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No. 50

Decommissioning Strategies for Facilities Using Radioactive Material

IAEA

International Atomic Energy Agency

DECOMMISSIONING STRATEGIES FOR FACILITIES USING RADIOACTIVE MATERIAL

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FOREWORD

The planning for the decommissioning of facilities that have used radioactive material is similar in many respects to other typical engineering projects. However, decommissioning differs because it involves equipment and materials that are radioactive and therefore have to be handled and controlled appropriately. The project management principles are the same. As with all engineering projects, the desired end state of the project must be known before the work begins and there are a number of strategies that can be used to reach this end state.

The selection of the appropriate strategy to be used to decommission a facility can vary depending on a number of factors. No two facilities are exactly the same and their locations and conditions can result in different strategies being considered acceptable. The factors that are considered cover a wide range of topics from purely technical issues to social and economic issues. Each factor alone may not have a substantial impact on which strategy to select, but their combination could lead to the selection of the preferred or best strategy for a particular facility.

This Safety Report identifies the factors that are normally considered when deciding on the most appropriate strategy to select for a particular facility. It describes the impact that each factor can have on the strategy selection and also how the factors in combination can be used to select an optimum strategy.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Globally, there are thousands of facilities[1] using radioactive materials that will require some form of decommissioning[2] over the next forty-five years [1]. These facilities range from large complex facilities (such as nuclear power plants and reprocessing facilities) to simple facilities (such as research and university laboratories). Each of these facilities will have particular concerns, but the basic strategies that will be used to complete the decommissioning process will be the same.

The selection of a strategy for decommissioning a facility has an impact on almost all phases of the planning and implementation process. The determination of the strategy can have a significant impact on safety, waste volumes, cost, staffing and social issues. Selecting the best decommissioning strategy can be complex when all factors are considered.

Over the years, several methods have been used for describing the decommissioning strategies that are available to the owner of a facility. In the past, one of those methods included a system of referring to various decommissioning strategies as either stage 1, 2 or 3. This was not very convenient because the definitions of the various stages were open to interpretation and they were mostly tailored to nuclear power plants. Since 1996, this nomenclature has not been used in IAEA publications; instead, the approaches are identified by three decommissioning strategies: (1) immediate dismantling, (2) deferred dismantling and (3) entombment. These strategies are, in principle, applicable to all facilities. However, some may not be appropriate owing to political concerns, safety or environmental requirements, local conditions or financial considerations.

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[1] A facility is defined as a building and its associated land and equipment in which radioactive material is produced, processed, used, handled or stored on such a scale that consideration of safety is required.

[2] Decommissioning is defined as those administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility.

1.2. OBJECTIVE

The objective of this Safety Report is to provide information that can be used by decision makers to decide on which decommissioning strategy is best for their facility. The report can be used by owners and operators of facilities, project managers and regulatory bodies. It reiterates the standard definition of the acceptable decommissioning strategies.

1.3. SCOPE

The information provided in this Safety Report applies to all facilities using radioactive material, with the exception of waste disposal facilities. However, it does apply to support facilities related to waste disposal activities such as packaging, processing, handling or conditioning.

1.4. STRUCTURE

The main text of this Safety Report is organized as follows. Section 2 describes in detail the three main decommissioning strategies that are available. Section 3 identifies the factors that need to be considered during the strategy selection process and how they can be used in combination to select a preferred or optimum strategy. Section 4 discusses the advantages and disadvantages of each strategy and Section 5 provides a summary that is based on the presented information. An example framework of a process for selecting a decommissioning strategy is provided in the Appendix.

2. DECOMMISSIONING STRATEGIES

2.1. GENERAL

The principle objective of decommissioning is to place a facility into such a condition that the decommissioned facility poses no unacceptable risk to the public, the workers or the environment. In order to ensure that at the end of its life the risk from a facility is within acceptable bounds, some action is normally required. If facilities were not decommissioned, they could degrade and potentially present an environmental radiological hazard in the future. Simply abandoning or leaving a facility after cessation of operations is not considered to be an acceptable alternative to decommissioning.

The overall purpose of a decommissioning strategy is to achieve the final end point of the decommissioning programme. Therefore, a timely, cost effective programme, that maintains high standards of safety, security and environmental protection, needs to be developed. The key objectives associated with the development and implementation of decommissioning strategies are:

(a) To ensure the continued safety of the public and the workforce and the protection of the environment;
(b) To reduce hazards through proper planning of associated tasks;
(c) To achieve an appropriate balance in the use of environmental, social and economic resources, both now and in the future;
(d) To remove facilities, material, equipment and sites from regulatory control wherever possible.

In addition, the following are applicable in the development of strategies and plans for decommissioning:

(a) Strategies are compliant with national regulations and take account of the views of interested parties and industry issues.
(b) Decommissioning is undertaken as soon as it is reasonably practicable to do so, taking account of all relevant factors.
(c) Identification of preferred strategies is conducted in a systematic, consistent and auditable manner using best available scientific, engineering and economic knowledge and taking account of social and political factors, risk and uncertainty.
(d) A wide range of options[3] is considered, but priority is given to options that have already been tried, rather than employing 'first of a kind' approaches.
(e) A flexible approach to strategy development is maintained, so as not to foreclose options prematurely, thereby maximizing the capability to

[3] Options are discrete variations of the possible approaches to achieving a given decommissioning strategy (e.g. length of time for deferred dismantling period). Such options are considered as part of the overall decision making process on decommissioning strategies.

accommodate changes related to, for example, technical and regulatory developments or the availability of waste disposal facilities.

(f) Strategies and plans are reviewed regularly during the course of development and implementation of the decommissioning project to ensure that they continue to meet the end state requirements, to learn from experience and to take account of any changes in the initial assumptions and of emerging technologies.

(g) Throughout any decommissioning deferral period, any remaining radioactive waste is managed and a passively safe state of the facility is maintained in order to minimize the need for control and safety systems, maintenance, monitoring and human intervention.

Appropriate knowledge and records also need to be retained and maintained throughout the decommissioning period. This is particularly applicable where any decommissioning activity is to be deferred.

The chosen strategy for decommissioning may vary from site to site and from facility to facility. All decommissioning strategies involve some degree of dismantling and the generation of waste that will require proper management. As noted previously, there are three general strategies for decommissioning facilities: (1) immediate dismantling, (2) deferred dismantling and (3) entombment. These strategies will be discussed in the following paragraphs.

2.2. IMMEDIATE DISMANTLING

Immediate dismantling is the strategy in which the equipment, structures, components and parts of a facility containing radioactive material are removed or decontaminated to a level that permits the facility to be released for unrestricted use as soon as possible after permanent shutdown. In some cases, where unrestricted release is not feasible, the facility may be released from regulatory control with restrictions imposed by the regulatory body. The implementation of the decommissioning strategy begins shortly after permanent termination of operational activities for which the facility was intended, normally within two years. Immediate dismantling involves the prompt removal and processing of all radioactive material from the facility for either long term storage or disposal. Non-radioactive structures may remain on-site. Immediate dismantling is the preferred decommissioning strategy [2].

2.3. DEFERRED DISMANTLING

Deferred dismantling is the strategy in which the final dismantling of the facility is delayed and the facility is placed into long term storage where it is maintained in a safe condition. This strategy may involve some initial decontamination or dismantling, but a major part of the facility will remain for a certain time period in a caretaker mode. This time period might range from a few years to over 50 years, after which time the decommissioning process will be completed and the facility can be released from regulatory control. The deferred dismantling option is often used at multifacility sites when one or more of the facilities are shut down while others continue to operate. This is especially true of facilities that share some common systems.

2.4. ENTOMBMENT

Entombment is the strategy in which the radioactive contaminants are encased in a structurally long lasting material until the radioactivity decays to a level that permits release of the facility from regulatory control. The fact that radioactive material will remain on the site means that the facility will eventually become designated as a near surface waste disposal site and criteria for such a facility will need to be met.

3. ISSUES FOR CONSIDERATION

3.1. GENERAL

This section is intended to highlight the various factors that are considered when formulating a decommissioning strategy.

The operating organization[4] is required to develop a decommissioning plan for each facility [2]. It is necessary to initiate planning with an initial or preliminary decommissioning plan in which the various strategic options are

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[4] The term ‘operating organization’ refers to any organization or person applying for authorization or authorized to operate an authorized facility and responsible for its safety. This might be the owner of the facility.

discussed and evaluated. If this preliminary plan is not produced during the construction and licensing phase of a new facility, it needs to be produced before final shutdown in order that the appropriate strategy for decommissioning can be formulated and agreed.

The decommissioning strategy of a facility takes into account the characteristics of the site where the facility is located. The capabilities of the other facilities (if any exist on-site, either in operation or in shutdown mode) may be used, as well as the experience of the site's personnel. These considerations may enrich the study and lead to optimization of the preferred strategy.

The choice of a decommissioning strategy is strongly influenced by major issues such as availability of adequate funding, availability of radioactive waste storage or disposal facilities, cost of waste disposal, expected use of the site after decommissioning, available technology and experience in using it, spent fuel management options, continued operation and strategies for decommissioning of other facilities at the site, the need to protect the health and safety of the public and interested party opinion. An operating organization does not need to consider only one decommissioning strategy, but may initially consider all strategies. Indeed, although evaluation of the prevailing factors could clearly indicate one strategy, constraints and overruling factors may occur in practice and these may necessitate adoption of a combination of strategies or exclusion of the first choice. For example, after operations permanently stop at a facility, an operating organization could use a short deferred dismantling period and eventually finish the decontamination and dismantling processes at a later date. It is even possible that after a long period of deferred dismantling, an entombment strategy may be adopted, if an appropriate safety assessment can be made, followed by a revision of the decommissioning plan and approval by the regulatory body.

3.2. TYPE OF FACILITY AND EXTENT OF CLEANUP NECESSARY

The type of facility, its past functions and the extent of cleanup needed (e.g. soil/sediment, groundwater) will have a major impact on the strategy selected. The facilities can be categorized by residual radionuclides according to the activities that were performed, the size or the location of the facility and its relationship with other facilities. During the operating life of a facility, operational incidents may have occurred which may or may not have been adequately documented. A thorough review of all records is needed using experienced operating staff to supplement missing data. A good knowledge of the operation of the facility will have a crucial influence on the selection of the appropriate strategy, as it will form a basis for waste, dose and cost estimates and any special procedures or techniques that might be required.

3.2.1. Immediate dismantling

Immediate dismantling is the preferred option except when justification exists for alternative options. For a facility that only used intact sealed sources, decommissioning can be achieved by certifying that all previously possessed sealed sources have been transferred to an authorized recipient (such as the supplier). A facility that contains long lived isotopes such as uranium, thorium, or transuranic radionuclides (such as a fuel cycle facility, uranium recovery facility, reprocessing facility or enrichment facility) will not benefit significantly from the radioactive decay of the residues owing to their extremely long half-lives and therefore immediate dismantling is appropriate.

Small facilities that are incorporated as part of a larger non-nuclear complex (such as a university laboratory or research reactor) are also recommended for immediate dismantling. Often these facilities fall into disrepair once the originally intended programme has been completed. Priorities are shifted to other programmes and personnel might be reassigned. In many cases space is a limiting factor at some of these facilities and the decommissioned area is wanted for other purposes. If it is not decommissioned in a timely manner, there is a possibility that cross-contamination and unnecessary exposure of workers and the public will occur. Large facilities are more visible and may draw the attention of the general public and this will be a reminder that a liability is still present.

3.2.2. Deferred dismantling

One of the advantages of placing a facility into deferred dismantling mode is to allow the decay of short lived radionuclides. For a facility that used material containing only relatively short lived isotopes, placing it in a safe storage configuration for a few months or years may reduce any residual radioactivity to levels that are below the clearance values. If more than one facility is located on a site, it may be more beneficial to place the oldest facilities into a deferred dismantling status until the remaining facilities are closer to permanent shutdown. This will allow the decommissioning workforce to move from one facility to the next, permitting more effective decommissioning and a more efficient use of the personnel.

3.2.3. Entombment

Entombment is not relevant for a facility that contains long lived isotopes because these materials are not suitable for long term surface disposal. Consequently, reprocessing facilities, fuel fabrication facilities, enrichment facilities or facilities that use or process thorium or uranium would not be appropriate for entombment. However, entombment could be a viable option for other nuclear facilities containing only short lived or limited concentrations of long-lived radionuclides, i.e. in order to comply with the site release criteria.

3.3. DESIRED END STATE

An important consideration when selecting the decommissioning strategy is the desired end state[5] of the facility following completion of the decommissioning. The preferred end state would be to achieve a situation whereby the site is released for unrestricted use (with or without buildings) or a situation whereby it may be released for restricted use. Other end states could involve partial release of a site or release of a site under restricted conditions to control its future use. The foreseen end states for the three different strategies are shown in Fig. 1.

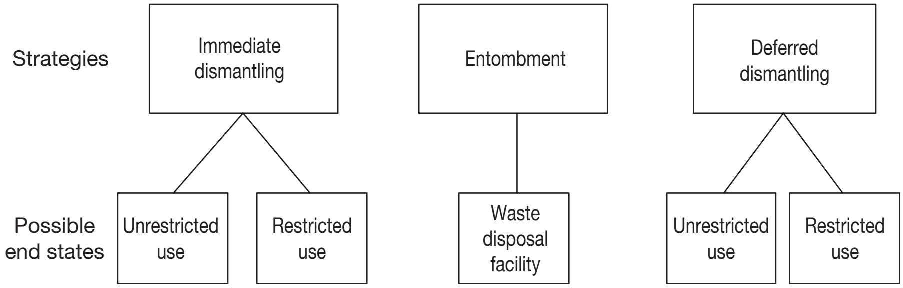

FIG. 1. Possible end states for the use of areas in the three decommissioning strategies.

[5] The end state is defined as a predetermined criterion defining the point at which a specific task or process (i.e. decommissioning) will be considered complete. The actual end state is tailored to address the safety and environmental needs of each situation.

3.3.1. Immediate dismantling

Immediate dismantling is appropriate for any suitable desired end state of the site. Immediate dismantling allows reuse of the site in a more timely manner than alternative strategies.

3.3.2. Deferred dismantling

Deferred dismantling may be a viable option for facilities seeking any desired end state. In addition, deferred dismantling may be an appropriate strategy for sites where there is a strong probability that the desired end state could change in the future as a result of cost, economic or social factors.

3.3.3. Entombment

Since the end state of an entombed site is equivalent to a waste disposal site, the end state cannot satisfy unrestricted release conditions. An entombed site will need some measure of monitoring and control well into the future, which will be undertaken by either the operating organization or the regulatory body. Since the area required for an entombed facility is normally less than that of the original facility, the remaining area of the site could be used for other purposes, including industrial applications. This option may also be considered if a waste disposal site does not exist within a Member State; the waste disposal facility could be created at the facility site. Such a new waste disposal facility would be of the 'near surface disposal' type that could receive radioactive waste from other sites, but only waste containing short lived radionuclides.

3.4. STATUS OF NATIONAL POLICIES AND REGULATORY INFRASTRUCTURE

It is essential that policies be in effect and that a suitable regulatory framework for decommissioning be established. In countries where decommissioning has never been undertaken, it is possible that regulations relating to decommissioning do not exist or that regulators are not adequately trained in the special requirements for decommissioning. The infrastructure needed to support decommissioning activities needs to be able to develop and to enforce the laws and regulatory requirements. This is the case with any operating facility. Where laws and regulations pertaining to decommissioning do not exist within a country, international standards can be used.

It is recognized that different regulatory expertise may be needed and this might have an impact on the strategy selected, as discussed below. Typical regulatory body activities consist of the issuing of regulations, review and approval of decommissioning plans, oversight and inspection, and communication with the public.

Typical regulatory related activities to be performed by the operating organization consist of the preparation of plans and reports and ensuring compliance with all licences and regulations. These activities include:

(a) Disassembly of the process systems or major components;
(b) Site clearance surveys to support licence termination;
(c) Generation and movement of large quantities of radioactive material;
(d) Increased attention to non-radiological safety arising from increased worker safety issues associated with dismantling and demolition;
(e) Verification to ensure that the operating organization is able to complete decommissioning (and will not allow the facility to be placed in an unsafe condition owing to lack of funding, deficiency in human skill, etc.).

One major factor that is considered in addition to the regulatory infrastructure is the overall nuclear infrastructure within the country. If the country has a substantial nuclear programme, it is likely that academic institutions and industry will continue to provide properly educated personnel who can provide the required expertise in the future. This situation might allow the deferred dismantling option to be chosen. If there is a very limited programme within a country (i.e. only one research reactor or limited research and medical facilities), the academic institutions might decide that maintaining a nuclear engineering or radiation protection training programme is not cost effective and may drop the programme or courses from the curriculum. This means that people trained in nuclear safety may not be available in the future, giving greater weight to immediate dismantling or entombment as the preferred option. However, in cases where deferred dismantling is chosen, a regulatory body may choose to use consultants or specialist contractors to satisfy these needs.

The regulatory control of decommissioning can be achieved by issuing a single licence or authorization, or separate licences or authorizations for individual phases of the decommissioning activities, or through direct control by a regulatory body. Whichever method is adopted, it is important that this control be established and that the time-frame allowed to obtain a licence or approval be realistically estimated. The different strategies may require very different timescales, particularly to gain acceptance for long periods of deferral or entombment. For all strategies, resolving the problems of waste management and spent fuel disposal may involve significant challenges, delays and costs. It is unlikely that a licence for any of the strategies will be granted until these problems have been resolved.

3.4.1. Immediate dismantling

Immediate dismantling permits the regulatory body to effect a direct transition from regulating facility operations to regulating decommissioning. The total length of time from facility shutdown to release of the site is such that, although there will be regulatory staff turnover there is an opportunity to provide continuity in the regulatory body's staff.

The regulations for immediate dismantling will need to be available in order to allow the approval of the decommissioning plan and the implementation of the decommissioning activities. Clearance regulations will also be needed prior to release of any material or facilities, including land, from regulatory control [3]. Clearance criteria will be agreed between the operating organization and the regulatory body on a case-by-case basis. However, a lack of regulations (e.g. on clearance of materials) could lead to inaccurate cost estimates for the decommissioning.

3.4.2. Deferred dismantling

In the case of a small national nuclear programme, deferred dismantling will normally result in the regulatory body replacing its staff during the long term enclosure period of the facility. With the exception of regulatory controls required during the deferred dismantling period and the periodic review of the decommissioning plan, there is essentially no need to maintain large regulatory staffs who are knowledgeable regarding decommissioning practices. It can be assumed that an essentially 'new' regulatory staff would need to be hired and trained prior to the end of the long term storage period.

The deferred dismantling strategy will also require an essentially complete set of regulations similar to those needed for immediate dismantling. There are no significant differences in regulations between deferred dismantling and immediate dismantling, with the exception of those regulations necessary to control long term surveillance and monitoring activities.

3.4.3. Entombment

The entombment strategy has many similarities to the immediate dismantling strategy insofar as it affects the regulatory body. The regulatory staff will initially make the transition from operations to decommissioning. However, with this strategy, the regulatory staff will also have to be knowledgeable with regard to the requirements for near surface disposal facilities [4], since this is the end point of the decommissioning project. Once the decommissioning is completed, the staff will have a disposal site to regulate. There are limited international practice precedents for entombing facilities.

The main difference in the regulatory requirements for entombment will be that in addition to the decommissioning regulations being necessary there will also need to be regulations for the near surface disposal of radioactive waste. Since it is unlikely that the site of the operating facility was evaluated to serve as a location for a near surface disposal site, such an evaluation may be conducted as part of the approval process for the entombment strategy.

3.5. SPECIFIC SAFETY ISSUES

Worker, public and environmental safety are important in completing a decommissioning project. All decommissioning strategies require the same attention to safety. Any strategy that allows continuity in the trained facility staff that will conduct decommissioning activities will result in a higher confidence that a safe project will be achieved. Strategies that require dismantling work to be done early on in the project permit the use of experienced facility staff, where appropriate, but require that the work be done in higher radiation level conditions, since there is less benefit from radioactive decay. Those strategies that postpone dismantling activities until after a long term enclosure period, as with a deferred dismantling strategy, permit the work to be performed possibly in lower radiation level conditions, but may require that the work be done by a staff not experienced with facility operations and maintenance activities.

Most importantly, all strategies need to consider the safety of workers, the public and the entire site. On the one hand, decommissioning activities at one facility will not be allowed to have a negative impact on the safety of another facility, but on the other hand, a global study of decommissioning implementation options, including the capabilities of other facilities on the site, could lead to better safety options.

3.5.1. Radiation exposure of decommissioning workers

The types of radionuclides used at a facility can have a major impact on the exposure that workers may receive during the decontamination and dismantling activities. If a facility undergoes immediate dismantling, most radionuclides will not have had sufficient time to decay and therefore this strategy may not provide a reduction in the worker exposure. Facilities that contain highly activated or contaminated components may pose the highest risk of significant unplanned radiation exposure during the immediate dismantling strategy, but this risk can be mitigated by good characterization and work planning. Also, high radiation doses can be reduced by more extensive use of shielding or remotely operated equipment, although the latter might result in a higher overall cost for decommissioning.

A facility that undergoes deferred dismantling may benefit from the radioactive decay of residual radionuclides during the long term storage period. However, this benefit will not generally result in sufficient dose savings to justify deferred dismantling without other factors being taken into consideration. In situations where deferred dismantling can be shown to result in significant dose savings, this option becomes important.

If the radionuclides have a half-life of more than a few years, deferred dismantling may not be a suitable option but this will depend on the weight given to the reduction in the radioactive inventory. Often, ^{60}Co will dominate in reactors from which the fuel has been removed. In such cases, a reduction in the inventory by factors of 10, 100 and 1000 would require storage periods of 17, 34 and 51 years, respectively. Thus, there would be some benefit from radioactive decay, even if the long term enclosure period were less than 50 years. As an alternative to deferred dismantling, entombment might be considered for radionuclides having short half-lives. A facility that is entombed relies on radioactive decay to effect the eventual release of the site from regulatory control.

If radionuclides with very long half-lives are present, there is no incentive to delay the decontamination and dismantling activities at all and immediate dismantling is the preferred strategy. This is especially true for reprocessing facilities, enrichment facilities or facilities that use or process thorium or uranium. Entombment is not an option because waste that contains long lived radionuclides should not be placed in near surface disposal facilities [5].

3.5.2. Public radiation exposure

Although minimal, the main radiation exposure pathway to the public during decommissioning is normally expected to result from the transportation of radioactive waste from the facility site to the waste disposal site. If low level radioactive waste is taken for disposal off-site shortly after shutdown (early availability of a permanent disposal facility), the risk of public radiation exposure (through transportation) dictates the following order of strategies from highest to lowest risk: (1) immediate dismantling (material is transported without significant decay), (2) deferred dismantling (potentially reduced amounts of material are transported following radioactive decay) and (3) entombment (essentially all material is buried on-site and there is minimal handling of waste for disposal). If the availability of the disposal site is delayed until after the deferred dismantling period, only the entombment strategy provides any advantage, since little or no waste is transported, presupposing that interim storage in a temporary storage facility on-site is not an option.

Regardless of the decommissioning strategy selected, if transportation of the radioactive material is conducted in accordance with IAEA transport requirements [6] there will be no significant difference in radiation exposure risk to the public from any of the decommissioning strategies.

3.5.3. Environmental safety

Normally, implementation of all decommissioning strategies removes highly mobile sources of contamination (fluids and externally contaminated surfaces) during the early stages of decommissioning. Technologies for dismantling systems and decontaminating surfaces are assumed to be the same for all strategies, although the source term (amount of radioactivity to be disturbed) for each strategy will vary.

3.5.3.1. Dismantling activities

Immediate dismantling will require working with the highest levels of radiation, whereas deferred dismantling requires the least amount of physical work on highly activated or contaminated components. Therefore, immediate dismantling has the highest radioactive inventory available to contaminate the environment in the event of a loss of ventilation control, whereas deferred dismantling and entombment will have lower source terms due to radioactive decay. However, during the long term enclosure period before deferred dismantling, the risk of contaminating the environment still exists and the appropriate protection systems have to be installed and maintained. It is assumed that all dismantling activities will use appropriate engineered containment boundaries to preclude release of radioactive contamination to the environment such that these sources can be safely controlled when implementing any dismantling strategy. As a result of the long enclosure period, the facility staff conducting final dismantling in the deferred dismantling strategy may be newly trained or specialist contractors. Even though the radioactive inventory is reduced, there may be a risk of environmental contamination due to a lack of familiarity with the facility and systems.

3.5.3.2. Building deterioration

The deferred dismantling strategy requires that buildings be secured and maintained for an extended period in order to preclude disturbing the activated and contaminated material. In the immediate dismantling strategy, although the buildings will need to be maintained to support the dismantling and decontamination activities, there are generally sufficient staff on-site that are dedicated to ensuring the appropriate radiological controls are applied. The immediate dismantling strategy may pose a lower risk of environmental contamination due to building deterioration. The potential risk of environmental contamination (the spread of contamination outside the buildings) is highest for the deferred dismantling strategy, but would normally be controlled during the long storage period by adequate building management and inspection. This deferred dismantling option generally presupposes a refurbishment investment being made before beginning the dismantling work, because of the progressive deterioration of different components and systems over time.

3.5.4. Non-radiological safety

It is assumed that the decommissioning activities will be undertaken in a manner that protects worker health and safety, utilizing suitably qualified and experienced staff. However, there are strategies that may increase the risk of serious, non-radiological accidents occurring during dismantling activities.

Non-radiological hazards during dismantling activities may pose the greatest risk to workers. Chemical hazards such as exposure to asbestos, solvents and other toxic materials present potentially significant occupational health hazards. In addition, common construction site industrial hazards such as tripping and falling, electrical shock, dropped loads and fire pose potentially serious risks to the workers.

More demanding radiological conditions, including higher airborne contamination levels, will result in greater expected use of respirators and portable shielding, dictated by the optimization of radiation protection. The wearing of additional protective equipment potentially reduces audio and visual capabilities and increases the risk to worker safety. Similarly, the use of portable shielding requires greater work effort and may increase the congestion or limit access in a work area. Both of these working conditions are expected to be more prevalent in the immediate dismantling strategy than they would be if equipment were removed after a prolonged deferred dismantling period where there has been significant decay. However, as in the other strategies where the dismantling and decontamination activities are delayed until after a deferred dismantling period, there may be increased risks due to the new staff's unfamiliarity with the facility.

Systems and structures will progressively deteriorate over time during the dormancy period, before deferred dismantling begins, creating hazards to the workers. The physical condition of the facility at shutdown, or the expected condition after a dormant period and the corresponding necessary investments, will be a factor in selecting an appropriate strategy. If the condition of the structures is assessed as being (or soon to become) poor, then the operating organization may be obliged to undertake immediate dismantling.

Many systems and structures were constructed with a design lifetime in mind. Before this design lifetime is exceeded, an evaluation needs to be performed to determine if the system or structure will still perform its intended purpose within the required safety margin. If not, the system or structures may need modification, repair or replacement.

3.6. COST AND AVAILABILITY OF FUNDS

The cost of the decommissioning programme is highly dependent on the chosen strategy or options. Therefore, the cost studies may develop several options to allow optimization.

The site on which the facility is located has a major influence on decommissioning cost and thereby on strategy. In the case of a multifacility site, it could be useful to take advantage of the learning experience gained from decommissioning of the first facilities by redeploying the now experienced personnel or using the capabilities of one facility to help with the decommissioning of another. Funds may be saved by sharing on-site expertise or tools. These considerations could help to optimize a selection of strategies for the overall site.

It is not only the cost of decommissioning that can have an impact on the strategy selection, but also the availability of funds to perform the required tasks. If the funds are available, it is suggested that immediate dismantling would be the preferred strategy. There have been a number of cases where the lack of funds has required that a deferred dismantling strategy be selected when this might not be the preferred option based on other factors. In principle, if decommissioning is delayed for several decades, the trust fund may have sufficient time to build up to the amount needed to complete all the work. However, there is some risk that the fund performance may not be sufficient or that the decommissioning costs may rise faster than the fund growth. Decommissioning costs have escalated over the years at rates generally higher than normal inflation rates. The cost drivers are typically more rigorous regulatory requirements, the rapidly rising cost of waste disposal and technical scope changes from the owner/licensee or the interested parties. In any event, these escalation factors are to be taken into account and close monitoring is necessary to ensure the availability of funds when needed.

The best approach for ensuring that funds are available when the facility permanently ceases operation is to perform a preliminary cost estimate for decommissioning during the design stage of the facility. This cost estimate is based on a large number of assumptions since the actual operating conditions are not known, but with experience and sound engineering principles, a realistic cost estimate can be developed. As the time approaches when the operating facility will be permanently shut down, the initial assumptions are replaced with facts based on experience and current conditions. On the basis of this cost estimate, funds may be collected during the life of the facility through a tax on the products produced (e.g. electricity, radioisotopes). This allows a gradual buildup of the decommissioning fund. In the case of facilities that do not produce products, such as a research or academic facility, other means of acquiring the necessary financial resources for decommissioning may be needed.

In many countries, decommissioning was never considered during the design, construction and operation of facilities using radioactive material. Now, many of these facilities are coming to the end of their operating lives and there are no decommissioning funds available. Neither are there any funds to ensure proper management of the spent fuel and operational waste. Unless the government of the country provides the funds, there is little choice other than to place the facility into a deferred dismantling mode and begin collecting the required funds through other means, since the facility is no longer operating. In such cases, appropriate steps may be considered necessary to ensure proper long term control and security of the facility and collection of funds.

3.7. WASTE

Different aspects of waste generation and waste management can have an impact on the selection of a decommissioning strategy. Among the most important aspects are: the overall national waste management strategy, the amount of waste, the types and categories of waste (both radioactive and non-radioactive) and the facilities needed to process, handle, store and dispose of the waste.

It is important to consider established national waste management policies when selecting a decommissioning strategy, or to seek the establishment of a policy where one does not exist. This policy establishes the overall national framework for the management of all types of waste that will be generated during the decommissioning activities. It also establishes the classification of the waste and its final disposal. The main categories of decommissioning waste include [5]:

(a) Low level radioactive waste;
(b) Intermediate level radioactive waste;
(c) High level radioactive waste;
(d) Hazardous, non-radioactive waste (chemicals, heavy metals, etc.);
(e) Non-radioactive and non-hazardous waste (cleared material that complies with clearance levels [3]).

Each category of waste has its own unique concerns and specific management requirements. The absence of a waste management policy for any of these waste categories will introduce uncertainties in the decommissioning strategy selection process and may not yield a secure strategy. If no disposal route exists for a particular waste category, the only option may be to store the waste on-site in regulated storage facilities.

Lack of a disposal facility is in itself insufficient reason for not performing immediate dismantling. The waste can be placed into an interim storage facility that will also require decommissioning eventually, once a final disposal scheme for the waste is decided upon. If the nuclear programme within a country is very limited and the type of facility to be decommissioned is amenable to entombment, then this may be the preferred option. As stated previously, an entombed facility has to be considered as a near surface waste disposal site and needs to meet the regulatory requirements for such a facility. This means, for example, that no or only limited amounts of long lived radionuclides are allowed in an entombed facility. If the country has not prepared the necessary infrastructure for a low level waste disposal facility, then entombment may not be feasible. However, the facility could be placed into a short deferred dismantling mode until such requirements can be put into place.

The type of waste is also a factor that is considered during the selection of the decommissioning strategy. If there is a large amount of alpha emitting or long lived waste, consideration has to be given to its final disposal. In most cases, this type of waste cannot be disposed of in a near surface disposal site and may require deep geological disposal. Establishment of a geological disposal site may take considerable time to achieve and in the interim may lead to the selection of a deferred dismantling strategy. However, if a disposal site or interim storage facility is available, then immediate dismantling is the preferred strategy.

Certain types of waste may require special consideration during their management, such as spent fuel from a power reactor, research reactor or reprocessing facility. This material is managed as part of the shutdown operations of the facility and is not normally considered as part of decommissioning. However, there have been cases where this material has been left or abandoned long after the facility has been shut down. In this case, the operating organization maintains responsibility for management of the material and this is an important consideration in the decommissioning strategy. If a reprocessing route is not available, the only options are for long term storage or geological disposal. Each of these may take considerable time to implement and may lead to a deferred dismantling strategy. As mentioned earlier, this type of material cannot be left in an entombed facility. However, if the situation arises where several facilities have spent fuel in their buildings it may be useful to consolidate the spent fuel at one facility to allow the decommissioning of the others.

There might be other types of material that will require special handling and disposal consideration due to their volume and contained radionuclides. One of these might be graphite that contains long lived radionuclides at very low concentrations (e.g. ^{14}C or ^{3}H).

3.8. TECHNOLOGY

The techniques needed for dismantling activated or contaminated facilities will be common to all the decommissioning strategies. It is assumed that the necessary techniques already exist and that there are few advantages to be gained from waiting for technology to progress. For all the strategies, the dismantling of external, unusable support systems and equipment will generally be performed using standard techniques. Much of this will be uncontaminated material that can be released from regulatory control and therefore needs to be segregated from contaminated material. The uncontaminated material can be released only when the clearance criteria are met.

There will be differences in dismantling techniques between immediate and deferred dismantling. Higher dose rates resulting from high activation or contamination levels may require remote techniques for immediate dismantling of some facilities. Much of this, however, can be undertaken within shielded structures such as a reactor spent fuel pool or hot cell. For deferred dismantling, it is possible that some of the waste will have decayed to low levels and special techniques may not be needed during the dismantling phase. This will depend on the initial level of contamination of the specific structures, equipment or facilities to be decommissioned. It is desirable to plan for deferral periods if this will allow decay to low levels of contamination to simplify decommissioning.

If the entombment option is exercised soon after shutdown, then any preparatory dismantling or modifications will experience similar problems to those encountered in immediate dismantling. However, if entombment is delayed towards the end of a long deferral period, then simpler techniques may be used to prepare the facility as a near surface disposal site.

It can be reasonably assumed that most of the existing facility support equipment (e.g. lifting devices and bridges, utilities, water cleaning and filtration facilities, ventilation, sanitary facilities) will not be available after a prolonged deferred dismantling period without some type of refurbishment or replacement. It is probably also true that not all of the equipment will remain available and reliable in the immediate dismantling option, but at least some advantages can be realized by selecting the immediate dismantling option in preference to deferred dismantling. The same applies for early entombment as it does for immediate dismantling as all the required decommissioning operations are carried out immediately after facility shutdown.

Decommissioning of facilities can be carried out with existing technology. There is no significant advantage in waiting for further progress in technology development, but in some particular cases (e.g. treatment/conditioning of special material such as graphite and the remote controlled tools needed for dismantling the reactor internals) some improvements may be expected and this could probably favour deferred dismantling in these particular cases. Nevertheless, there currently exists remote handling technology that allows the performance of this type of activity.

3.9. SOCIAL AND ECONOMIC IMPACTS

The selection of a particular strategy for the decommissioning of a facility can have some significant social and economic impacts at local, regional and national levels. The shutdown of a large facility will have a direct impact on local employment. The social and economic impacts of the closure of a facility may be the most important aspects of any decommissioning strategy selection, as this directly impacts employment and local revenues. If the duration of the decommissioning is spread over an extended period, the social and economic impacts of facility closure may be less acute. However, a long period of safe enclosure at a minimum level of activity may be unacceptable to the local communities. All decommissioning strategies will need to take into account interested party engagement and, potentially, extended public information and feedback programmes.

When the impact on the local economy is an important issue, immediate dismantling might be the preferred strategy because this will reduce the negative social effect while continuing to stimulate the local economy and provide employment for the local workforce.

The number of workers needed to implement a decommissioning strategy is dependent on the strategy selected and the type of facility to be decommissioned. For most facilities, the number of employees needed will generally be less than the number employed during facility operations. If deferred dismantling is selected as the option, the workforce will be reduced considerably during the enclosure period and then may increase again during the dismantling phase. For small facilities (e.g. research reactors) undergoing either immediate or deferred dismantling, the number of workers might increase during the decontamination and dismantling activities.

If the planning for permanent shutdown is performed well in advance, as is recommended [2], there is enough time to take measures to reduce the employment impact of any of the decommissioning strategies, but the political impact is difficult to estimate. It is important to take into account that the decommissioning process and the former operating phase require different human skills and that an early decision can help ensure that the associated necessary training is provided.

An entombment strategy may be difficult for the local population to accept because a structure containing radioactive waste is normally left after the decommissioning activities are completed. This structure is permanent and may be visible to the local population. Therefore, the potential selection of this strategy will need to take into account an extensive public information and feedback programme.

The potential demand for reuse of the site either for specific restricted or unrestricted purposes is a consideration for the decommissioning strategy decision makers. Reuse of the site is generally not compatible with entombment and is generally not optimized in the case of deferred dismantling, except in the case where reuse means the siting of new nuclear facilities on the existing site [7]. This could be the case if the creation of new nuclear sites is difficult for political or social reasons.

3.10. OTHER FACTORS

Following facility closure, staff skills and knowledge of the facility and system operations will diminish. This experience and expertise is in operation and maintenance activities and not in future decommissioning processes. There may also be a loss of radiation safety knowledge if no other facilities are being built in the country. As a result of this, the immediate dismantling strategy presents an advantage in terms of availability of knowledge and skills, recognizing that there will be the need to retrain some staff in different skills for decommissioning.

3.11. DECISION MAKING ON THE OPTIMUM STRATEGY

From the above issues, it can be seen that the selection process is complex. The strategies need to be assessed thoroughly to ensure that the most appropriate one is adopted. A selected team having appropriate experience and expertise is normally assembled to discuss and analyse all of the applicable issues associated with the various strategies. The team members are not only from the operating organization and its subcontractors (facility technical and managerial staff and decommissioning experts) but may also include regulatory, government and local community representatives and other appropriate interested parties. The discussion and conclusions are carefully recorded and documented for inclusion in the decommissioning plan or a reference document.

The factors for discussion and debate on an optimum decommissioning strategy may encompass the following:

(a) Compliance with the laws and regulations;
(b) Radiological conditions of the facility;
(c) Safety assessments;
(d) Physical status of the facility;
(e) Waste management arrangements;
(f) Spent fuel management issues;
(g) Availability of financial resources;
(h) Availability of suitably trained personnel and managerial staff;
(i) An appreciation of environmental, social and economic impacts;
(j) Proposals for reuse of the site;
(k) Taking account of lessons learned from similar decommissioning projects.

There are a number of aids, usually computer based, that can be used to apply weighting factors to the various factors that are considered during the strategy selection process. A sensitivity analysis of the results is also part of the overall discussions. Cost–benefit, multivariant or multiattribute analyses are typical aids used to give a systematic evaluation. It is important that the analyses use realistic estimates of both costs and radiation doses and that significant uncertainty be identified. It is more difficult to evaluate factors such as public opinion and the timing of certain events such as the availability of an off-site national waste disposal facility, but suitable weighting factors can be used.

It is necessary to note that radiological safety may not be a significant variable if it is assumed that all activities are conducted within the regulations and worker and public dose commitments. However, procedures and tasks undertaken during decommissioning would be different from those performed during operation and the radiological impact, particularly on the working environment, could therefore be different during decommissioning.

The decision making process does not end with the definition of an 'initial' preferred strategy. The evolution of the context during the decommissioning implementation (i.e. over several years) may be of consequence. It is therefore necessary to review periodically the overall site and facility specific decommissioning strategies. At each stage, it is important to seek consensus from a wide circle of interested parties.

4. GENERAL ASSESSMENT OF DECOMMISSIONING STRATEGIES

Considering the issues involved in the choice of a decommissioning strategy, as noted in Section 3, the selection process is a complex task. It is therefore useful to have an understanding of the advantages and disadvantages of the various decommissioning strategies.

4.1. IMMEDIATE DISMANTLING

Immediate dismantling assumes that suitable waste disposal sites or interim waste storage facilities are available for both low level and other intermediate and high level radioactive wastes (such as reactor fuel and highly activated reactor vessel internals), as well as for hazardous waste and cleared material. The equipment, structures and parts of the facility and site that contain radioactive contaminants are removed or decontaminated to levels that permit releasing the site for restricted or unrestricted use and terminating the licence. The advantages of the immediate dismantling strategy include:

(a) All radioactivity above specified levels is removed and properly disposed of or stored at an interim facility.
(b) The site may be used as soon as possible for other activities.
(c) The operating workforce, which is highly knowledgeable about the facility, is available to support (and possibly plan and carry out) the decommissioning activities.
(d) Potential limitation of the social impact of shutdown on the local community.
(e) Utilizing currently available waste disposal facilities removes any uncertainty with respect to their future availability.
(f) Potential cost savings resulting from future price escalation (because most activities that are undertaken during immediate dismantling would also be performed during deferred dismantling).

The disadvantages of the immediate dismantling strategy include:

(a) The potential for higher worker exposure (because there will be less time for radioactivity to decay);
(b) A larger initial commitment of financial resources;
(c) A larger immediate commitment for waste disposal or storage space.

4.2. DEFERRED DISMANTLING

Even though the choice of the decommissioning strategy is left to the operating organization, some Member States require that decommissioning be completed within a certain period (e.g. 60 years) after the permanent cessation of facility operation. The operating organization needs to be mindful of other regulatory constraints that could limit the choice of decommissioning strategy.

In situations where interim waste storage or disposal sites are not available, a period of safe enclosure might be the only available choice. Deferred dismantling generally assumes that the fresh and spent nuclear fuel has been removed from the facility and that radioactive liquids have been drained from systems and components and then processed. Also, all operational wastes have either been removed from the building or have been processed and packaged for storage and eventual disposal. The facility is then placed in a safe, stable condition and maintained in that state until it is subsequently decontaminated and dismantled to levels that permit licence termination. The advantages of the deferred dismantling strategy include:

(a) Initial lower cost during the years immediately following permanent cessation of operations;
(b) Reduction in radioactivity as a result of radioactive decay during the enclosure period;
(c) Possible reduction in worker dose during the dismantling phase;
(d) Potential reduction in the amount of waste disposal space required;
(e) Potential reduction in public exposure because of fewer shipments of radioactive material to the waste disposal site;
(f) Time to acquire the necessary decommissioning funds.

The disadvantages of the deferred dismantling strategy include:

(a) The site will not be available for alternative use during the extended enclosure period.
(b) In cases where dismantling is deferred to a much later time, the facility personnel will probably no longer be available and their expertise and corporate memory will be lost to the decommissioning team. Record keeping requirements become much more important.
(c) Uncertainties regarding potential changes in regulations, availability of funds, and availability and costs of radioactive waste sites will become more important.
(d) There will be a continuing need for maintenance, security and surveillance and funds to cover the associated costs.
(e) The potential for higher total cost for the subsequent decontamination and dismantling will increase, assuming typical price escalation during the time the facility is shut down.

4.3. ENTOMBMENT

Before the start of entombment, the fresh and spent fuel is permanently removed from the facility and either shipped off-site or stored in an independent storage facility on the site. Radioactive liquids are drained from systems and components and then processed. After preliminary decommissioning activities are completed, radioactive contaminants to be left on-site are placed, or left, in the reactor building or other substantial structure. The radioactive contaminants are entombed by constructing barriers that can reliably isolate them from the environment and from intruders.

Two basic scenarios for decommissioning via the entombment strategy are:

(1) *Early entombment*, wherein disassembly, packaging and placement of radioactive material within the entombment enclosure occurs immediately following reactor shutdown activities and the enclosure is sealed and monitored for a set duration. Much of the occupational radiation exposure associated with immediate dismantling would also be received during immediate entombment, because the disassembly and packaging activities for the contaminated systems and equipment outside the entombment enclosure would essentially be the same in both cases. Similarly, the labour costs for those activities would also be about the same in both cases.

(2) *Delayed entombment*, wherein the facility is placed into an extended enclosure period, followed by disassembly, packaging and placement of residual radioactive material into the entombment enclosure. The enclosure is then sealed and monitored for an additional agreed upon duration. After the extended storage period, the surface contamination and induced activation levels throughout the facility will have decayed, which means that additional surface decontamination may not be needed. Labour costs could also be expected to be lower from this activity.

In determining the viability of entombment, important considerations are an assessment of the isolation of the enclosure in retaining the residual radioactivity and the analysis of the exposure to the public from the likely exposure pathways from the entombed waste. Particular attention needs to be given to the long term physical integrity of the entombment enclosure structure and its capability to exclude groundwater. The length of time that the entombed structure needs to remain effective depends on the specific radionuclides present in the entombed structure and the time for those radionuclides to be reduced, through radioactive decay, to a level that is acceptable for licence termination. Monitoring and institutional controls may be needed during the period of entombment.

The entombed facility can be considered as a disposal facility and an operating organization studying this decommissioning strategy needs to be aware of the requirements for this type of facility. International requirements for these types of facility are given in Ref. [4]. The advantages of entombment include:

(a) Relatively low cost of associated waste transport and disposal;
(b) Reduced amount of work involved in encasing the facility in a structurally long lived substance;
(c) Reduced worker exposure compared with the exposure from decontaminating and dismantling the facility;
(d) Reduced public exposure from transported waste to waste storage, processing or disposal sites;
(e) Reduction in the size of the controlled area;
(f) Possible reuse or conversion of the site to a waste disposal site for other facilities.

The disadvantages of entombment include:

(a) Unsuitability for facilities with long lived radionuclides;
(b) Cost of long term monitoring and institutional controls;
(c) Public acceptance of creation of a near surface waste disposal site.

5. SUMMARY

5.1. DECOMMISSIONING STRATEGIES

This Safety Report outlines those factors that need to be considered in formulating a decommissioning strategy. A systematic approach is necessary and it is important to document the basis of the decision making process in the decommissioning plan. The type of facility, its past functions and the extent of cleanup needed (soils/sediment, groundwater) will have a major impact on the decommissioning strategy selected. This selection has a significant impact on almost all phases of the planning and implementation of the decommissioning process.

Three different decommissioning strategies are defined, namely immediate dismantling, deferred dismantling and entombment. All three strategies require the same attention to safety and, consequently, they all involve some degree of decontamination, dismantling and waste generation. The information provided in this Safety Report applies to all facilities using radioactive material, except waste disposal facilities. However, it does apply to supporting facilities related to waste disposal activities such as packaging, processing, handling or conditioning. As different aspects of waste generation and waste management could have an impact on the selection of a decommissioning strategy, decommissioning waste considerations are also addressed.

5.2. ASSESSMENT OF DECOMMISSIONING STRATEGIES

The basic objective of decommissioning a facility using radioactive material is to place it into a condition where it poses no unacceptable risk to public health and safety or to the environment. Worker, public and environmental safety during a decommissioning project is therefore elaborated upon in the report.

The implications of implementing various decommissioning strategies in order to identify their advantages and disadvantages are assessed. Assessment of different decommissioning strategies is rather complicated. An important consideration when selecting the best strategy is the desired end state of the facility following completion of decommissioning. The Safety Report elaborates on possible end states in terms of site release for unrestricted or restricted use.

5.3. SELECTION OF AN OPTIMUM DECOMMISSIONING STRATEGY

Selection of the optimum decommissioning strategy is complex. There are a number of aids that can be used when considering the various factors during the strategy selection process. Decisions on the best or optimum strategy for decommissioning facilities using radioactive material may well go far beyond purely radiological protection considerations. Most decisions, therefore, require multiple criteria to be taken into account when choosing an optimum strategy and most of the necessary factors or attributes to be considered are addressed in this Safety Report. When the optimum strategy is not self-evident, the comparison can be performed using a quantitative decision aiding technique. Of the different techniques available, cost–benefit analysis, multivariant analysis and multiattribute utility analysis are typical aids to be used to give a systematic evaluation. The Safety Report illustrates a simple methodology to select the best strategy from among the three defined general strategies for decommissioning facilities.

Even though the selection process indicates one strategy, constraints may occur during the implementation of the decommissioning process that may necessitate a combination of strategies instead of the initial selected strategy. It is, therefore, necessary to review the process periodically. It is also important to consider the characteristics of the other facilities at the site and use the capabilities of these facilities, as well as the experience of the personnel, in an overall site strategy.

Appendix

EXAMPLE FRAMEWORK FOR A PROCESS TO SELECT A DECOMMISSIONING STRATEGY

A.1. GENERAL

The basic requirement for selecting a decommissioning strategy including periodic review and assessment of decommissioning activities is covered in IAEA safety standards [2]. The objective is for decommissioning strategies to be appropriate, realistic, technically practicable, appropriately timed, comprehensive and appropriately financially estimated and funded. It is recommended that an operating organization select a decommissioning strategy via a documented selection process and that the strategy be periodically reviewed in order that it remains appropriate, responding to changing circumstances and influences.

In selecting a preferred strategy, it is beneficial to demonstrate that the range of options for decommissioning identified in this Safety Report have been examined, covering different timescales and including technical, safety, social and financial factors. Major assumptions and uncertainties can be identified together with the approach needed for their resolution.

This Appendix provides an example framework for the selection of consistent, comprehensive, systematically produced and transparently reported decommissioning strategies to satisfy regulatory and operating organization requirements.

A.2. PROCESS FOR STRATEGY DEVELOPMENT

A decommissioning strategy development/review process is described below. The aim of this process is to ensure that the strategy selected is appropriate and detailed to the extent that it reflects the real (e.g. cost) or perceived (e.g. political) importance of the decision. The degree of complexity of the decision analysis will determine the extent of review and verification. Significant decisions on an appropriate decommissioning strategy will be expected to have entailed more detailed and stringent analysis, especially on the sensitivity of the outcome.

It is useful to develop a plan to involve interested parties and to ensure that it is approved prior to any strategy assessment, including establishing and maintaining appropriate interface arrangements with the regulatory bodies for communications and formal meetings on strategic issues. An ongoing review process results in no ‘surprises’ during production or review of strategies, enabling all interested parties readily to provide input in the decision making process.

It is noted that the development of a decommissioning strategy may focus on developing an initial range of potential strategies and options to enable an early, structured discussion with the interested parties, rather than generating a preferred strategy for formal endorsement. In such cases, subsequent actions and endorsement to enable implementation would be determined by the outcome of future discussions.

Table 1 shows the recommended steps to be used in the selection of a decommissioning strategy for a facility using radioactive material.

TABLE 1. DECOMMISSIONING STRATEGY SELECTION STEPS

Step	Explanatory note
Step 1: Establish the decision context	
(i) Identify the nature of the issue — define the scope and objective(s) together with the desired end point, the relevant decision makers and interested parties	This allows all parties to achieve a common understanding of what is to be achieved. Objective(s) need to be measurable. Scope for any peer review of the assessment is also clearly defined and agreed.
(ii) Outline roles and responsibilities of the decision makers, strategy analysts, peer reviewer(s) and key interested parties	Peer reviewer(s) are ‘independent’ of the assessment. Interested parties can be external or internal to the operating organization.
(iii) Identify and outline the decision constraints	These are necessary to shortlist options which do not meet decision constraints/criteria such as safety, policy, legislative compliance or technical feasibility (using currently available technologies).
Step 2: Identify the decommissioning strategies	
(iv) Produce an initial list of all potential strategies and options	This stage of the process needs to be comprehensive in the range of strategies and options within strategies produced, irrespective of the constraints.
(v) Screen against the constraints and produce a shortlist of strategies and options for further assessment	The reasoning behind the rejection of identified constraints of any strategies and options needs to be fully and transparently reported. Caution needs to be exercised so as not to foreclose or preselect strategies and options.

TABLE 1. DECOMMISSIONING STRATEGY SELECTION STEPS (cont.)

Step	Explanatory note
Step 3: Define assessment criteria	
(vi) Determine which attributes will be used in the decision making process	Attributes include consideration of all factors relevant to the decision and would normally cover the following areas: 3.1. Type of facility and extent of cleanup necessary: Nature of radiologically impacted facilities, equipment and material Facility condition Residual radioactive material Historical assessment of operations, including spills, contamination events, releases, waste burials, etc. Relevant facility surveys 3.2. Desired end state: Release for unrestricted use (buildings remain) Unrestricted release with no sign of previous use (no buildings) Release for restricted use Partial site release 3.3. Status of national policies and regulatory infrastructure: Adequacy of existing decommissioning and waste management policies to support proposed activity Need for new policies where none exist Adequacy of regulatory body staff experienced in decommissioning Need for experts on decommissioning 3.4. Decommissioning worker safety: Significance of dose savings from decay during any deferred dismantling period Need for remotely operated equipment to support decontamination and dismantling under considered options 3.5. Public radiation exposure: Potential public exposure from waste transportation for the considered decommissioning options Potential public exposure from events or releases due to decontamination and dismantling for the considered decommissioning options 3.6. Environmental safety: Radiological impacts from airborne and liquid effluents and releases due to the considered decommissioning options Chemical impacts Disturbance Impact from credible accidents Building deterioration

TABLE 1. DECOMMISSIONING STRATEGY SELECTION STEPS (cont.)

Step	Explanatory note
	3.7. Non-radiological safety: Chemical hazards present or created during considered decommissioning options Industrial hazards (electrical, falling, tripping, dropped loads, etc.) Fire risks Impact on workers of the use of personnel protective equipment and portable shielding during considered options Anticipated deterioration of facilities and equipment
	3.8. Cost and availability of funds: Cost estimates of options considered Factors affecting cost uncertainties Current and future availability of adequate funds Funding methods
	3.9. Waste: Categories of waste generated Availability of waste disposal for the categories generated Waste storage options Status of national policies affecting waste management
	3.10. Technology: Technologies needed to support considered options Confidence in the technology Need to modify, refurbish or maintain existing facility systems to support decommissioning Potential for technological improvements affecting facility specific decommissioning strategies
	3.11. Social and economic: Impacts on local employment and revenues Consideration of the views of interested parties Consideration of local interested party acceptance Demand for reuse of site
Step 4: Select appropriate methodology	
(vii) Select appropriate methodology to assess decommissioning strategies and options against these attributes	The most appropriate methodology is dependent on the scale of the decision to be made, the complexity of the issues to be resolved and the availability and quality of data and information. A number of methods such as financial analysis, pros and cons analysis, cost–benefit analysis and multiattribute decision analysis can be used.
(viii) Collect relevant information, calculate and verify quantitative attributes (e.g. cost, dose) only to the detail and level of accuracy required to allow an informed decision to be made	The detail and accuracy of attributes required will depend on the extent to which changes in the data will affect the robustness of the assessment. In some cases it will not be necessary to calculate attribute data when it is clear that there are no significant differences between those attributes for the decommissioning strategies and options under consideration.

TABLE 1. DECOMMISSIONING STRATEGY SELECTION STEPS (cont.)

Step	Explanatory note
Step 5: Assess strategies	
(ix) Compare the shortlisted strategies using the objective attribute data and, where relevant, subjective attributes	The comparison needs to be qualitative or quantitative, depending on the importance and complexity of the decision. It is not always necessary to use computer based analytical tools. For strategic optimization assessment, the complexity of the issues in general requires analytical techniques such as multiattribute decision analysis, where scores and weights are assigned for each attribute. These are combined to give preliminary total weighted scores.
Step 6: Present the results	
(x) Identify provisional choice of a lead strategy as well as an alternative strategy	
(xi) Test the robustness of the assessment	Sensitivity analyses are carried out by varying the weight and/or scores of an attribute or a combination of attributes. In addition to weighting based on facts (swing weight, the difference between the best and worst option), the comparison may also take into account the 'value' (preference weight, the importance of an attribute or a group of attributes relative to the others) perceived by the different (particularly external) interested parties. Suggested weighting scenarios include: (1) safety and environmental bias, (2) technical bias and (3) economic bias. This will allow more complex sensitivity analyses on the nature of differences amongst interested parties. Risk and potential conflict with other strategies should be identified.
(xii) Assess socioeconomic and political factors and risks which may influence the decision	Factors such as regulatory opinion and public perception need to be assessed first by describing the benefits and detriments for each of the options. Where appropriate, these are then scored and weighted as part of the multiattribute decision analysis.
(xiii) Report the outcome of the process in a fully transparent manner to all interested parties	Explain the use of the multiattribute decision analysis and how the weighting factors expressing the relative weight of each of the attributes have been assessed for all the attributes. Also, explain how the scores for each of the decommissioning strategies have been selected or assessed. Finally, explain the outcome of the analysis that resulted in the selected strategy.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of the Decommissioning of Nuclear Facilities Around the World, IAEA, Vienna (2004).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Facilities Using Radioactive Material, IAEA Safety Standards Series No. WS-R-5, IAEA, Vienna (2006).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of the Concepts of Exclusion, Exemption and Clearance, IAEA Safety Standards Series No. RS-G-1.7, IAEA, Vienna (2004).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Near Surface Disposal of Radioactive Waste, IAEA Safety Standards Series No. WS-R-1, IAEA, Vienna (1999).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of Radioactive Waste, Safety Series No. 111-G-1.1, IAEA, Vienna (1994).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Regulations for the Safe Transport of Radioactive Material, 2005 Edition, IAEA Safety Standards Series No. TS-R-1, IAEA, Vienna (2005).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Release of Sites from Regulatory Control on Termination of Practices, IAEA Safety Standards Series No. WS-G-5.1, IAEA, Vienna (2006).

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The selection of the decommissioning strategy can have a significant impact on the overall safety and efficiency of a decommissioning project. This selection process can be complex and must consider a number of factors that are not normally considered during the normal operation of a facility. This Safety Report identifies the main decommissioning strategies and the factors that should be considered during the selection process.

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