revision. Some transition period operations that may not need specific regulatory approval but may need detailed administrative procedures are the following:

— System drainage, cleaning, dismantling or retirement (e.g. cleanup of the SFP following fuel removal);
— Confinement modification;
— Dismantling;
— Chemical decontamination;
— Removal, packaging, storage, shipment and disposal of hazardous material.

Additionally, even if some decommissioning operations appear to be routine, simple or of low safety consequence, they may necessitate approved procedures owing to uncertainty in some conditions. For example, high levels of radiation or non-radiological hazards may be present in some facility areas and systems that may not have been accessible or surveyed during facility operations. Furthermore, construction and/or operation records may not accurately or completely characterize the radiological or non-radiological conditions in the particular areas or systems that have been isolated from monitoring, such as those in hot cells. These situations need to be evaluated and proper procedures established to prevent unplanned radiation exposure or other hazards.

In a nuclear facility undergoing the transition from operation to decommissioning, structures, systems and components are being modified and/or retired and their mode of operation may be changing. The operators of these systems need to be informed about and knowledgeable of these changes to ensure proper system operation. As such, it is very important that the operating procedures and drawings be revised accordingly and in a timely manner. Furthermore, as structures, systems and components are changed, modified or retired for decommissioning, quality controls need to be developed and implemented to ensure that:

— Plant and system drawings are updated;
— System and facility operating procedures are revised accordingly;
— Approval and authorization controls are established and documented;
— Scheduling and sequencing of systems to be changed, modified or retired are co-ordinated so as to have no impact on the systems and processes required for operations during the decommissioning process.

The effectiveness of the above quality controls and decommissioning cannot, in general, be assured without management oversight and personnel training. Prior to and during the transition to decommissioning, the operating organizations of nuclear facilities need to conduct training for managers, operators, technicians and other staff on particular safety significant activities to be accomplished during decommissioning. It is important that a periodic training programme also be developed and implemented, since many new people will be assigned to the facility to conduct the work necessary for decommissioning. Those people most familiar and experienced with the facility, systems and operations may leave for other jobs as they see their employment coming to an end.

4.2. SOCIAL AND ECONOMIC ASPECTS

The transition period from operation to decommissioning will cause stress in the workforce who may be concerned about the uncertainty regarding their future employment. It is necessary, in the short term, to retain suitably qualified and experienced staff to ensure that systems and equipment continue to be operated within their safe limits. A programme needs to be developed to ensure that key staff members are given sufficient incentives (financial or otherwise) to continue to work during the transition period. In addition, the overall impact of facility closure on the local community with regard not only to direct employment but also to secondary considerations, such as local services, must be planned well in advance of facility shutdown. In the initial stages of decommissioning for large facilities, however, there may be a need to reduce staffing levels so as to reduce the overall costs of the decommissioning programme in a timely manner (early costs are largely dominated by salaries). This is a clear dilemma and has to be managed in a sensitive way. Key operations staff must be retained in sufficient numbers during the early part of the programme to ensure that work is carried out safely and efficiently.

4.3. HANDLING AND TEMPORARY STORAGE OF NUCLEAR FUEL

One of the first priorities after permanent shutdown of a nuclear power plant, research reactor or reprocessing plant is removal of the fuel from the facility that is going to be decommissioned. This section specifically considers the safety implications inherent in defuelling a reactor. Even though the removal of fuel from a reactor is considered part of normal operations, it is included here in order to provide a complete picture of the transition period (also see Ref. [10]). This section also discusses some safety measures that operators of nuclear power plants can evaluate and implement to provide a greater degree of safety during the transition period (Section 4.3.1). Additionally, this section also provides some insight into the radiological significance of fuel handling and storage accidents (Section 4.3.2). Beyond storage accidents, many other accidents are possible at nuclear facilities that are undergoing the transition from operations to decommissioning. These accidents generally have lower radiological significance. However, they have the potential to result in conditions that are adverse to human health, the environment or decommissioning activities (Section 4.3.2).

Most of the fuel handling sequences and accidents to be described may have been taken into account in the original design bases of the plant. This needs to be verified before conducting new assessments. In many cases, existing operating and emergency procedures are already capable of coping with these accidents or may be easily updated to do so. However, for non-routine procedures, additional operator training will be required. Special attention also needs to be paid to the safety assessment of fuel handling sequences that are different from those occurring during routine operation.

4.3.1. Safety considerations

4.3.1.1. Scheduling of fuel handling

The removal of spent fuel is a critical step for a number of major nuclear power plant decommissioning activities. This means that most decommissioning activities cannot be performed without fuel removal and storage being first completed. Therefore, since fuel removal from the reactor vessel must occur, the handling and storage of spent fuel must have the highest priority.

4.3.1.2. Fuel handling in reactor vessels

Removal of all the spent fuel from a reactor vessel that has been operating may lead to situations requiring safety evaluation. Additionally, the removal of all the fuel from the reactor vessel may not be a routine operation since in most Member States on-line refuelling is performed or only a part of the reactor core is refuelled, and hence special engineering and oversight considerations are needed. For example, as fuel is removed from the reactor vessel, engineering considerations, such as the type of reactor, the safety significance of moderator void formation, and the effect on cooling geometries, criticality and structural loading, need to be evaluated, if these evaluations are not available in the design bases of the plant.

In addition, radiation shielding, defence in depth and management oversight have to be implemented. Radiation and airborne contamination monitoring, alarm and control is also necessary. Criticality monitoring and source range nuclear instrumentation need to be operable, chemistry needs to be within specification, and other subcriticality control devices and features need to be in operation.

4.3.1.3. Fuel handling in spent fuel pools

The placement of all reactor fuel in an SFP is, for some Member States, an infrequently performed operation. As such, prior to this activity, the spent fuel pool storage capacity, cooling capability, structural loading and spent fuel rack capacity need to be carefully considered. In some cases, a full core off-load may not have been evaluated as to its possible adverse effect on structures, systems and components.

Operators of nuclear power facilities need to assess the impact of a full core off-load (with fuel at its operational conditions, i.e. actual burnup, heat generation rate, enrichment and poison concentrations) on the capability of the spent fuel storage system to maintain adequate cooling, subcriticality and storage.

Inspection of the spent fuel racks needs to be conducted to ensure that corrosion, plate buckling or boron expansion has not reduced annular tolerances (between the fuel assembly and storage rack) to below acceptable limits. These spent fuel rack inspections will facilitate efficient fuel handling and contribute to safe fuel storage. If fuel assemblies have been stored in the rack for a long time it is possible there might be binding between the rack and the assembly, preventing the removal of the assembly. A contingency procedure has to be in place if an assembly becomes stuck in a rack. An improperly stored or seated assembly would represent a potentially unsafe condition.

Visual or photographic inspection of areas below the spent fuel racks and alongside of the racks (between the racks and walls) also needs to be performed to ensure that natural or forced circulation of cooling water is sufficient for spent fuel cooling. On the basis of experience, it has been found that dirt, corrosion products and foreign material tend to accumulate under and along the sides of spent fuel racks. If coolant flow is insufficient this could represent a safety concern. The loading of spent fuel racks adjacent to the spent fuel pool wall (typically lined with stainless steel with a supporting concrete structure) may increase radiation levels to areas adjacent to the exterior portion of the particular wall because of the closer proximity of the spent fuel to the wall and possibly because previously inaccessible areas are now accessible to plant personnel due to the dismantling of surrounding rooms, bulkheads or systems, or soil removal external to the fuel storage pool.

The safety significant effects of a full core off-load on SFP subsystems also need to be evaluated. SFP subsystems include, but are not limited to: structure and leak prevention features (e.g. liners, concrete and supports); water and air cooling systems (e.g. pumps, heat exchangers, and SFP building humidity and temperature control); filtration and/or purification systems (to ensure that water clarity allows spent fuel inspection for storage and transport); and chemical control systems for criticality and/or corrosion. More information on spent fuel handling and storage systems can be found in Refs [10–13].

4.3.1.4. Spent fuel island concept

In order to facilitate decommissioning of structures, systems and components that are in the vicinity of the SFP subsystems, some operators have elected to install a completely new SFP subsystem, sometimes referred to as an SFP island. The SFP island is functionally and operationally equivalent to the original subsystems, which may have included refill and drainage capability, filtration, purification, isolation, pump, pipe, heat exchanger and instrumentation subsystems. However, the SFP island has typically been much smaller, because of the lower heat load represented by the spent fuel that has cooled longer or not been exposed to reactor criticality operations. This smaller size facilitates use of the system immediately adjacent to the SFP, insertion into the SFP and perhaps the portability of the system.

An SFP island can contribute to the safe storage of spent fuel if properly designed. Its design would have to be based on the spent fuel conditions, as well as the SFP size, chemistry and proposed use. Additionally, the design needs to incorporate the defence in depth concept by incorporating independence, diversity and redundancy in its instrumentation, electrical power supply and mechanical system. Proper reviews and approvals are needed prior to operation.

As stated above, the SFP island can facilitate the decommissioning (dismantling, decontamination and retirement) of structures, systems and components in the buildings and rooms that contain (1) the original plant systems associated with spent fuel storage, maintenance and control and (2) the systems and components requiring decommissioning. Other potential benefits of an SFP island may include:

- Reduced occupational exposure (the SFP island may be located in areas of low radiation dose);
- Lower cost of operation (spent fuel decay heat will decrease after shutdown, thereby allowing the installation of smaller, more efficient, pumps and heat exchangers);
- Efficiency (the SFP heat exchanger may utilize water to air, thereby reducing the need for a service water or sea water support system);
- Improvements in maintenance and system performance (obtained through a design that implements or incorporates independence, diversity and redundancy of electrical, mechanical and instrumentation systems);
- Practical safety applications (the SFP island services and systems can be colour coded and labelled to distinguish them from other plant systems and components, to provide some assurance that decommissioning activities will not be performed on the SFP island);
- Physical protection (more easily applied because of the SFP island's smaller physical size).

4.3.1.5. *Techniques for spent fuel handling*

Because a full core off-load will be conducted during the transition period, strong consideration has to be given to minimizing the total number of spent fuel moves to remove the fuel from the reactor vessel, transfer the fuel into interim storage (e.g. an SFP or dry storage unit) and move the spent fuel into a transport container for shipment to the disposal, storage or processing facility. Minimizing the number of spent fuel moves will reduce operator radiation exposure and reduce the probability of a spent fuel handling accident.

To reduce the total number of spent fuel moves, an operator could consider:

(a) Conducting spent fuel inspections during fuel movement without ungrappling;
(b) Reracking the SFP prior to core off-load to segregate various types of spent fuel (e.g. burnup and enrichment) for shipment;
(c) Conducting inspections of the spent fuel racks to ensure that the dimensional tolerances necessary for fuel storage have not changed.

Moreover, efficient placement of spent fuel in storage racks will also minimize the number of subsequent spent fuel moves, possibly reduce radiation exposure in areas external and adjacent to fuel storage walls and better utilize the available space in the SFP for other decommissioning activities.

Further factors may be identified that will influence the defuelling and shipping rate, including identification of bottlenecks in the fuel route, which will shorten process times, identification of critical plant items and operating times as a route to performance improvement, and improvements in cask loading factors when these can be justified on safety grounds. Duplication of plant items may be considered to speed up the defuelling process where this can be justified on economic grounds.

To summarize, spent fuel operations and spent fuel racks need to be identified, characterized and evaluated prior to fuel handling. If these verifications are not possible prior to fuel handling, they have to be done while performing fuel moves for operational reasons (e.g. fuel unloading, SFP unloading or transport).

Formal procedures always need to be followed for spent fuel handling, even during the transition period. Verification and validation methods have to be implemented, spent fuel characteristics (both engineered and physical) have to be documented and evaluated, and management oversight utilized. Strong consideration should be given to the utilization of mechanical devices to limit crane travel and speeds through limit switches and load cells. Fuel handling should be conducted using one dimensional moves; safe lay-down areas for spent fuel should be pre-evaluated and pre-identified in anticipation of a possible handling problem; and independent operator verification and documentation should be utilized for all fuel grappling, movement, inspection and storage activities, and other quality controls should be established, if at all possible.

4.3.1.6. Operator training

Only trained and qualified individuals may conduct fuel handling according to specific procedures. Fuel operators must always be present at the controls while moving, handling and storing nuclear fuel. The fuel operator training and the number and types of operators performing fuel handling during the transition period should be no different than those during normal reactor refuelling operations.

The importance of operator training following final nuclear facility shutdown must be equivalent to that of the operator training provided when the plant was operating. As discussed in Section 4.3.2, the number and magnitude of accidents involving fuel are approximately the same for fuel handling during core refuelling and fuel handling during final reactor defuelling. This same philosophy is applicable to fuel handling from the SFP to a transport cask, interim storage facility, reprocessing facility or deep geological repository.

To illustrate the importance of operator training there is one postulated accident that has been reviewed in the United States of America that could be more severe than those discussed in Section 4.3.2 and which operators could initiate. In addition, accident precursors could be present during the transition period, as well as during reactor operation or decommissioning.

This postulated accident is initiated with the unmitigated drain-down of the SFP water to a point where inadequate cooling of the spent fuel assemblies occurs. Without timely restoration of cooling (either by liquid submergence or possibly spray), the spent fuel will, for almost all cases, continue to heat up in the air environment. Within hours, without operator action, the fuel cladding temperature could be sufficient to initiate a self-sustaining exothermic oxidation of zircaloy fuel clad material, leading to ever higher temperatures. In other words, based on computer modelling, the cladding will catch fire (i.e. a ‘zirc fire’) if sufficient cooling is not restored [14, 15].

A ‘zirc fire’ accident has major radiological consequences but a very low probability of occurrence. It has been shown that for pressurized water and boiling water reactors such an accident could result in off-site radiological dose consequences approximating those of a major at-power reactor accident, with both immediate and latent fatalities. If spent fuel is present then, depending on its storage conditions, this type of accident could occur years after final reactor shutdown. Fortunately, there is a very low probability that such an accident could ever occur because of the very low likelihood of the accident initiators occurring. The reviewed initiators include, in part, a very large seismic event (beyond design basis earthquakes), heavy load drops on or in the vicinity of the SFP and any unauthorized intervention that results in an unmitigated loss of SFP water.

The purpose of describing this accident is to stress the importance of safe fuel handling and storage in all phases of decommissioning, including the transition period and the period beyond. Plant operators and operators performing fuel handling and storage need to strictly follow the fuel handling procedures and to be aware that, even with reactor shutdown, significant radiological accidents can occur. The current mitigating strategy is the practice of designing spent fuel storage facilities to withstand seismic events, effective control of heavy loads and adequate physical protection requirements.

4.3.1.7. Engineering for fuel handling and storage

Engineering evaluations are performed to assess the status of the spent fuel. The engineering assumptions and design considerations associated with spent fuel transport and storage are based on the actual status and condition of the nuclear fuel. Inaccuracies or errors in the verification and validation of the engineered design requirements for nuclear fuel may result in unsafe transport or storage. Therefore, it is necessary during the transition period to make a careful and accurate evaluation of design features, such as the following:

- Decay heat rate;
- Energy produced per tonne of burned fuel, MW·d/t (necessary, for example, for criticality, cooling and dose evaluation);
- Uranium enrichment and poison concentration;
- Critical dimensions of pin and assembly;
- Manufacturer, serial number and material (construction and/or exotic material).

Additionally, the operators of facilities that contain spent fuel need to characterize and evaluate the physical condition of that fuel properly by using videocamera and remote inspection techniques either at the pool side or in a hot cell facility, to assess:

— Surface corrosion;
— Pinhole leaks in fuel cladding (found, for example, by analysis of escaping gas);
— Cracking in the cladding;
— Circumferential and radial weld integrity;
— Pin spacers, dividers and other mechanical devices;
— Plastic deformation (e.g. age and radiation induced creep, and expansion).

Proper identification, characterization and evaluation of spent fuel engineered design requirements and physical condition contribute to safety because these and other key attributes form the bases and assumptions for all fuel storage and transport designs [12, 13].

4.3.1.8. Storage and transport of fresh fuel

Operators of nuclear power plants, research reactors and fuel manufacturing plants need to ensure that the storage and transport of fresh (unirradiated) reactor fuel is carried out safely as a 'routine' operation with established procedures. This can be accomplished through appropriate inspections, evaluations and physical protection. For almost all Member States, it would be considered an infrequent operation to ship fresh fuel from a nuclear power plant or research reactor back to its manufacturer or to a disposal facility; therefore the safety consequences of this activity need to be evaluated.

Similar to the inspections and evaluations performed for the transport and storage of spent fuel, shipments of fresh fuel from a facility require evaluation to assess the engineered characteristics required (i.e. identification, critical dimensions and mechanical integrity). Physical protection is provided to prevent the diversion or use of this material by unauthorized individuals. Appropriate regulatory reviews and approvals may also be necessary.

4.3.2. Accidents in fuel handling and storage

The handling of spent nuclear fuel is probably the most safety significant activity occurring during the transition period at a nuclear power plant or research reactor. The handling of spent fuel represents the highest radiological source term and highest heat load of any activity following the permanent cessation of power operations. Accidents involving spent fuel have a high potential to result in high occupational and public radiation exposure [11, 16]. Additionally, spent fuel accidents could cause the dispersal of radioactive contamination on and off the site, beyond the controlled area of the facility.

This will complicate decommissioning and final release of the site for subsequent use and will significantly increase the cost of decommissioning, will result in considerable media attention and will harm public relations.

Whenever possible, the lifting of heavy components in and around spent fuel is to be avoided, because failure of the lifting mechanism or operator error may result in an impact of the heavy load on spent fuel or its storage systems. This could result in a pipe rupture or SFP leakage, which removes the shielding provided by water, causing high radiation exposures to operators, site personnel and persons at the site area boundary. Similarly, the dismantling of structures, systems and components in the vicinity of fuel handling and storage equipment also has a potential adverse impact on fuel, because these activities may inadvertently de-energize control and instrumentation systems or may break system pipes or support structures. As such, operators need to schedule heavy lifting operations, such as those for steam generators, process vessels, pressurizers, shield blocks and shield tanks, outside the time period identified for fuel handling and storage.

Accidents involving spent fuel, within both the reactor vessel and the SFP, may include those in which fuel assemblies are dropped or fuel is uncovered. The radiological severity of these spent fuel handling accidents is, for most cases, in the short term, inversely proportional to the time after shutdown and dependent on the short lived radionuclides (principally ^{131}I) present in the fuel pin gap. Following this decay of the short lived dominant radionuclides, the radiological consequences of a spent fuel accident will remain generally unchanged, dependent on the longer lived isotopic contributions. It would require an external propellant (e.g. heat, air or liquid) to contaminate the environment with mobile particulates.

In most cases, the potential radiological severity of handling accidents with nuclear spent fuel at nuclear power plants or research reactors is greater immediately after reactor shutdown, with the fuel in the reactor vessel core, rather than if the fuel was subsequently placed in an interim or long term storage facility. In the reactor vessel, the nuclear fuel is the thermally hottest and most radioactive part, especially considering that the fuel gap activity will be dominated by the short lived iodine isotopes.

Additionally, if a fuel assembly becomes detached from the fuel handling apparatus and falls back into the vessel, the distance the assembly falls will probably be large, resulting in more damage to both the dropped assembly and those assemblies it impacts inside the core. The mitigating strategies are the use of containment (Section 4.9) to prevent the spread of airborne radioactive contaminants to the environment, sufficient radiation shielding, and proper fuel handling procedures and training.

Similarly, fuel handling accidents can occur while transferring the nuclear fuel to the SFP or from the pool to some other facility[1]. To the operators and workers involved, these accidents can be as severe as those in the reactor vessel because the gap activity is still present. However, it is also possible that these out-of-vessel handling accidents can be more severe from a wider perspective, because there may not be the defence in depth or containment structure present. Without the engineered features that make up defence in depth, radioactive contamination and radiation exposure have a potential impact on people outside the facility.

Encompassing a fuel handling accident is the larger set of accidents generally referred to as fuel related accidents. These accidents generally have precursors or initiators that may or may not be related to spent fuel but could result in adverse radiological conditions as a result of spent fuel impacts. Examples include:

— Cask or heavy load handling accidents;
— Loss of SFP cooling;
— Loss of water from the SFP;
— Loss of off-site or on-site electrical power;
— Criticality.

For insights into a very low probability fuel storage accident that could result in radiological dose consequences equivalent to those of a major at-power reactor accident, see Section 4.3.1.

4.4. DRAINAGE OF SYSTEMS

The systems and components that were used during facility operation are drained as part of the transition phase prior to the implementation of the decommissioning strategy. The processing of the resulting liquids is also part of the transition period.

Experience has shown that the drainage of systems and components can result in conditions adverse to safety, since it may cause changes in radiological or non-radiological conditions. Planning for the drainage and isolation of these systems starts when the operator of the nuclear facility determines which structures, systems and components may be placed in a storage configuration

[1] This may be a cask used for transport, a cask used for spent fuel storage or some other engineered structure or system specifically designed for fuel transport or storage.

for later use or for ultimate dismantling and decontamination. In general, the systems selected should no longer be necessary for:

(a) The safe performance of decommissioning activities;
(b) Plant security;
(c) The safe control, maintenance, processing or storage of nuclear material;
(d) The safe monitoring, processing, control or release of solid, liquid or gaseous radioactive effluents.

Then the operator determines when drainage can occur by determining what plant conditions are necessary to support drainage of the systems and components.

In addition to determining whether and when the system or component will be drained and placed into a laid-up condition, the operator evaluates the effects of the draining. For example, changes in and effects of the following are evaluated:

— Criticality;
— Dose rates;
— Cooling geometries;
— Oxidation and other corrosion mechanisms;
— Generation of radioactive gases;
— Generation of aerosols and explosive or toxic gases;
— Exposure to polychlorinated biphenyls (PCBs), lead or asbestos.

The drainage of systems can result in the spread of radioactive contamination to other parts of the facility and systems not intended to be drained. For example, if resin beds are utilized, is the chemical composition of the resin compatible with the temperature, zeta potential, affinity and particulate nature of the media being drained? Are wastes being mixed so that they represent a difficulty for packaging, transport and disposal? Is the cation to anion ratio appropriate to ensure effective resin utilization? Draining may spread radioactive contamination to other parts of the system such as low points where contamination may settle or can be drained into the drain basin or receptacle. In all cases, the drainage has to be evaluated as to its potential impact on receiving systems, on radiation monitoring procedures that need to be implemented, and on contamination control devices to be installed to monitor for local transitory radiation and contamination levels.

Drainage of circuits during the transition period may also generate high volumes of radioactive fluids, which need to be treated. In some cases, this has been especially true in facilities that have operated for many years and that may have been designed without proper construction material specifications, efficient resin filtration and purification, effective chemistry control or other mitigation strategies. These fluids may require filters to retain more radioactive material than during normal operation. Consequently, the filter dose rate may exceed the handling or transport limits. In some cases, it may be relevant to monitor the filter dose rate and to remove the filter according to a dose rate criterion instead of a pressure loss criterion. This higher than normal dose rate and different filter operation procedure may present new conditions to facility operators; therefore appropriate training needs to be conducted. For gases and aerosols, additional filtration may be necessary prior to discharge. Administrative procedures need to be developed and implemented to provide assurance that changes made to facility structures, systems and components are properly controlled, for example by:

— Updating of facility and system drawings;
— Revision of system operating procedures;
— Establishment and documentation of approval and authorization controls;
— Planning and co-ordination of scheduling, and sequencing of systems to be drained or modified, so as to have no impact on systems and processes in operation.

Engineering evaluations need to be performed to assess whether:

— Partial drainage of systems will adversely impact the functionality or operability of the remaining system or part of the system. For example, pump head, head loss and flow are evaluated to ensure that they are sufficient and within design specifications following the partial drainage;
— The drainage process may result in changes in radiation exposures due to a loss of water (i.e. fluid) shielding;
— There is an impact on intersystem relationships (e.g. heat exchanger differential pressures for leaks and liquid separation);
— The liquid processing system is of sufficient capacity to handle the large volumes of liquids;
— The locations for venting, siphon break and drain path are adequate.

Operators determine whether efforts are needed in preservation to support future storage of the system or component. Drying, atmospheric control of humidity and temperature and introduction of a corrosion inhibitor are all viable preservation techniques.

4.5. CLEANING AND DECONTAMINATION

Experience has shown that the cleaning and/or decontamination (both radiological and non-radiological cleaning and/or decontamination) of systems and components during the transition period may result in unsafe conditions if not properly conducted and implemented. Such operations may: (a) cause changes in radiological or non-radiological conditions, resulting in higher than normal exposure or unplanned exposures, or (b) generate flammable, noxious or deadly gases or conditions that may affect workers without their being aware of exposure. Planning starts when the operator of the facility determines which structures, systems and components will be cleaned and/or decontaminated.

On the basis of operational and decommissioning experience, cleaning and/or decontamination efforts have typically been undertaken to:

- Prepare the system or component for final disposal or storage;
- Separate mixed waste (radiological from non-radiological, asbestos from non-asbestos and oil from non-oil) to facilitate conditioning, disposal or transport;
- Reduce disposal requirements for a particular waste by reclassifying it from a higher to a lower waste category;
- Reduce occupational radiation exposure during dismantling activities;
- Reduce public exposure during radioactive material transport.

In some Member States, cleaning and/or decontamination efforts have been strongly influenced by the cost of such undertakings. Operators of nuclear facilities have to consider performing cost–benefit studies to evaluate the time, capital and resources needed to conduct cleaning and/or decontamination and to determine whether there is a benefit.

The operators determine when cleaning and decontamination can occur by considering the following items:

- Location and status of nuclear material within the system or component;
- Temperature, pressure, direction and flow of the cleaning and/or decontaminating reagent;
- Type and chemical characteristics of the radioactive material;
- Temperature of the systems and components to be cleaned and/or decontaminated;
- Status of containment or confinement;
- Further uses of the system or equipment;
- Value of the equipment;
- Possible hazardous interaction effects;

— Compatibility of the secondary wastes produced with the existing waste treatment and conditioning systems.

The operator evaluates the effects of the proposed action. For example, changes in the following aspects are evaluated because they could represent radiation concerns or other hazardous conditions:

— Radiation monitoring indicators;
— Oxidation and other corrosion mechanisms;
— Generation of radioactive gases (such as those from graphite reactors);
— Generation of aerosols and explosive or toxic gases;
— Worker exposure to hazardous materials such as PCBs, lead or asbestos.

4.5.1. Chemical decontamination

Of particular importance is the assessment of chemical effects on the material when it is exposed to cleaning or decontaminating solutions. In most cases, a liquid will be used as a reactant or reagent to facilitate cleaning and/or decontamination; in other cases, a gas may be used. Regardless of the phase or form of the reactant or reagent, the operator needs to evaluate the chemical reactivity between the solution and the materials of the facility.

Although chemical cleaning is well understood and utilized periodically, each application needs to be specifically evaluated as to its effects, because chemical reactivity is highly dependent on the specific facility material exposed to the reactant or reagent. For example, the following facility and system materials have exhibited accelerated corrosion or erosion or degraded integrity characteristics after being in contact with certain cleaning/decontaminating solutions:

— Weld filler material and heat affected zones of welds;
— Transition pieces between dissimilar metals;
— Base metal (exposure due to cladding defects);
— Non-metallic or non-ferritic material used in instrumentation and valves.

Similarly, if the facility uses sodium or gas cooling or some other exotic medium, the chemical reaction between the solution and any residual cooling medium needs to be evaluated.

Chemical reactivity is highly dependent not only on the temperature of the reactant or reagent but also on the temperature of the material being cleaned and/or decontaminated. In general, higher temperatures are used to support chemical cleaning and/or decontamination. Therefore, the mechanism to achieve and maintain this high temperature is evaluated and the effect of this temperature on the functions of the system, components and instrumentation is also evaluated. Particular attention is focused on temporary systems (such as piping and hoses) because these systems may not be as well insulated as the original system or may not be appropriate in the higher temperature environment.

Chemical reactivity between the reactant or reagent and the metal being processed will often result in the formation of other chemical products. On the basis of experience from particular cases, these secondary chemical reactions have included the formation of hydrogen gas (explosive) and chlorine and carbon monoxide (both poisonous) as well as other noxious, flammable or deadly gases. Collection, sampling and mitigating procedures need to be developed to ensure occupational and environmental protection.

4.5.2. Spread of radioactive contamination during cleaning or decontamination

Cleaning and/or decontamination may spread radioactive contamination to other parts of the system such as low points where contamination may settle. These situations may lead to high radiation levels owing to the formation of radiation hot spots. Additionally, while the decontamination process will reduce the level of beta–gamma radionuclides, there have been instances where the alpha contaminant has not been reduced, for example at the Würgassen nuclear power plant in Germany. Radioactive contamination may also be transported to drain basins or filters, purification components and support piping. This spread of radioactive contamination can be a radiological hazard because concentration levels may be higher than those experienced during reactor or facility operation and the operators may not be aware of this situation. Therefore, prior to beginning cleaning and/or decontamination activities, the following aspects have to be considered:

— Identification and assessment need to be carried out of the possible parts of the system where contamination may settle, as a product of cleaning and/or decontamination activities;
— Monitoring and detection devices need to be installed and operated;
— Contingency procedures for spills and emergency situations need to be implemented;
— Evaluation of the effects of the cleaning and/or decontamination waste products on the normal waste processing system needs to be performed;
— Control devices need to be installed to shut down the operation or mitigate leaks;

— Containment devices (temporary damming material, walls, sumps or absorbents) need to be used if leaks develop.

4.5.3. Administrative procedures

Administrative procedures should be developed and implemented to provide assurance that cleaning and/or decontamination can be conducted safely without undue radiation exposures or impact on the environment. For example:

— Facility and system drawings are modified to indicate any temporary equipment connections;
— System operating procedures are revised;
— Approval and authorization controls are established and documented;
— Scheduling and sequencing of systems are co-ordinated so as not to have an impact on systems and processes in operation.

Clear criteria should be developed to determine when the cleaning and/or decontamination has been completed or has to be stopped. This is an important safety consideration because it: (a) facilitates the removal of a harsh chemical reagent or reactant from a system that is not designed to confine it; (b) stabilizes system conditions; (c) stops or slows the removal of base material by erosion, corrosion or chemical reactivity, thereby preventing possible leakage and failures; and (d) reduces the amount of radioactive waste. For example, the cleaning and/or decontamination process could be halted on the basis of:

— Contaminants and/or base material removed;
— Radiation dose or contamination levels;
— Purification and/or filtration limits;
— Time.

Following the cleaning and/or decontamination process, the operator will determine whether the efforts they have made were effective and whether preservation efforts are needed to support future decommissioning stages such as safe enclosure. Drying, atmospheric control of humidity and temperature and introduction of a corrosion inhibitor are all viable preservation techniques.

4.6. ESTIMATES OF THE INVENTORY OF RADIOACTIVE MATERIAL

Following decontamination and drainage of circuits it is important to revalidate any earlier estimates of the inventory of radioactive material (activity and remaining contamination) and also of other material such as conventionally toxic material, which may pose hazards during later decommissioning activities. These inventory estimates generate a reference level of activity on which future decommissioning operations are based. Numerous techniques are available, including sampling of the contamination and subsequent measurement, measurement of the radiation fields with comparison against standards and calculation using computer codes, which are widely used for the estimation of the activity of radionuclides in reactor systems. This process is broadly termed characterization and allows forward planning for:

— Radiological protection of workers, the public and the environment;
— Waste classification;
— Selection of dismantling techniques (manual, semi-remote or fully remote) and decontamination processes;
— Estimation of cost.

An appraisal of the overall characterization process for reactors that have been shut down is given in Ref. [17].

4.7. CONDITIONING AND REMOVAL OF OPERATIONAL WASTE

The conditioning and removal or proper storage of operational waste is important during the transition period because it has the potential to adversely affect safe decommissioning. This operational waste includes combustible materials such as rags, wood, oils, plastics, anti-contamination clothing, gloveboxes and other items used during facility operation. It also includes any liquid waste drained from the systems or solid waste generated as part of the transition process. Removal of most operational waste prior to implementation of the decommissioning strategy is recommended in IAEA Safety Standards [4–7].

Experience has demonstrated that if a waste management plan (evaluating waste volume, variety, composition, treatment and conditioning) is developed before shutdown, there is a greater likelihood that operational waste will be adequately conditioned, on-site storage will be safe and waste transport will not affect other activities. Early planning will also provide assurance that decontamination processes will not generate waste that cannot be accepted at storage or disposal facilities.

Waste removal operations undertaken during the transition period are normally considered part of the operational activities. These operations may increase the volume and variety of the generated waste. Temporary on-site storage should take into consideration the following aspects:

- Response to physical security threats,
- Response during radiological or non-radiological facility emergencies,
- Fire detection and suppression capabilities,
- Facility operator activities and monitoring of system performance,
- Safety system operation and availability,
- Exposure of workers,
- Containment of radioactive contamination by reducing the potential for the spread of contaminants.

In some Member States, piping and system heat insulation is removed early in the transition period to improve the accessibility of equipment. Although this practice may generate very high volumes of low level radioactive waste, asbestos or insulating material requiring temporary storage, it has been shown that the benefits of early removal have contributed to dose and cost savings in the long term because the systems identified for decommissioning are more accessible. Similarly, because the risks associated with non-radiological hazards generally do not decrease with time, the removal of conventional waste may result in an overall decrease in risk to facility operators and workers conducting eventual decommissioning activities. Consequently, in some Member States, waste containing asbestos, oils or other chemicals is removed as soon as possible from buildings containing radioactive material. After waste removal, the fire protection system needs to be assessed according to the remaining risk and some fire protection features may be retired or require modification.

Drainage of circuits may generate new varieties of waste, which may be different (in volume or chemical composition) from that experienced during facility operation and therefore be unfamiliar to operators and maintenance personnel. Waste that may be of concern includes:

- Sodium,
- Heavy water,
- Mixed radioactive waste,
- Oil laden asbestos,

— Alpha contaminated waste,
— Sludge tainted with PCBs and radioactive contamination.

It is important that waste in temporary storage does not compromise the structural stability or integrity of buildings. For example, waste in temporary storage must not affect compliance with maximum floor load or fire safety. Additionally, temporary storage of waste must not affect safety systems and structures, or prevent an operator from performing assigned duties. Identification, segregation and monitoring need to be carried out to provide additional assurance that operational waste will not affect decommissioning activities and that it can be safely stored, transported and disposed of.

When the safe enclosure option is chosen, conditioned waste may be stored inside the containment of nuclear power plants that have been permanently shut down, but this is not preferred. An engineering and safety evaluation is required to assess this decision. Similar to the previous discussion, this evaluation would assess fire loading, conduct of operator duties, emergency response and physical protection requirements.

4.8. RETIREMENT, RECONFIGURATION AND PLANNING FOR THE PROVISION OF NEW SYSTEMS

During the transition period it may be decided that a number of systems will not be required any longer, some may require modification and others may be needed for later stages of decommissioning. Retirement or reconfiguration of systems will be strongly influenced by the progress of actions to be taken during the transition period. Additionally, new systems may also be required. In general, systems can be categorized as follows:

— Those that are required to continue to operate or need to be modified to support decommissioning,
— Those to be removed,
— Those to be installed to facilitate decommissioning.

Other recommendations and guidance on controlling activities relating to modifications of nuclear power plants in order to reduce risk and to ensure that the configuration conforms to the approved basis for granting a nuclear power plant operating licence are given in Ref. [18].

4.8.1. Systems to support decommissioning

The systems necessary to support the eventual decommissioning activities need to be identified, justified, recorded and/or modified if necessary. For safety systems or systems operating in areas containing radioactive material, this process is supported and justified by a safety assessment. Appropriate redundancy, as required in the design phase, needs to be available (e.g. in the electrical supply, fuel element cooling, ventilation system and instrumentation).

The systems or parts of systems that have to be available in the transition period need to be periodically tested and inspected, and maintenance carried out as necessary. Operating limits and conditions, operating and maintenance procedures, and test, inspection and emergency procedures need to be updated and recorded to reflect the changing condition of the facility. For example, existing ventilation systems may require upgrading or modification to support future decommissioning activities.

If the immediate dismantling option is chosen, additional prefiltration may be necessary in the ventilation systems to cope with the increased dust loadings which are likely to be present whenever thermal cutting techniques are employed; otherwise standard high efficiency particulate air (HEPA) type filters will be easily ‘plugged’ and require very frequent and dose intensive replacement. Additionally, radiological monitoring equipment may need to be modified or replaced, in lieu of the systems used during operations, to better suit the decommissioning process. In general, such equipment needs to be identified to ensure that the monitoring capability is compatible with the radioactive inventory remaining in the facility.

Some existing systems (e.g. the main crane) may be either temporarily shut down or preserved for future use during decommissioning. These systems are required to be properly conditioned, protected and inspected, if necessary, during the transition period. Appropriate engineering evaluations need to be performed and startup procedures prepared before putting the equipment or system back into operation when needed.

4.8.2. Systems to be removed

Some existing systems will be removed and the consequences of their unavailability on the necessary remaining systems will need to be assessed (e.g. removal of electrical supplies may result in disconnection of some redundant systems or affect retained systems). The systems removed need to be isolated from the operating systems or from the environment if they contain radioactive material. Systems need to be removed or strengthened if they have a potential to damage the operating safety systems or structures by falling down or collapsing during seismic or other external events.

4.8.3. New systems to facilitate decommissioning

New systems and facilities will need to be planned early in the pre-shutdown phase to support, for example, waste management by the construction of waste conditioning and treatment facilities, together with interim storage facilities if required. Additionally, planning for dismantling of equipment is to be carried out early with the identification (and development or modification of existing technologies, if required) of systems and equipment, to carry out the reduction in size of facility equipment. As mentioned above, new power sources may need to be constructed to support the decommissioning phase.

4.9. CHANGES TO CONFINEMENT BARRIERS

4.9.1. General considerations

A multilayer (defence in depth) system of provision for protection and safety commensurate with the magnitude and likelihood of the potential exposures involved is applied to nuclear facilities. It includes the utilization of confinement barriers to prevent and control the spread of radioactive contamination.

These barriers may be the facility structures, systems and components such as piping, tanks, hot cells and concrete structures that contain or encapsulate the radioactive material. The integrity of these barriers is maintained and provisions established to ensure their continued integrity throughout the course of decommissioning, irrespective of which option is selected. Confinement barriers need to be subject to effective design control requirements such as procedures, drawings and specifications to provide adequate assurance that maintenance or dismantling activities adjacent to or in the vicinity of confinement barriers will not adversely impact their functionality.

In the case where a confinement barrier is not directly associated with the facility, such as canisters, casks or other containers associated with waste packaging and transport, it is usual for the supplying contractor or manufacturer of the waste transport and storage package to conduct these engineering evaluations on the basis of the requirements of existing regulations which may include pre-identified accident, transient and environmental conditions. In this latter case, it is incumbent upon the operator to ensure through evaluation that the intended use of the supplied item is within the accident, transient and environmental design specifications furnished by the supplier.

Because the analysed postulated accidents may change following the permanent cessation of operation of the nuclear facility and permanent removal of all nuclear and other radioactive material from the facility, containment requirements may also change. There are instances where containment requirements (in the historical sense) no longer apply during the conduct of decommissioning because the containment regulations and design basis requirements were focused on the operational phase. For example, the design bases associated with leak rate testing of a containment may no longer be applicable during decommissioning because there is no design basis accident that could result in a pressure characteristic requiring containment.

However, operators of nuclear facilities are not exempt from adequately controlling and preventing the spread of radioactive material (through the use of confinement systems such as gloveboxes, ventilation under reduced pressure, barriers and other engineered features). In some Member States, radiation protection measures and environmental monitoring and sampling are still required at levels equivalent to those during facility operation. In the USA, some decommissioning licensees have voluntarily decided to maintain their containment systems for the control of radioactive materials during spent fuel handling and the removal of major radioactive components, to provide substantial assurance that these activities conducted during the transition period will not be detrimental to the environment if radioactive contaminants are released.

4.9.2. Safety analysis

Formal safety analysis needs to be carried out to justify any changes to confinement barriers or associated systems. Changes to containment barriers could be necessary to simplify the decontamination and dismantling of structures, systems and components, provide consistency with the actual radiological risks present within the facility, or facilitate working conditions or removal of equipment for disposal. Because changes to containment barriers could have a strong impact on safety and on the operability of systems and components, such changes are assessed and justified by safety analysis.

The analysis has to take into account both internal risks (e.g. fire, explosion, load handling, and leakage of vessels and systems) and external risks (e.g. earthquake, flooding, aircraft crash, conventional industrial accidents, intrusion and severe climatic conditions), as required by the regulatory body. Special attention needs to be paid to the impact of external risks on the facility, because buildings and structures may have weakened structural integrity owing to ageing or modification.

An example is a situation in which polar cranes located within the primary containment of a pressurized water reactor share load bearing members with the containment structure itself. If the containment is modified to facilitate the removal of large components, the change on the load bearing characteristics of the containment structure may adversely affect the load capacity of the polar cranes. In addition, it has been observed that cuts in floors to facilitate equipment removal can seriously compromise floor loading capability. This is important to safety when modifications are made adjacent to or in the vicinity of the SFP, the reactor vessel or the foundations of large components.

Additional barriers are installed if the risks increase due to a planned work activity. Furthermore, barriers could be modified to specifically contain or confine high risk areas from other sections of the site or facility. This strategy could be effective during high pressure, high temperature decontamination operations.

4.9.3. Exposure of personnel

During transition phases, areas within containment and/or confinement barriers may be open for access to personnel which were previously secured during facility operation. These areas need to be assessed to ensure that proper atmospheric controls are present to support human activities. Effective radiation monitoring and personnel exposure controls have to be established based on the conditions prevailing during the activity. This takes into account transient radiation levels that could result from the modification or dismantling of structures, systems and components, system flushes and decontamination, or changes to installed or temporary radiation barriers consisting of water, metal, concrete or plastic materials.

Furthermore, dismantling or changes to structures and ventilation systems may represent unanalysed changes in air pathways, which can significantly affect radiation dose modelling. Appropriate controls need to be the subject of formal procedures and to be implemented to account for changes. Installation of additional radiation monitoring devices needs to be considered and personnel need to be trained to recognize that decommissioning has a high potential to increase radiation exposure or to give rise to unanalysed pathways for the release of radiation.

To maintain adequate or appropriate levels of leaktightness or control, work procedures and personnel dose estimates need to be established for all activities involving modification of penetrations passing through or entering containment or confinement barriers or their related subsystems. Strategies and procedures also need to be implemented to prevent and/or identify unmonitored pathways for the release of radiation (e.g. through access doors, air locks and walls) throughout the transition, since this is the time when the majority of site and facility changes will be made.

4.9.4. Considerations for long term storage

The behaviour of containment and confinement barriers when exposed to external phenomena is assessed with account taken of the current source term and internal and external risks. The external events may include fire, earthquake, flooding, low external temperature and high wind. These factors become more important as changes are made to the contamination barriers over the course of the transition period.

During the transition period, the likelihood of an unintended or unplanned radiological release is less than during facility operation because the high pressure and temperature conditions associated with facility operation no longer prevail. In addition, if a majority of the facility systems are in an inactive static condition, the radiological source term continues to decrease with the decay of radioactive isotopes and, for some facilities, there may be gaseous to liquid or liquid to solid phase changes associated with the media containing the radioactive material, thereby simplifying its control.

In either case, the safety assessment must take into account these changes, resulting in a decrease in the requirements associated with containment and confinement structures and systems. Specifically, the necessity of containment negative pressure requirements, elevated release pathways and dilution methodologies may no longer be needed. The removal of such containment and confinement controls offers the opportunity to increase accessibility, improve working conditions, enhance the scheduling of activities and facilitate the dismantling of additional structures, systems and components. This same evaluation could also be broadened in scope to justify changes in methodology and criteria specifications for system operation, maintenance, testing and periodic inspection, leading to further gains in efficiency.

4.10. OTHER ACCIDENTS POSSIBLE DURING THE TRANSITION PERIOD

This section provides a brief summary of some other possible radiological and non-radiological accidents that could occur during the transition period. These accidents are similar to those that may occur during facility operation;

however, this list is not all-inclusive and is not representative of all nuclear facilities. The important point to understand is that safety considerations should be applied not only to facility operation, fuel, waste storage and handling or transport but also to other activities.

Other accidents involving radiation may occur during the transition period that could result in adverse radiological conditions. These accidents could involve solid, liquid or gaseous radioactive waste and the processing, packaging and shipping of such waste. Specifically, rupture of process piping and tanks containing radioactive material may occur. In particular, the likelihood that such accidents occur may increase during the transition period because of all the activities that then take place in and around the nuclear facility. Also, because the structures and buildings are changing as a result of decommissioning, there is a high probability that new or previously not considered radiological effluent release pathways may be created. These pathways may not be monitored with appropriate instrumentation and alarms to warn of adverse impacts on the environment.

Related accidents include, but are not limited to:

— Accidents relating to decontamination, such as leakage of the chemical reagent used for decontamination;
— Accidents relating to radioactive material handling, such as falling containers and spillage of radioactive material;
— Accidents relating to dismantling, such as falling of heavy components;
— Loss of high efficiency air filtration;
— Leakages of radioactive liquids, and gaseous or solid waste processing system leaks;
— Failure of containment or enclosure;
— Spent resin accidents;
— Vacuum filter bag ruptures;
— Unauthorized activity.

On the basis of this list and the discussions on fuel handling accidents, the types of accidents and malfunctions of equipment associated with the transition period are not entirely different from those of a facility in operation. However, the analysed accidents and equipment malfunctions evaluated and documented in site specific safety analysis reports, licensing basis documentation or other regulatory based documentation are different, in part, because the operational phase of the plant is changing. The activities that occur during decommissioning are similar to activities such as decontamination and equipment removal that are commonly conducted during maintenance outages at operating facilities. However, during decommissioning such activities may occur more often than similar activities during operation. Therefore, the accidents that may result could have a greater probability of occurrence during decommissioning than during facility operation.

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