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Design Lessons Drawn from the Decommissioning of Nuclear Facilities

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DESIGN LESSONS DRAWN FROM THE DECOMMISSIONING OF NUCLEAR FACILITIES

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FOREWORD

Considerable experience has been gained over the past 20 years or more in the decommissioning of a large range of nuclear facilities and in managing the waste from operational and dismantling activities. Difficulties have been experienced in most decommissioning projects and it was believed that many of these could have been avoided or at least ameliorated by attention being given to final shutdown and dismantling at the planning, design and construction stages. Lessons learned have been well documented in numerous publications usually made available at workshops, seminars and international conferences. There are large numbers of commercial organizations and state bodies that have specialized in decommissioning and waste management.

Based on early decommissioning efforts, it would be useful to assemble a compendium of features that should be considered during the planning, design, construction and operating stage of a facility which would facilitate decommissioning. Publications have been issued by various organizations such as the United States Nuclear Regulatory Commission, the OECD Nuclear Energy Agency (OECD/NEA) and the IAEA.

This report is a review and update of a previous IAEA publication issued in 1997. It takes account of recent attention being given to the decommissioning aspects of new nuclear facilities, especially a new generation of large nuclear power plants that are now being planned, designed and constructed. Regulators have become more aware of the need to pay closer attention to decommissioning and waste management at the planning and design stages. In part, this is due to the emphasis placed on this issue in IAEA Safety Standards Series No. WS-R-5 (Decommissioning of Facilities Using Radioactive Material), which states that “for new facilities, consideration of decommissioning shall begin early in the design stage and shall continue through to the termination of the practice or the final release of the facility from regulatory control”. This report aims to support this requirement by providing planners, designers, constructors and operators of new nuclear facilities with recommendations for lifetime planning and the incorporation of desirable features that will facilitate decommissioning and waste management.

This report was prepared as part of a collaboration with the OECD/NEA on a related initiative. The IAEA technical officers responsible for this publication were M. Laraia and P. Dinner of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

SUMMARY

This report provides an updated compilation incorporating the most recent lessons learned from decommissioning and remediation projects. It is intended as a "road map" to those seeking to apply these lessons. The report presents the issues in a concise and systematic manner, along with practical, thought-provoking examples. The most important lessons learned in recent years are organized and examined to enable the intended audience to gauge the importance of this aspect of the planning for new nuclear facilities. These will be of special interest to those seeking to construct nuclear facilities for the first time.

In Sections 1 and 2, the current situation in the field of decommissioning is reviewed and the relevance and importance of beneficial design features is introduced. A more detailed review of previous and current lessons learned from decommissioning is given in Section 3 where different aspects of the decommissioning process are analysed. From this analysis beneficial design features have been extracted and identified in Section 4 which includes two comprehensive tables where brief descriptions of the features are summarized and responsibilities are identified. Conclusions and key design features and key recommendations are given in Section 5. Two Annexes are included to provide lessons from past projects and past experience and to record notes and extracts taken from a comprehensive list of publications listed in the References on page 47.

1. INTRODUCTION

1.1 Background

Decommissioning of nuclear facilities has been on-going for a number of decades and a considerable number of projects have been successfully completed. It has been reported that 404 research reactors including critical assemblies, 192 fuel cycle facilities and 14 full size power reactors have been completely decommissioned [1]. The IAEA Director General's background report for its "Vision of the Future" [2] estimates that a total of some 100 research reactors will be shut down between 2010 and 2020 — implying the need to decommission around ten such facilities/year. The past few decades saw a general worldwide decline in the number of new nuclear facilities being constructed or even designed but the situation is now changing with growing interest in a range of new or improved designs for large nuclear power plants [3–7] and reports on developing small and medium sized reactors [8–9], especially in the rapidly growing economies in Asia. While "new-build" has been slow to develop in western countries, the large-scale retrofits of existing nuclear power plants has provided an opportunity to observe where features akin to those for decommissioning would have facilitated these retrofits, thereby providing substantial near-term cost and dose savings.

The available literature on decommissioning of other types of nuclear facilities is also slowly increasing. There are also reports on decommissioning of medical, industrial and research facilities [10–12] and also improved approaches and practices for managing waste from non fuel cycle facilities [13].

The IAEA published a technical report (TRS 382) in which experience and lessons learned from decommissioning projects up to 1997 were documented [14]. These were formulated into beneficial design features that were expected to facilitate decommissioning. This document builds upon the features identified in TRS 382 and adds additional features that have been identified from current experience.

In many countries decommissioning was seen to be a new activity in which there was little previous experience of planning and implementation. Many lessons were therefore reported. These lessons have continued to be reported in recent years and some regulators are now insisting that these be taken into account during operation, for shut down and for future decommissioning activities. Many regulators are also interested in features that may facilitate decommissioning.

With a revival of interest in constructing new nuclear facilities, there are currently about 45 new power reactors being constructed, 9 research reactors and about 19 fuel cycle related facilities [1]. It has been apparent for many years that design to facilitate decommissioning had been minimal during the early years of the nuclear industry although there were publications that have identified desirable design features from as early as 1984, e.g. [6], [14-17]. Many of the publications have considered material properties and their impurities to minimize neutron activation products. These documents and studies are discussed further in sections below.

Several studies have reported lessons learned. The US NRC has undertaken a compilation of studies and reports relating to lessons learned [18–19]. There was also an international conference in Athens in 2006 which specifically addressed lessons learned [20]. The main purpose of recording lessons learned is to benefit those who are engaged in or are planning to engage in decommissioning and subsequent waste management. There is now an additional interest in feeding current decommissioning experience back for the consideration of designers and constructors of new plant and facilities.

1.2 Objectives

The objective of this document is to review lessons learned from decommissioning as reported in international publications and forums and to derive from these the features that can feedback into new designs. A structured approach is proposed to provide a meaningful introduction of justified design features so that those persons or organizations might take responsibility for implementation. The intention is that the logic behind the proposed changes should also be easily understood by potential owners of new facilities so that they can discuss the relevant points with suppliers and designers.

Suggestions for beneficial features to facilitate decommissioning can only be brought to the notice of designers and policy makers. This document does not aim to provide explicit advice. All beneficial design features must therefore be clearly justified in the context of their application. Some features may have safety implications or worker dose considerations and the regulator may also be an important stakeholder in the justification process. Many of the enhancements discussed may also facilitate operational waste management, routine maintenance, refurbishment, retrofits and life extension. The objective may thus be stated as bringing to the notice of designers, policy makers, future owners and other stakeholders the principle that whole life cycle planning of a new facility includes the significant impact of decommissioning and that some relatively prudent considerations during design and construction can be extremely beneficial and cost effective in the long term.

It is also important to note that the design and construction features identified in this report as potentially beneficial to large scale retrofit and decommissioning have been considered on a qualitative basis only and have not been ranked with respect to their cost-benefit.

1.3 Scope, Expected Outcome and Responsibilities

1.3.1 Scope

The document considers the most important nuclear facilities for which decommissioning experience from Member States is available and for which there is a justifiable need to introduce features into new designs that will both facilitate and reduce the cost and timescales of decommissioning. The facilities under consideration range from large power plants and fuel cycle facilities to smaller facilities including research reactors, waste management facilities, nuclear and medical laboratories and radioactive prototype installations. It will also apply to other nuclear facilities with a potential for exhibiting high levels of radiation and significant levels of contamination. It will not include waste disposal, mining and major site reclamation enterprises or recovery from major accidents.

1.3.2 Expected Outcome

The expected outcome will be that actual improvements in design and the design process of new facilities will occur by introducing features that will facilitate decommissioning. Areas of expected improvement include:

- Increased awareness for designers and policy makers of the importance of whole life cycle planning,
- Improved safety and security during operation, maintenance and decommissioning,
- Lower costs and shorter timescales for decommissioning operations, including, licensing, site maintenance, retrofits, dismantlement, waste management and site surveillance and monitoring,
- Less delays in starting decommissioning and a smoother transition from operating to shutdown phases,
- Improved public acceptance when it can be shown that there has been adequate attention given to design, whole life planning, provision of all necessary funding and respect for visual and environmental impact.

Users of this document are expected to vary widely because the design and construction of a nuclear facility, whether large or small, involves complex issues and many interrelated disciplines. These issues and disciplines range from strategic and project planning, complex technical design and construction disciplines, safety requirements, waste and spent fuel management, waste management and disposal options, funding and costs, environmental considerations, national policy, socioeconomic factors and, of course, eventual plans for dismantling and site release.

The document is primarily intended for managers and professionals involved in the preparation of requirements, design and procurement of nuclear facilities and will be of assistance to decision-makers involved in such projects, including operators, regulators and contractors.

1.3.3 Responsibilities for Decommissioning

The stakeholders engaged in the development of any new nuclear facilities include national and local policy makers, financial stakeholders, environmentalists and other public-interest groups and the all important organizations contracted and subcontracted for design, construction, training and sometimes also for operation. Operation may be undertaken by the owner, licensee or alternately under contract with other organizations or specialists. Design, construction, training, regulatory and operating organizations may not in fact exist in some countries that wish to invest in nuclear facilities. All the necessary input, training and financing may then have to be obtained or derived from abroad. This can result in multiple, overlapping and shared responsibilities. This leads to an important lesson learned from such situations applicable to all projects but is especially important for nuclear projects where cultural transition from early design through construction and operation is significant: *that it is necessary to assign lead responsibilities to a single organization and to a single individual within that organization as part of a clear and well-understood top-down structure*. There may also be insufficient suitable facilities in a country for long term management of waste arising from both operation and decommissioning. It is common for some countries to procure nuclear facilities from developed countries through competitive contracting. Lack of suitable specialist contract and project expertise in some countries presents problems.

Training is an essential part of the process to ensure future owners, operators and regulators gain appreciation of the importance of interaction with design and construction activities in planning for decommissioning and understand the design process sufficiently to make effective, timely contributions to it. This will ensure that the relevant design features that will facilitate operations, maintenance, retrofit and eventual decommissioning and dismantling are recognised. Facilities purchased from abroad will eventually have to be handed over to the national licensed authorities who must appreciate the full implications of nuclear liability and waste management. Decommissioning after final shut down is likely to be well into the future and will be the responsibility of the owner/licensee existing at that time. Legislation within the country should provide the framework necessary to ensure that licence conditions are complied with. It is appreciated that, in some countries, all the necessary legislation may not exist. It is possible that some facilities may be under state control e.g. medical applications, research and defence but this does not alleviate the need to define and assign full life cycle responsibilities.

1.4 Report Structure

In Sections 1 and 2 the background in the current nuclear field is reviewed and the relevance and importance of beneficial design features is introduced. A more detailed review of previous and current lessons learned from decommissioning is given in Section 3 where different aspects of the decommissioning process are analysed. From this analysis beneficial design features have been extracted and identified in Section 4 which includes two comprehensive tables where brief descriptions of the features are summarized and responsibilities are identified. Conclusions and key design features and key recommendations are given in Section 5. Two annexes are included to provide lessons from past projects and past experience and to record notes and extracts taken from a comprehensive list of publications referenced in Section 6.

2. SETTING THE SCENE

It is important to review previous studies to identify the concerns that reported from planned, existing and completed decommissioning projects.

2.1 Review of previous studies

One of the earliest identified studies giving some consideration of beneficial design features appeared in a report in 1984 on the design of gas cooled reactors in the UK [15]. The construction of two of the latest design of advanced gas cooled reactors (Heysham II and Torness) was being completed at that time and it seemed appropriate to record some of the decommissioning related features that had been included. This was done without any systematic compilation and analysis of feedback experience from actual decommissioning. The features included detailed attention to contamination control, the careful selection of materials to minimize activation products from trace elements and better facilities for waste management than in the past. There was also attention given to access for the intact removal of active components during dismantling. A preliminary dismantling plan existed.

A first IAEA report on methodology and techniques to facilitate decommissioning was issued back in 1986 [21].

A CEC report was issued in 1990 concerning the influence of design features on the proposed decommissioning of a large sodium cooled fast breeder reactor [17]. It considered the problem of activated products and proposed some solutions for reducing the presence of cobalt. It also made recommendations to improve plant layout especially concerning the effective drainage of all residual liquid metal coolant.

In 1992, Framatome (now Areva) in France completed a study of design improvements to facilitate decommissioning of the French nuclear power plants [6]. It concentrated on limiting the formation of radioactive products particularly from activation but also looked at various decontamination techniques. There was also attention given to plant layout and simplification of pipework and the overall reduction of components. The importance of good record keeping was also highlighted.

In 1992 there was a detailed study intended for public use issued by the US Department of the Army [16]. It covered a wide range of facilities such as power reactors, research reactors and accelerators, radiographic facilities, depleted uranium management and research laboratories. It included some detailed design aspects and recommendations.

As result of increasing awareness of avoidable problems during decommissioning as reported in numerous publications from those involved in decommissioning, the IAEA compiled and published a detailed technical report (TRS 382) in 1997 [14]. This document drew on feedback from nearly 70 published references and included some reported national experience in appendices. The TRS was comprehensive and specifically addressed plant layout, biological shielding, material specification, material handling, contamination and post shutdown considerations. It recommended that designers should be aware of decommissioning needs and should consider beneficial design features. The document was made available to all Member States. It is not clear to what extent this document has been referred to in current designs.

A recent publication for the new Westinghouse AP1000 reactor show encouraging attention to beneficial design features for decommissioning and shows recognition of lessons learned from the past [3], [4], [22], [23].

In 2007 and 2008, the European Utility Requirements (EUR) Coordination Group issued two documents for new LWR designs. There are chapters dedicated to decommissioning requirements [24], [25].

A study of decommissioning activities at the Atomic Weapons Establishment (AWE) in the UK was presented at an international conference in 1998 and addressed the problems of decommissioning a wide variety of non-power plant facilities [26]. It emphasised the need for considering decommissioning aspects during design and proposed value engineering workshops to highlight awareness at all stages of design.

The US Department of Energy (DOE) has proposed a task to identify design and operation features with respect to improving Generation IV reactor designs (the future designs [7]).

In 2006 The US NRC produced a list of decommissioning lessons learned in support of a Standard Review Plan for new reactor licensing [18] and in 2008 the OECD produced a vision statement called: Decommissioning Experience – added value for design of new plants [5].

Although carried out specifically from the waste management point of view, a recent IAEA study [27] provides a broad-based look at the value of early attention to design for decommissioning to minimize waste.

There have been a number of other publications mainly presented at seminars and conferences by companies and individuals which are discussed in section 3 below where relevant or included in Annex II .

2.2 Policy, Strategy and Life Cycle Planning

The main task

One of the main tasks is to try and influence design organizations and policy makers about the importance of taking account of the needs of decommissioning in new designs. It is recognised that introducing the concepts into these organizations is complex and could be problematic. However it would be incorrect to say that the designers and policy makers of the earlier generation of nuclear facilities did not consider decommissioning and waste management issues but actual experience in decommissioning was minimal and there were only vague perceptions. The greatest attention for designs at that time was given to safety, constructability, operability, reliability, maintenance and the possibilities of operating life extension. It is noted that attention was given in earlier designs to limit the amount of trace elements in materials that would give rise to long lived activation products. This was largely to reduce operator exposure. Consideration was also given in some cases to contamination control, particularly concerning primary circuit activity, but much of this was to facilitate maintenance.

In recent years it became very clear, due to a number of reported incidents, that little attention had been paid to the decommissioning and waste management of numerous small non fuel cycle components and facilities in the industrial, medical and research field and this prompted world wide attention. Disused nuclear sources were a particular problem but there were also larger items like accelerators and cyclotrons that had no plans for decommissioning or any specific features to facilitate this and no funding. A detailed IAEA Technical Report was published in 2003 [10] which highlighted the decommissioning problems in small facilities. There is now legislation in force and guidelines in most countries to control the use, management and decommissioning of these small nuclear components and facilities.

Delays in engaging in decommissioning

The legacy of minimal experience in decommissioning and the primary attention given to operational and safety priorities, has contributed to the current technical difficulties, to delays and cost of decommissioning. Indeed it has only been in recent years that the high cost of decommissioning and waste management has been fully realised. Much of this burden has now to be borne as intergenerational debt since decommissioning may take many decades to complete. This is reflected in the relatively small number of the larger facilities that have been dismantled satisfactorily as reported in Section 1.1 above. A number of shutdown facilities have been put into a safe enclosure status awaiting funding, waste disposal facilities and incentives and impetus to engage in conclusive decommissioning. There are a few instances of in-situ decommissioning e.g. the encapsulation of a research reactor core in concrete in the Republic of Georgia (entombment) [28], but many shutdown facilities have been left with no decommissioning plans or funding.

Some decommissioning projects however have been taken to completion in circumstances where funding and expertise was available and sometimes where a public demonstration of the ability to completely dismantle a facility was thought to be desirable. Some projects have been undertaken where a site needed to be reclaimed for reuse e.g. at universities or research laboratories. It is generally accepted that there are a few facilities that can not be promptly dismantled. This is usually due to very high dose-rates and/or contamination from an accident or other unusual situations.

Whole lifecycle planning

Life cycle planning with a view towards eventual decommissioning has been discussed in several reports [29], [30]. It is now being recognised by many state and international organizations that attention must be given to the whole life cycle planning of a facility and inbuilt features and measures must be incorporated to achieve a cost effective enterprise. It is important to note that waste management is a vital part of the whole life cycle planning. The options and facilities for waste storage and eventual disposal must be taken into account. Whole life planning also includes a consideration of the future uses of the site.

A company involved in decommissioning has produced a paper on design-for-decommissioning (DfD) which emphasises the importance of planning and designing for decommissioning. The term DfD (design-for-decommissioning) is used by the authors to connote this activity and it is compared with the strategy of Defence-in-Depth (DiD) for safety systems. The authors claim that the huge cost of decommissioning a large facility can be minimized by considering whole lifecycle design and cost and recognises that decommissioning requires new facilities which, in turn need decommissioning and the aim should be to minimize this self perpetuating cycle [30].

As noted in the preface to this document, all new nuclear facilities are expected to have a decommissioning plan (DP) that is acceptable to regulators to meet the widely-endorsed IAEA expectations. Many reported “lesson learned” emphasise that the plan needs to be prepared during the design phase of a new facility. It should be recognised that this can only be in preliminary form (PDP) at the early design stage and may not, in itself, necessarily identify all features that might facilitate design. Reasons for this are that the final decommissioning plan will depend on facility operating history and legislation at the time of decommissioning. To counter this, the available decommissioning experience must be fed into the organization as the design develops. Until now the main purpose of the preliminary decommissioning plan has been to identify a feasible decommissioning methodology and to yield sufficient information for a budgetary cost estimate required for the decommissioning fund.

The task ahead will be to try and influence the policy makers and design organizations to incorporate whole lifecycle planning as the design progresses in order to include desirable features that will truly simplify and expedite decommissioning. Some features are likely to add to overall initial costs and will have to be justified against the potential cost saving during the entire plant life-cycle i.e. operation, maintenance, waste management, retrofit, decommissioning, waste disposal and preparation of the site for re-use. Design organizations are generally quite independent of organizations that are currently undertaking decommissioning. In fact, the incentive and motives will be quite different for designers, these being essentially to concentrate on licensing, safety, operational performance, efficiency, constructability, life expectation and cost of new plant. The influence of policy makers is particularly important in this respect because they should have overall responsibility and be more able to address long term planning issues and convince designers that attention and expenditure during the design phases is justified.

Role of Regulators and State Organizations

The regulator plays an important role in encouraging (and sometimes prescribing) the attention to be given to planned decommissioning and waste management activities. In fact a decommissioning plan (DP) is now a licensing requirement for nearly all new facilities. This establishes a need to consider decommissioning strategy, proposals and cost estimates but, in general, does not deal with specific dismantling details. Features that may reduce or limit the risk of exposure to operators and even the public during decommissioning will be of interest to the regulator. Features that will shorten decommissioning times and hence reduce risk will also be of interest to the regulator. Shutdown and dismantling is often so far into the future, that the present-value discounted cost of decommissioning can be quite modest over these long timescales (currently 60 year operating life is being considered for some NNP facilities). Therefore, incorporating features that may incur investment costs today and may result in additional manufacturing and construction delays may not be easy. The government authorities in a country have many roles and must consider the net benefit to the community balanced against the long term risks and costs. There is a responsibility to protect the environment and the economy in terms of risks and hazards as well as benefits. Attention must therefore be given to the entire plant life-cycle.

It is also very important for owners/licensees/ policy makers to consider the local and national public impact of any proposed new nuclear facility. This is dealt with in some detail in terms of decommissioning in a relevant IAEA publication [31]. The broader issues associated with public relations and public acceptability are outside the scope of this report but the question of the decommissioning liability is included. For new facilities, it will be most important to be able to demonstrate that all lessons learned from decommissioning activities are being considered in new designs and that features are included to minimize the impact of decommissioning in terms of cost, feasibility, safety, demand on resources and waste management. A reduction in intergenerational debt will help to engender public support for new facilities.

2.3 Approach

A large amount of published information is available on experience from decommissioning all types of facilities. Much of this accumulated information has been translated into lessons learned to feedback into decommissioning projects that are planned, are about to start or already on-going. Much of the lessons learned experience is directed at avoiding problems and pitfalls for current or immanent decommissioning projects but many lessons have identified desirable features that might be incorporated into new designs.

The approach adopted in this report is to analyse available and relevant published documents and to extract factors and features that could and should be incorporated into new designs. This has sometimes meant interpreting information in the literature and extracting items that should be considered. This has been done and recorded in Annex II. Many authors of publications did not, at the time, envisage any feedback to new designs, but saw their publication or conference paper as a means for reporting success and/or difficulties experienced during a particular decommissioning project. Where such valuable and meaningful information is revealed, it has been drawn upon in Annex II to formulate features to feedback into designs. There are also a number of publications that are specifically written to highlight beneficial features. These are particularly those produced by large organizations such as the IAEA, US NRC, US DOE, OECD/NEA etc. In addition, due to design certification procedures currently required by major designers, much information on decommissioning is available on Safety Bodies web sites. These documents and studies have been consulted and the purpose here is to enhance and build on these using the most recent information.

The approach adopted is to collate and clarify particular design features and identify those who might be responsible for assessing, justifying, or modification of new designs. Suggestions are made on how the beneficial features might be communicated to designers and policy makers. Some conclusions are given with recommendations.

Annex I contains examples of lessons learned from past and ongoing decommissioning projects. Annex II is included to record extracts and interpretation of relevant material from published references that have an important input to this report.

3. SUMMARY OF RELEVANT LESSONS LEARNED FOR DECOMMISSIONING

A detailed survey has been made of published literature on lessons learned from decommissioning projects in hand or completed. There have been significant similarities between many of the lessons learned and in recommendations made which reinforces their validity and importance. Some lessons are somewhat specific and unique to a particular project but can provide meaningful features that could be applied elsewhere. The information on lessons learned has been grouped loosely into 4 sections in Annex II. In order to present the information below in a more systematic way the following categories have been used.

3.1 Policy and Strategy

A most important requirement for all future nuclear facilities is to have an appropriate decommissioning plan. This has been a long standing licensing requirement called for by most regulators. Recommendations for the contents of a decommissioning plan (DP) have been available for some time and included in a number of IAEA reports [32], [33] [94] This document will initially have to be a preliminary decommissioning plan (PDP) and will be replaced or enhanced as design and construction progresses. The regulator will generally not provide an operating licence until the DP has been approved. The DP will need regular review and updating during operation and at final shut down. It should be realised that the actual shutdown of a facility can be earlier than planned and the DP should be ready for such an eventuality.

There must be at least sufficient detail in a preliminary plan to establish the feasibility and practicality of decommissioning to satisfy the regulator and other stakeholders and to derive reasonably reliable cost estimates to enable a decommissioning fund to be set up. The PDP does not and usually cannot enter into descriptions of detailed activities and techniques and it is not possible to finalize the document until the design is complete. Information needs to be exchanged between the designers and the PDP author(s) as the design develops. It is usually recognised that higher management and policy makers together with the national regulatory authorities within a country should accept responsibility for establishing policy and strategy pertaining to this process. Future uses of the site should be reconsidered at least at the beginning of the decommissioning phase after shutdown, if not earlier.

It may not be possible to decide on the final dismantling strategy at the early design stage. This is because available information and national policy may not be able to resolve the relative merits of such alternatives as immediate dismantling of the reactor core, or long term safe enclosure or even the feasibility of in-situ decommissioning and there will be waste management issues. The IAEA has published a technical document on the subject of on-site disposal (in-situ) as a possible or necessary strategy for decommissioning some facilities [28]. The alternatives may be considered and options explored but they may not be finally decided upon. This may affect some aspects of design. For example, if in-situ dismantling is selected, then the importance of activated materials within the core may be less significant than the very long term durability of the enclosure as a waste containment for the safe enclosure option. The characteristics of activated materials will, of course, be important for a safety case for any decommissioning strategy. The careful design of the external and accessible systems will however always be important if the dismantling of these involve radioactive contamination and waste generation. In the earlier stages of conceptual design, it is likely that the details of these systems and the associated peripheral plant and equipment will not be specified or available. During the early design stage it is important that the basic principles of decommissioning are understood by those involved so that design-for-decommissioning (DfD) can be implemented.

A further difficulty will be the need for establishing early cost estimates for decommissioning and waste management as a basis for provide a long term decommissioning fund. There is flexibility in this because the monetary discount rate for this fund can and will be adjusted over time. There also exists published data on the cost of some completed decommissioning projects and methodologies for making estimates. This is referred to in Section 4.

Very often those involved with current or completed decommissioning projects have been operators who are very familiar with the plant or have been specially trained in decommissioning and sometimes in maintenance or retrofitting. Some also have related experience in waste management. However, not many engineers with such decommissioning experience were involved in the earlier generation of designs since much of the design and construction was performed many decades ago before such experience was generally available. Likewise, the current generation of design and construction engineers involved in current designs are unlikely to have decommissioning experience, since their training rarely involves engagement with decommissioning and waste management practice. This lack of appreciation for the importance of decommissioning experience to design means that the existing published information on decommissioning (and the associated lessons learned), while extensive, is not easily assimilated by design organizations. This gap needs to be bridged and is a challenge to managers, policy makers and especially educators. It is emphasized here that design organizations should include decommissioning expertise in the design team and have access to additional experts who would be available for consultation as the design develops.

There have been concerns expressed about the diminishing pool of nuclear skills, which has prompted positive training initiatives in Europe. This was reported in a UK publication on lessons learned [34]. The UK Department of Trade and Industry is leading a Nuclear Skills Initiative and the UKAEA is sponsoring a postgraduate degree course. The response is not confined to formal training: the EC Framework Programme supports the establishing of networks and consultative committees. There are institutes in the North of Scotland in the Dounreay area, in France at the National Institute of Science and Nuclear Technology (INSTN) and centres in Rome and Ljubljana which support such training. In the US there is a centre at the Idaho Falls National Laboratory.

The importance of sharing decommissioning experience and working together within the world nuclear community is a notable recommendation from lessons learned [34].

3.2 Licensing and Safety

All nuclear facilities must be licensed. This is sometimes in the form of multiple licences issued separately for design and construction, operation, shutdown and decommissioning and possession. Alternatively, an all-encompassing licence can be issued with the intention that it will only be revoked when all radioactive material has been disposed of or is no longer in the possession of the owner or licensee. The practice varies from country to country and may have an influence on responsibilities for decommissioning.

The prime role of the regulator is to ensure safety during construction, operating and decommissioning and when a site is made available for reuse. The regulator may not have a direct interest in features that facilitate decommissioning provided more general safety requirements are upheld but some regulators may take a greater interest. If, for technical or financial reasons, decommissioning is delayed or postponed indefinitely due to technical or funding difficulties, then the level of regulatory interest may rise. The cost burden of delaying the completion of a project and engaging in necessary care and maintenance is likely to be borne by the owner. In some countries the cost of regulation may be passed onto the licensee and may be significant. Design features that will permit prompt completion of D&D and de-licensing of a facility can be very beneficial and cost effective. Final release of a site for general use after extended delays is often a difficult problem and subject to significant regulation and cost. Furthermore the surrounding population of a non-producing or a shutdown facility may be less supportive of its presence if it no longer employs significant numbers of local staff or does not serve the local community. Public pressure may accelerate dismantled so that the facility can be replaced with one providing beneficial use. The potential for conflict between regulatory requirements and cost, schedule and programme control is an important consideration driving increased early attention to decommissioning [30].

3.3 Radiation Protection and Optimization of Shielding

Of concern to operators and the regulator is control of radiation exposure to operators, the public and the environment. During operation some exposure to operators is unavoidable during certain activities such as inspection or maintenance and this exposure, which must be within the legal limits, is tolerated due to the net benefit that operating the facility yields. During decommissioning however there is little direct benefit or revenue derived and there is greater incentive to minimize exposure. Considerable attention may be given during the design phase to achieve this but all additional costs must be justified and the degree of shielding optimised. It is appreciated that this justification is not always easy to quantify. Proposals have been made to provide modular shielding for easy removal. There is an incentive to avoid over-design of shielding because segmenting and dismantling of massive shielding structures has been a particular problem associated with significant costs during decommissioning.

There is also the risk of additional exposure as a result of an unexpected increase in radiation levels that may be experienced during dismantling. This could be a result of increased doses from operating or decommissioning activities, operational incidents or as a consequence of poor working practices. The consequences of poor design and operating practice may also result in site and ground contamination which will have serious consequences for final site release and clearance. It is recognised that operational radiation exposure was taken into account in designs made many decades ago but this was directed mainly at protecting operators and maintenance workers and usually did not take account of situations with partially dismantled structures. There is also the additional exposure that may result from the handling and storage of waste. There is a need to pay attention in design to provision of appropriate storage facilities for waste produced: additional hazards are created when operational wastes that have been stored in inappropriate facilities are recovered for conditioning e.g. from poorly maintained underground concrete bunkers.

3.4 Project Design and Management

While many of the studies of "lessons learned" have reported on features that could have significantly reduced the problems encountered during decommissioning projects, to simply list these is not sufficient. Motivation of the project owners, managers, regulator and other stakeholders must be considered. It is the responsibility of management and policy makers to ensure that beneficial features are considered and incorporated where justified. In this regard, the interests of the owner and financial investors is to ensure that appropriate attention is given to factors affecting overall benefit versus liability of a nuclear facility. Management willingness to focus on features mitigating decommissioning may be reduced by competing design challenges and priorities. For example, many facilities are now being designed for 60 year operating lives compared to only 30 years in previous designs, which puts great emphasis on expensive-to-achieve features such as component life. Finally, while expecting the facility owner/operator to consider features facilitating decommissioning, the regulator may choose to impose its authority only on matters directly related to safety regulations or defined in licence conditions.

Nevertheless, there is evidence the message concerning the importance of incorporating features to facilitate decommissioning at the design stage is being heard. In Member States where mature design, operating and decommissioning experience exists in an integrated nuclear industry, the benefits of design features sympathetic to decommissioning are now more likely to be recognised through experience. See references [3], [4], [6], [7], [35], [36]. There have been particular initiatives taken in the EU where designers Westinghouse and Areva have submitted design proposals incorporating features beneficial to decommissioning of the AP1000 and EPR reactors [23], [24]. There still remain the overriding incentives to develop designs with efficiency, economy, reliability and easy-build as prime objectives. Facilitating decommissioning is not likely to be considered as a primary objective.

The inclusion of additional desirable features may be more problematic for Member State organizations who are embarking on or considering nuclear facilities for the first time and who are reliant on importing developed technology. They could be vulnerable to domination by large vendors if they lack suitable expertise and experience in specifying their particular needs, design features and factors that are in their own interests. International competitive tendering is particularly difficult because any additional costs to allow for beneficial features for decommissioning in the distant future may not be on offer under intense competition. Guidance and appropriate training will be needed to empower these organizations and advantage should be taken of existing international expertise and technical cooperation in this regard. It will be in the long term interests of countries investing in new nuclear facilities to obtain expertise able to assist them in formulating and negotiating their requirements concerning features to facilitate decommissioning.

3.5 Waste Management and Decontamination

It is apparent that in the planning, design and construction of nuclear facilities decades ago, the potential problem of waste management associated with decommissioning was not understood or it was deferred for future attention which often never occurred until the decommissioning phase. In recent times, extensive examination of the problem has resulted in provisions for processing and storage of decommissioning waste. This is reflected in the reporting of numerous lessons learned from problems previously encountered.

Those involved in the management of spent fuel have also reported similar problems to resolve. In many cases the lack of facilities and procedures to deal with both waste and spent fuel seriously delayed decommissioning of shut down facilities. In the period from 1980 to the early 1990s, there was extensive international activity to develop additional on-site wet and dry spent fuel storage facilities (ISFSIs) at many nuclear power plant sites due to the unavailability or shortage of reprocessing or centralised interim storage facilities. The more recent provision of licensed interim spent fuel facilities on and off-site has benefited some decommissioning projects. This has now enabled shutdown reactors to be defueled promptly and decommissioning projects to proceed. While there are still no major licensed waste disposal facilities in most countries for long lived radioactive waste material above the lowest activity levels (i.e. above LLW and VLLW levels), the availability of on-site interim safe storage of waste has also enabled many decommissioning projects to proceed. The licensing and timely provision of waste conditioning and interim spent fuel storage facilities is now an undisputed requirement of new nuclear facilities. This need for interim storage applies not only to nuclear power plants and fuel cycle facilities, but also to licensed medical, industrial and research establishments. This has often been overlooked. Waste management is still a costly process and numerous reported lessons learned reflect the inadequate attention to waste stream identification, waste minimization, spread of contamination, process simplification and recycling.

In many countries there is no clear long term waste management strategy and a minimal legislative or regulatory framework. In the absence of well-defined disposal acceptance criteria, the result has been the interim storage of waste without conditioning for disposal. This situation is unsatisfactory for decommissioning, as it is not possible to optimize the decommissioning waste management (or even the segmentation and characterization steps of decommissioning) without a complete picture of the anticipated waste management practices. Without this clear picture, design features facilitating waste-management for decommissioning are also impeded.

3.6 Documentation and Records

There are numerous reports concerning the inadequacy of records identified and retained for decommissioning. There have been important publications in recent years to give guidance in addressing this persistent problem [32], [33], [37]. The operators of facilities have generally been responsible for records and experience has shown that the emphasis has been dominated by attention to safety records, operating records, operating and maintenance procedures, operating licence requirements and a tendency to retain all original design and construction details. This volume of records can amount to millions of hard copy sheets. Needless to say the number of records useful and essential for decommissioning have been swamped and very often lost because there was little perception by operators of the needs for decommissioning. Similar situations have occurred in smaller nuclear facilities which include medical, industrial and research facilities. There are numerous instances of records of spent sources being lost and minimal records available for research and industrial facilities. The loss of records has not usually resulted in an inability to dismantle or to manage waste but costs have increased due to re-establishing data by measurement, inspection and sampling and risks may be higher due to delays [10–12].

It is concluded that the main reason for inadequate record keeping for decommissioning has been a lack of any understanding of the specific requirements for decommissioning and a misguided belief that, if everything pertaining to a facility is retained, this will suffice. Experience has shown that the essential records required for dismantling purposes are often quite modest and there is a need to identify these during the design phase and to retain them as specific documents. As part of the transition to decommissioning at the time of shut-down, it has been recognized that a concerted effort to segregate important documents for decommissioning is vital for future decommissioners. This requires checking these documents for accuracy against the current plant configuration and to augment them with anecdotal information from operational staff. It should also be noted that not all important records are in paper form. Sometimes photographic records are more valuable than paper records or obsolete drawings. Important records include samples of the original structural material that is likely to be activated or contaminated and also details of the original radiological Characterization of the site as a baseline for eventual site clearance. This information often has little apparent value for operators who have been the custodian of records during the operating years.

Many modern records will now be in electronic form which raises a new problem of retention in readable format and maintaining the necessary processing hardware and software over periods of up to 100 years. This must be addressed by present designers and managers and operators who may be the custodians of records.

4. DESIGN FEATURES TO FACILITATE DECOMMISSIONING

This section extracts the beneficial features that should be considered throughout the planning, design, construction and operating phases of a nuclear facility. While many of the features are specifically relevant to nuclear power plants, research reactors and fuel cycle facilities, most apply to other facilities using nuclear materials such as research laboratories, industrial and medical facilities. It is recommended that those responsible for planning, design and construction of such new facilities interpret and use those most appropriate to their particular facility.

4.1 Basic Considerations

The overall process of incorporating beneficial design features can be simplified by recognising that the problem can be addressed by initially identifying the plant and equipment which is most likely to become activated or contaminated and thereby give rise to radioactive waste. Access for component disassembly and removal, barriers to prevent release of contamination, adaptation of auxiliary facilities and services such as electricity and ventilation and the change of use of areas of the plant to permit them to be used for disassembly should also be dealt with in the overall design philosophy. In terms of a nuclear power plant, this mainly concerns the nuclear island but includes some external facilities such as interim storage and essential services. Design consideration should ensure external non nuclear systems and services do not become contaminated. All conventional plant could then be subject to conventional industrial demolition. Special features in their design, other than those required to implement general industrial safety, are less likely to be relevant. Consideration should be given to items such as active drains or pipes that might pass through conventional plant areas. Radiochemical and fuel cycle facilities can be more complex and much of the site may involve systems for conveying radioactive process materials and wastes. However such designs should aim to confine activity to hot cells and glove boxes or other forms of containment. Piping radioactive liquids across a site should be minimized or avoided. If they are required, these pipes should be double-contained with monitoring and leak detection.

Life-cycle planning is a policy issue for all new designs [29–30]. This leads to an important aspect to consider in designing plant layout and the interconnection of services between multiple units on a site. Unless recognised and planned for, problems will occur when part of the facility or site are shut down for decommissioning while other parts remain in operation. There are many instances where this has occurred in practice. Often services and other plant and equipment are shared during normal operation and sometimes provide redundancy and back up safety features. How the shut-down portion of the plant is to be separated and detached while the remaining portion of the plant remains in operation needs to be considered in design. This should be integrated with consideration of routine maintenance planning.

4.2 Facility Design and Operational Design Factors

It has been found from experience reported internationally from numerous decommissioning projects, that very few dismantling problems are insurmountable but difficult problems cause delays, cost increases and potential safety hazards. This has lead to many lessons learned being reported which need to be considered in planning the design and operation of new facilities.

Some of the more obvious features to improve *both* operation and decommissioning were included in reactor designs made many decades ago. Much of this was to minimize activation to avoid exposure to operators and to facilitate maintenance. The excessive use of stainless steels in high neutron flux areas for example has increased the quantity of long-lived activated waste.

Features that will benefit or facilitate decommissioning vary in importance. Some will be inherent in the design and would be introduced for operational and maintenance reasons and some will be introduced as representing “good practice”. There may be no cost penalty for some but all the features should be identified if also intended as an aid to decommissioning. Some facility design factors will have cost and programme implications for design and construction as well as for operation and plant reliability and these may tend to push the design in opposite directions. For example, providing desirable features for decommissioning may be in conflict with optimum functional design for operation. Examples include the use of modular shielding, improvement of access provided specifically for final dismantling, provision of special features in pipework layout (e.g. design to avoid radioactive crud deposition) and the minimization of embedment of items in walls and floors.

Although the evaluation may be difficult and contentious, consideration should be given to all possible desirable features and a record made of their disposition. Whether features are subsequently incorporated in the design, or rejected, may have an impact on the estimated cost of decommissioning and systematic adjustments to both changes in facility cost and projected decommissioning cost will need to be tracked systematically. An IAEA document addressing radiation protection aspects of design for nuclear power facilities offers useful advice relevant to this process [44].

A surprising observation from a recent review of the Westinghouse AP1000 design is that several features which facilitate retrofit and decommissioning may actually reduce the reactor cost [3–4], [22–23]. These, of course, should be easy to justify for decommissioning purposes.

An important initiative has been the publication of Terms of Reference for future designs of PWRs in the EU [25]. This document refers in particular to the UK-EPR. There has also been particular attention given to safety issues [22], [38–39]. In Canada the regulator has included decommissioning amongst the technical and safety aspects of the for new reactor design [40]. The Canadian approach identifies and documents the disposition of all potential enhancements to design in order to facilitate decommissioning [41]. It is important to have the involvement of experts with direct experience in dismantling and decommissioning in the evaluation and disposition process of these design features.

Research, science and process facilities have characteristics and features in addition to those found at reactor plants. Equipment examples include hot cells, glove boxes, laboratory sinks and hoods; in particular, hot cells can become highly radioactive from internal surface contamination. Process facilities are often characterized with many chemical fluid systems and storage tanks of large size. A design review guidance report (60) written for application to the U.S. Department of Energy focuses on these types of facilities.

The range of beneficial design features that have been extracted from the published literature and are listed in Tables 1 and 2, together with suggested responsibilities for implementation. Summaries of the extracted information are given in Annex II. The most important features are highlighted and discussed as follows. These are mainly related to Table 1:

(i) Minimization of Activated Products

The need to minimize trace elements that will give rise to activation products from neutron flux has been well known in the nuclear industry for many decades. There are, however, still attempts to minimize this even further. Cobalt and Nickel present a particular problem where high strength corrosion resistant steels are necessary. For example, Framatome, (now Areva) in France has recently reviewed its specification of steels for pressure vessels, internal components and steam generators [6]. One approach considered in this review is to focus on narrowing the range of acceptable trace-element concentrations rather than on their reduction alone. In this way, management of the consequences of the activation can be made more uniform. The issue of activation product minimization is also being addressed in the Czech Republic by SKODA Nuclear Machinery [42]. In addition, BNFL in the UK are studying the optimization- of shielding design to minimize waste volumes during decommissioning [43]. A similar strategy has been proposed by Binner [98], who discusses the potential value of using am absorber for thermal neutrons on the outboard side of reactor bioshields. Important considerations are a balance between specifying material properties to meet exacting operating conditions for safety and durability versus the benefits of easy dismantling and waste management. The trend for future reactors is to increase performance and to have longer operating lives hence more durable materials may be exposed to higher neutron flux. It is possible that this may lead to increased reliance on a safe enclosure decommissioning strategy for some high performance facilities to gain the most from radioactive decay. For example in the UK a delay of up to 100 years before dismantling large graphite moderated gas cooled reactor cores has been considered to allow man-access and to avoid the use of robotic techniques. Initiatives to continue reduction of activation products in new designs are commendable, but pose difficult trade-offs involving additional costs, effects on operating life and system performance.

(ii) Rigorous Contamination Control and Provision of Decontamination Facilities

There are numerous reported lessons learned regarding the decommissioning of contaminated facilities where it was emphasised that good working practices could have avoided costly clean up activities. This begins with consideration of the flow and transfer of workers and material across the site, particularly from contaminated to non-contaminated areas. Some contamination may be attributed to the lack of suitable decontamination equipment when it was most needed. Such problems are sometimes exacerbated by the absence of records, especially if long delays take place before any action is taken or if no action is taken at all. The motivation to maintain high plant availability and reduce costs has sometimes contributed to this omission. There are many instances were decommissioning has been delayed by the discovery of unexpected contamination, often in routinely accessed places. The use of underground, embedded active drains has also presented frequent problems as have underground tanks with no provision for secondary containment or leak detection. It is clear that attention to such issues at the design stage could have avoided difficult problems during decommissioning.

There is an ongoing international development of decontamination equipment and techniques as well as new surface coating materials to serve as a barrier against ingrained contamination. An example recently published is the development of extremely durable epoxy surface-sealing membranes [45]. The essence of effective contamination control is good working practices and training of operators. Training in this regard is required before a plant is put into operation. The above considerations apply equally to small medical, industrial and research facilities. Research laboratories are particularly vulnerable to spread of contamination because of the transient nature of experimental work. Particular attention needs to be paid to waste routes, local waste management facilities and discharge systems from experimental facilities. Procedures should be in place to ensure that research projects include the requirement to dismantle all test rigs and apparatus and to decontaminate hot cells and glove boxes when a particular research project is concluded. Often equipment has been left “as is” and without adequate decontamination or documentation for the next experimenter.

(iii) Easy Access and Adequate Space for Dismantling Radioactive Items

The method of removal of large complex and highly contaminated items, where access is restricted and elevated dose-rates are present, requires particular attention by layout designers. While installation of new and complex items may be quite straightforward during construction i.e. when systematic hands-on component assembly can be done, the additional problems encountered can be quite severe when items are contaminated or deteriorated by corrosion or mechanically damaged so as not to be easy to disassemble. Sometimes the physical integrity of components may be suspect and even lifting attachments may have deteriorated. In addition to normal hazards associated with removal and lifting of heavy items, there may be changing radiological hazards to address in making dismantling safety assessments. Special equipment and procedures have had to be developed by decommissioning operators to overcome difficult access and removal problems when they could sometimes have been easily avoided by judicious and thoughtful design.

It is recognized that the provision of adequate access during layout design may be costly and difficult to achieve in practice because of the competition for space and the large number of factors that need to be considered. Additional access specifically for dismantling that will only be required in 60 years time or more may be difficult to justify. An important aspect is that designers also need to consider access for routine maintenance and for retrofit as part of long-term strategies for aging management and life extension. If adequate access is not implemented at the design stage, the problem should be recognised and suggested solutions included in the Decommissioning Plan together with a cost allowance for addressing these additional difficulties. An example of conflicting requirements for access is seen in a new proposed design by Westinghouse for the AP1000 reactor where the reactor island is considerably more compact to reduce material volumes, waste and complexity, raising the question as to whether there will be sufficient access for decommissioning as is claimed [4], [23]. See also aspects of modular design below.

The use of CAD (computer aided design) is now in common use in layout design and may help to anticipate future dismantling problems. Aspects and features of access that may facilitate dismantling need to be introduced to designers. This should include training in layout and access for decommissioning.

(iv) Modular Designing for Easy Removal

A number of difficulties have been reported in lessons learned regarding the removal of large items of contaminated plant because it was not possible to dismantle them in situ. It has been suggested that design and construction in modular form would greatly facilitate removal and reduce exposure to operators. It is appreciated that modular construction is likely to be more costly and may reduce reliability or integrity if prone to leakage or other faults and therefore a compromise must be reached. An approach avoiding this limitation is to make the whole facility smaller and modular. In particular, glove boxes and even hot cells should be designed for intact removal, if possible. For small and medium sized reactors and research reactors it may be possible for major components to be removed intact. There have been a number of decommissioning projects where the whole reactor vessel has been removed intact e.g. Big Rock Point (See Annex I) and the research reactor removed from a university building at Greenwich in the UK. Additional examples of new, small reactors which may offer this feature are given in references [8] and [9]. There is a small geothermal plant being developed in Germany, for which a key design feature is modular construction that allows the facility to be removed intact from site [46].

The new AP1000 Westinghouse reactor provides many examples of features, including modularization, that have been proposed as part of the decommissioning strategy [3–], [22]. These features include a much simplified plant design and layout, a common integral base mat for the reactor containment building, modularisation of many large components including shielding walls, attention to leakage containment especially for spent fuel pools, adequate space for work in radiological areas, facilities for major component replacement e.g. steam generators and special attention to waste management and contamination control.

(v) Segregation of Contaminated Items

There are likely to be a number of plant items and components that are delivered to site as large intact items such as heat exchangers, cooling pumps and motors. Very often these are built as self-contained units in the manufacturer's works and tested before dispatch. The ability to handle these as a unit may facilitate removal during decommissioning. This will require attention to the access pathways such as airlocks, which need to be large enough to accommodate complete units. Some items may only have particular parts contaminated and the ability to separate these easily from non-contaminated components will be useful. Quite often pumps have integral motors and exposed controls that can become contaminated internally. This leads to mixed wastes due to the various complex materials used for electrical wiring and insulation and may become a waste management and disposal problem. Lubricating oils should also only be used in non-contaminating situations, if possible, to avoid the difficulty of managing radioactive waste oil. Specifying drive units and electronic controls that are well-separated from the process streams through the use of housings, separate lubrication modules or special sealed bearings should be considered.

(vi) Providing the Ability to Segment Large Items In-situ

Proposals for segmentation should be outlined in the decommissioning plan and retained as a long-term record. Guidance procedures should be given in as much detail as possible

Ideally, areas of the plant needed for equipment lay down or dismantlement during decommissioning should be identified during design and provisions made to convert these for this use during decommissioning.

In some case the only practical solution may be to segment items in situ. In addition to size or complex geometry, this may be due to high activity levels in some components e.g. trapped or deposited-build up of contamination. This may also be driven by layout constraints or inadequate access for lifting equipment. It is appreciated that it may not always be possible to give adequate access for intact removal of components due to requirements of the design such as the need to maintain shielding and containment integrity. In this case consideration must be given to segmenting of items in situ and account should be taken of the practicality of this and the consequent dose to operators. A good example occurred with dismantlement of the boiling water Gundremingen reactor in Germany. This was part of a research project to overcome difficult problems in dismantling large reactor components. For the case in point, it was necessary to freeze water in the heat exchangers to create stiffness in the tubes which allowed them to be cut in-situ with a mechanical saw prior to removal in segments [47].

(vii) Design of Ducts and Piping Systems

Numerous problems have been reported concerning the build up of crud and contamination in ducting systems and pipework due to lack of attention to configuration and layout. Problems occur at regions of low fluid flow and at low areas or "inverts" where deposits can build up and become radiological hot spots. Changes of piping cross-section and pipe-junctions can result in build up of deposits. It is realised that sometimes invert sections of pipes and ductwork and certainly junctions are unavoidable and in these cases consideration should be given to drainage connections and inspection covers. The problem can be exacerbated when facilities are shut down for long periods or are finally shutdown and there is a delay in the start of decommissioning. Sludges and deposits can solidify in pockets in the pipework especially if the system is only partially drained. Examples of problems identified in pipe and duct layouts are given in an IAEA technical report [14] and elaborated in references [3], [16], [35–36] and [48]. Care should be taken when using passivating or decontaminating additives to inhibit/remove corrosion in pipes, as these can lead to chemically insoluble or impervious layers as well as crud formation.

The issue of sludge and deposits is exacerbated by the embedding of pipes and ducts in walls and floors, which should be avoided as far as possible. For dose reduction and to avoid spread of contamination, concentric pipes or ducts or similar confinement should be provided where appropriate. Leak monitors should also be provided. Where it is necessary to seal penetrations through walls and floors, design features should be devised to ease final removal without the need to cut concrete or masonry structures. Where possible, embedded sleeves would be preferable in order to allow sections of pipes and ducts to be slid out intact. The modular design of embedded devices, which can thus be removed or dismantled, is also preferable. It should be realised that cutting of concrete to remove embedded contaminated pipes or ducts usually requires hands-on action by operators with a consequent increase in exposure to radiation and risk of spreading contamination. Refer to references [35] and [36] for typical examples of problems in removing embedded pipes.

(viii) Limiting the Provision of Underground Services and Equipment

It is recognized that not all underground services can be avoided but they could be minimized or alternatives adopted. Examples of how the Westinghouse AP1000 have dealt with this issue are discussed in [4] as noted (iv) above. It has been common practice to allow contaminated liquids to drain by gravity to underground storage vessels via pipework that is embedded in the building floors and foundations. It is possible that these could corrode and/or develop leaks after many years of operation and some would be almost impossible to remove or decontaminate. A preferred arrangement, beneficial to decommissioning, would be to convey contaminated drains in double walled pipes to removable sumps and, as an alternative to gravity drainage, to arrange to pump liquids through accessible pipework to higher level tanks. This would allow all parts of systems to be inspected and provide access for final component decontamination and removal during decommissioning. Contaminated tanks, ducts and pipework should always be accessible for inspection.

(ix) Designing for Thorough Post-operation Clean Out

When piping systems are being designed consideration should be given to ability to achieve effective flushing, purging and drainage to allow all liquids, solids and dust deposits to be removed. Any decontamination agents and chemicals used also need to be completely removed to prevent subsequent corrosion. This will benefit future maintenance, retrofit and final decommissioning by reducing dose to operators and facilitating dismantling. After final shutdown, there is usually a post operative clean out (POCO) of the primary circuits. The potential to flush these out, using chemical cleaning agents and to completely drain and dry all liquid-carrying piping systems needs to be retained. This will also reduce internal corrosion if dismantling is deferred for long periods. The flushing of drainage systems is often overlooked and should be done promptly using existing liquid treatment and purification equipment wherever possible. It may be appropriate to provide special, well-marked cleaning fluid connections for decommissioning, blanking these off for normal operation.

The operational procedures and provisions for POCO should be included in the decommissioning plan with the explicit intent that it can be undertaken soon after final shutdown while experienced staff is still available. In this way it is possible to take advantage of the operating and maintenance staff with experience in cleaning systems for maintenance and good house-keeping.

Post-operation clean out does not only imply liquid carrying systems. Ducts carrying contaminated gas or active ventilation air, should be inspected and decontaminated as required. One approach involves purging using lances or air jets so that deposited and removable contamination can be collected on the main HEPA filters before dismantling. Contaminated ducts often follow contorted routes throughout the building and are particularly difficult to dismantle without the spread of airborne contamination. They are usually in operation for the entire life of the facility and ventilation systems may even be in operation for much of the dismantling work. Ventilation may be the last part of the plant to be shut down. Ducting systems are often constructed of thin-walled low carbon steel susceptible to moist air and corrosion in the long term. They are sometimes left in-situ if removal is particularly difficult and, although contamination levels may be low, they may be above release levels and thus affect the final facility cleanup. Consideration should be given in design layouts to minimizing the hazards of dismantling potentially contaminated ducts and to facilitate their decontamination. Volume reduction of segments of large contaminated ducts may be difficult to achieve without spreading contamination. It is essential to specify the metal type and thickness to provide adequate corrosion allowance for the required duct life, which may include long shut-down and decommissioning periods.

For research, radiochemical and other facilities where contamination will arise, such as hot cells and glove boxes, consideration also needs be given to the ability to decontaminate. This will include avoiding creation of inaccessible areas where contamination can accumulate. There are many instances of contaminated hot cells and specimen penetrations associated with research reactors which are extremely difficult to access and which incorporate transfer ducts embedded in the reactor block. One frequently troublesome location is the extraction ventilation ducts. Where dust or airborne particulates are present, equipment should be provided to minimize the build-up of radioactive deposits. Some facilities, particularly research facilities, will require special provisions for contamination monitoring and control to prevent cross-contamination during specific research projects, while others can be expected accumulate contamination throughout their operating lives — and such accumulations can be expected to contain a broad mix of isotopes.

(x) Designing for the Minimization of both Operational and Decommissioning Waste

The minimization of operational and decommissioning waste has received much attention in recent years. This had been prompted by the accumulating volumes of operating and decommissioning waste in temporary or engineered interim storage at most nuclear sites, the increasing cost of effective waste management and the scarcity of disposal facilities. Many earlier disposal facilities such as those in Eastern Europe have been closed and many approved LLW disposal sites in other countries are becoming full. The design capacity of interim storage facilities needs to address the whole operating and decommissioning period unless off site disposal facilities can be assured. This is often not the case.

In general, decommissioning projects can be undertaken in the absence of waste disposal facilities, where there is provision of safe, licensed, engineered interim storage. This has however increased costs and given rise to public concern. Waste management during the operation of earlier nuclear facilities has frequently been unsatisfactory. There is now a general awareness of the need for good practice, including waste minimization, in waste management. The IAEA has produced a major technical report on important considerations to be addressed for minimizing waste generation from the decommissioning of new nuclear facilities [27]. It gives 4 fundamental principles for waste reduction, 7 considerations for minimizing contamination and 8 important provisions for dismantling and segmentation. The US NRC has also now published a Regulatory Guide on this subject and includes specific design considerations for new designs which are drawn from lessons learned [49]. This Guide includes an extensive list of 26 measures and actions to minimize contamination and 5 specific measures to minimize waste generation. The OECD/NEA organisation has reported on related waste management issues pertaining to small users [13] and the IAEA has also published guidance documents on these aspects [10–12].

A recurring theme in the reviews noted above is the importance of contamination control to waste minimization in future designs. Experience and attention to detail is important, especially for the relatively complex situations presented by large power and fuel-cycle facilities. If this is to be accomplished at the design stage, it will be essential for waste management expertise to be continually available to designers. A degree of training in the principles of good waste management and contamination control for designers is strongly recommended.

There will be a particular need for expert advice for countries that are engaging in nuclear technology for the first time or are contemplating much larger and/or more complex facilities. So that "end points" for facility waste streams can be correctly visualized, this advice should be primarily directed at key policy makers, encouragement should be given for development of a national waste management strategy regulated by legislation and statutes and followed up by the development of waste acceptance criteria to facilitate implementation of the strategy. It should be appreciated that once a new nuclear facility is constructed and in operation, future waste management will become a national responsibility.

(xi) Providing Adequate Waste and Spent Fuel Storage Facilities

Lessons learned from the past show that many facilities experienced a critical situation during operation and shutdown that impacted decommissioning plans as a result of the lack of adequate spent fuel and waste storage facilities. Very often factors beyond the control of the facility operators were a cause and there were no contingency plans. Regarding spent fuel, a serious situation developed in Eastern Europe after the fall of the Soviet Union in 1989/90 when the return of spent fuel from nuclear power plants and research reactors was curtailed. Serious situations also occurred in the US when the transport of waste including spent fuel was prevented through neighbouring federal states. There was also difficulty in transporting spent fuel from abroad to reprocessing centres in France and the UK. In other countries planned facilities were cancelled.

As a result of this adverse experience and lack of planning, it is now important for all new facilities to provide a detailed plan, resource provisions and contingencies for spent fuel and waste storage. Designs for on-site interim storage facilities must usually be drawn up during the initial design and construction of a new facility. There are a number of guidance documents, some published by the IAEA, that give guidance in designing and establishing safety compliance for storage facilities [50–51]. It is recommended that these facilities be available when the new plant is put into operation. In particular, waste conditioning facilities should be available because it is now recommended good practice to condition operating waste as it arises and not to store raw unconditioned waste for indeterminate periods. There has generally been some limited provision at nuclear power plants and research reactors for at-reactor storage for spent fuel to allow post discharge cooling and to allow the discharge of a full core of fuel in case of technical problems. However, this provision is not sufficient for lifetime arisings. Many facilities have had to provide extended wet storage capacity or to adopt dry vault or dry cask facilities at considerable cost. Some of these may have to have very long design lives (typically up to 100 years) due to the uncertainty about reprocessing and disposal options. Such spent fuel and waste are likely to remain on a licensed site long after completion of dismantling and decommissioning of the nuclear facilities. This complicates final clearance of the site and must be considered in long term planning.

Regarding other non-reactor nuclear facilities, similar arrangements must be made to manage and condition waste arisings. Proper on-site storage arrangements must be available for spent sources from medical, research and industrial applications. This is needed even if there are contracted arrangements for their return to the supplier because it is unlikely that this can be guaranteed. Some countries are already adopting centralised waste storage facilities as a core feature of overall national waste management strategy. In many countries, however, the national waste management strategy is yet to be developed and ad hoc interim storage is being resorted to. In the absence of agreed waste disposal criteria (or repository waste acceptance criteria), waste is likely to be conditioned only for interim storage.

Waste from research establishments can be a particular problem because of the variety of radioactive materials and mixed isotopes that may be included in waste and the complex problem of conditioning and storage. Waste from industrial enterprises can also cause problems arising from the lack of proper control and the diversity of applications. Regulators, users and policy makers need to ensure that proper waste management arrangements are made [10–12].

(xii) Management of Records for Decommissioning

Experience has shown that, in general, records for decommissioning purposes have been poorly managed or not managed at all. There are many reasons for this. Among these are:

- little understanding of the requirements of decommissioning, especially the need for accurate configuration drawings and plant data;
- a belief that, if all records of the facility are kept this will suffice;
- lack of well-defined responsibility for decommissioning records within the organization;
- lack of priority being given to key records, such as those needed to sustain the operating safety case and for critical maintenance;
- after shutdown, the loss of interest in all records as operating staff is dispersed.

Important guidance on records management has been given in a technical report by the IAEA published in 2002 [37]. This discusses in detail the process of selecting appropriate records for decommissioning and preserving them as archive documents. Experience from a number of Member States was used in compiling this document. It is believed that a much better understanding of records management has now evolved and an appreciation of their importance is apparent.

It is now appreciated that decommissioning records are specific to the role they have to play and should not include every document associated with the facility right from its inception. What is clear is that essential records and categories of records for decommissioning must be identified and kept consistent with any changes to plant configuration during construction, operation and any retro-fitting. Routine information needs to be supplemented during the operating years with additional relevant data e.g. plant and equipment changes, incidents or accidents that could impact on dismantling, operating history of activation and contamination and the operating waste inventory. The records that are specifically for decommissioning purposes should be identified, reviewed for accuracy and preserved in a secure archive. Most other records, which can amount to over 90% of all facility records, are generally only of historical value after a facility has finally shut down. There will of course also be important general, non-technical records such as licensing, site Characterization, decommissioning financial fund statements and ownership deeds etc. needed when site release or reuse is contemplated.

The responsibility for management of records, including those for decommissioning, should be identified within the organization and should be subjected to appropriate quality assurance procedures.

4.3 Policy, Project and Regulatory Factors

It is believed that a most important but difficult organizational and managerial problem is to determine how the vast experience gained in addressing and resolving decommissioning problems and the lessons learned therefrom can be introduced into the planning, design and construction process of a new facility. There are encouraging indications from publications in the US and Europe of a general willingness to take account of decommissioning experience but the mechanisms or procedures for implementing this are often not clearly defined.

A suggested approach has been to include a team or group of persons with decommissioning experience in the design team. An immediate problem foreseen is that there are many aspects covering the extensive decommissioning process, the experience is very wide-spread and no individual or even a small group can provide guidance in all disciplines. A second problem is that the design of a large nuclear facility like a nuclear power plant or fuel cycle facility involves an extremely wide range of expertise which is likely to be provided by numerous contractors, subcontractors and specialist organizations. The design process could extend over many years. An approach aimed at addressing the above would be to introduce designers to appropriate aspects of decommissioning in a suitable training programme. For this, a general concept of decommissioning will be needed at the outline design stage with a more detailed and in-depth approach (with correspondingly more detailed decommissioning training for designers) required as the design proceeds towards construction.

At the construction stage, many factors relating to layout and access would be addressed and attention to facilitating maintenance and decommissioning would be needed. It is realised that involvement during the detailed design and construction stages may be more difficult due to the competition for available manpower and other resources and probably a pressing completion schedule for the new facility. Education of participants, including those from the purchasing and contracting organizations and regulators, would serve to complement the efforts aimed at training those in the design organizations. Third parties and stakeholders such as professional associations, consultants, local authorities and interested public bodies may also challenge the design organizations to demonstrate how they were taking into account the lessons learned from previous decommissioning projects and special training of spokespersons for the design and construction organization should be considered to address this.

The initial involvement at the conceptual or outline stage would seem simpler on the surface but there is a danger that a superficial input may not yield any meaningful features or principles, or that their identification will just be verbally acknowledged or deferred to the more detailed design stages and then lost from sight. It is not clear whether involvement of the regulator will help since the main concerns of the regulator will be for operational and public safety. In spite of the above reservations it is recommended that a team made up of a range of experienced decommissioning engineers and managers be included in the design organization with an independent reporting route to higher management. This team could also organize the required training drawing on additional specialist experience as necessary.

Important policy, project and regulatory aspects of decommissioning which should form part of early project design are outlined below:

(i) Decommissioning Strategy

The three main recognised decommissioning strategies are [95]:
- immediate (prompt) dismantling after final shutdown;
- engineered safe enclosure for a specified period, followed by dismantlement;
- entombment (on site disposal).

More detailed information can be found in numerous documents dealing with the planning for decommissioning, particularly for large facilities [33], research reactors [32] and medical, industrial and research facilities [10]. There are also specific IAEA documents on the issues and factors for selecting a strategy [28], [52].

The selection of an agreed strategy during the design phase is important because it will have a direct impact on the proposed method of dismantling and consequently on the cost. Many facilities are now being designed for operating lives of up to 60 years and when considering, for example, a safe enclosure option, the integrity of the containment enclosure may need to be maintained for well over 100 years. Even if prompt dismantling is adopted, the entire design life required for structures and containment could be 70–80 years for a large nuclear power plant. The choice of materials can be crucial in terms of activation, corrosion resistance, weathering and mechanical strength. It has now become apparent that the specified structural design life of earlier nuclear facilities had was only the operating life of about 30 years. Fortunately the design life of some important structural materials such as concrete and steel is generally much longer but this may not be so for other than the structural elements. For example, it may be much shorter for protective linings or coatings made of synthetic materials. It is also unlikely that most of the electrical and instrumentation systems would endure for 60 years or more without deterioration and obsolescence but the need to replace these during refitting for continued operation is usually well-known to designers and accommodated in the design. Nevertheless, the need for refit or retrofit needs to be considered carefully at the design stage, especially since this is likely to incur dismantling activities and incumbent waste.

The selection of an immediate dismantling option may require more extensive use of robotic techniques to avoid higher dose exposure to personnel and may increase waste management problems. Access and other requirements for this therefore needs to be planned for. The safe enclosure option will incur long-term care and maintenance costs which arise from surveillance, inspection, maintenance and physical protection as well as extensive retrofitting of auxiliary services. The third alternative of in-situ disposal or entombment will face difficult technical, environmental, licensing and public acceptance challenges. There have been cases where total radiological clearance of all radioactive materials or wastes from a site was not considered feasible and on-site disposal was taken to be an appropriate choice. This has been the case as well for large, contaminated radiochemical sites. For future facilities, especially on new sites, the goal of design-for decommissioning should be to permit dismantlement without protracted safe enclosure and the ultimate free release of the site.

Feasibility of in situ decommissioning (ISD) favours sites that will be under permanent institutional control of the government. ISD is implemented at three sites in the USA managed by the U.S. Department of Energy. The technical, regulatory and management strategy of these projects has been summarized for purposes of institutionalizing the ISD concept and for reference by future project managers [96].

It is seen from the above that the selection of an appropriate strategy presents many technical, environmental, financial and political difficulties. Nevertheless a defensible strategy must be put forward in order to gain licensing and public approval. The need to derive relevant guidance and advice from the extensive sources of current decommissioning experience is essential. This will be particularly important for countries that are considering the acquisition of nuclear facilities for the first time.

A flexible strategy is advisable since circumstances are likely to change over periods of 50-60 years or more. For example, many of the earlier decommissioning concepts proposed complete dismantling of all facilities including reactor cores to achieve “green field” site clearance. In many cases this was not found to be feasible, economic or consistent with the ALARA principle. This lead to the concept of safe enclosure when the high costs and absence of adequate waste disposal facilities were fully recognised. Recently, prompt dismantling is receiving favour once again in some countries especially due to public concern about intergenerational debt and even more so if substantial funding is being promised. An example is the case of Ignalina nuclear power plant in Lithuania where prompt dismantling of the large RMBK reactors are being considered even though it may be on an extended programme. In many cases, especially relating to small research reactors and other small facilities located in densely populated areas or cities, prompt dismantling has been necessary and has already been completed. Finally, growing pressure to re-use licensed site space has driven prompt dismantlement in several projects, notably at San Onofre in the USA and NECSA in South Africa.

(ii) Good Cost Estimating and a Secure Decommissioning Fund

The need for reliable cost estimates has not been properly recognised in the past, with the simplifying assumptions taken to establish a decommissioning ‘set-aside’ fund being used to represent actual decommissioning costs. For example, some countries have assumed a cost proportional to 10% of operating revenue. This has then been discounted at an assumed inflation rate to generate an expected generous future fund. A problem can arise if a facility shuts down prematurely due to technical or other reasons and insufficient funds have been accumulated. While a generous set-aside fund may be possible for large revenue-producing facilities such as nuclear power plants, it is unlikely to be possible for non-revenue-producing facilities such as in nuclear medicine and research. Quite often, even in developed countries, funds for decommissioning and supposedly set aside for decommissioning, have not been available due to diversion of the funds to other national priorities. In some countries there has been no fund at all due to economic and political changes, or a simple lack of recognition of the need! This has resulted in extensive delays in giving required attention to shutdown facilities in many countries. Sometimes there have been delays of 20 years or more when nothing has been done and care of the facility has been minimal. This approach is highly undesirable.

Such delays and lack of attention has been of topic of significant regulatory concern and there is now a widely applied requirement for a secure, independent and inflation-resistant fund to be set up as a licence condition. This has resulted in more robust and comprehensive estimates of future decommissioning costs. There are now established costing models available to formalize estimating [53–56]. In the United States, some studies have analyzed the adequacy of decommissioning funds using probabilistic models [57].

The process of updating cost estimates should extend throughout the design and construction stages, moving from preliminary estimates to more robust estimates when the design is well developed. Cost estimating is an iterative process needing regular review and refinement. Periodically during the operating period, updates to the Decommissioning Plan and cost estimates should be done to account for changes in physical plant or initial assumptions. Before final shutdown of a facility, it will be necessary to review the cost estimates to take account of any abnormal operating conditions, accidents and the operating history to determine the full extent of the radioactive inventory and waste volumes and also to take account of applicable developments in decommissioning technology. There will also be a need to review legislative changes that may have become more, or in some instances, less restrictive. All these factors are likely to have a significant effect on costs.

The experience available internationally from well-developed decommissioning projects will be invaluable. Identified contingency allowances should be made in the estimates to allow for changes in the plant, in decommissioning technology and for uncertainties over long periods of time. In many countries, e.g. the UK, decommissioning estimates require review every 5 years. Finally, decommissioning funds should be segregated in the financial records or, preferably, held by appropriate financial management institutions independent from the plant operator and owner.

Cost estimating for smaller, non-fuel cycle facilities in the research, medical and industrial fields may be easier to determine, but are equally important and it is necessary to ensure that users have the resources to deal with decommissioning and waste management. In general, it is good practice to estimate and in certain cases to include in the initial procurement, the decommissioning and waste disposal costs e.g. for radioactive sources for industrial and research facilities. This may also be an operating or possession licence condition. Where this has not been provided in the past and the operator/owner does not exist or has no funds, the liability has frequently become the responsibility of government authorities and the State has to bear the cost.

(iii) Considering Licence Termination Criteria, Site Location and Reuse

Difficulties have been reported from numerous licensees, particularly in the US, concerning the delays and costs associated with licence termination. Much of this has been a result of residual contamination, difficulties in agreeing on relevant isotopes in terms of radiological hazards and final site release criteria, public perception and the lack of an initial site Characterization database. Some sites have significant potential for reuse and are in desirable locations. If a site has the prospect of becoming a valuable future asset, it will be advantageous for developers to consider this at the inception of a new project because potential reuse of a site can be a good stimulus for decommissioning. Conversely, there are many instances where a site is of little commercial value and there is little interest in decommissioning and sites then become virtually abandoned. If the continued regulation, care and maintenance and physical protection of a shutdown site becomes a financial burden, then there may be stimulus for final clearance. IAEA guidance on this subject can be found in [95].

A number of useful papers were presented at an International Workshop in Rome in 1999 on exemption, clearance and authorised release of sites [58]

(iv) Initial Site Selection and Characterization

Attention to this is important both for final licence termination and in terms of the overall decommissioning strategy. It will also have an effect on the design itself. Of primary importance will be the need to ensure that the site is configured to permit sufficient areas to include both operational and decommissioning activities. If plant extension or enlargement is planned then this should not encroach on site areas allocated for future decommissioning.

There should be provision for on-site interim fuel storage (wet or dry facilities) and adequate engineered facilities for operational and decommissioning waste storage. This should accommodate all waste generated over the life of the facility (ILW, LLW and VLLW if applicable) unless there are secure national off site disposal facilities. Account should be taken of possible life extension and the volume of additional spent fuel and waste that might arise from this.

Routes and means to transfer these wastes to final disposal should also be considered at the design stage if a disposal facility has been identified and there is the required regulatory framework but it is realised that this is not usually the case and adequate interim storage must be provided. LLW and VLLW waste may present the greatest challenge if the waste volume is high.

Thorough initial radiological and environmental site characterization is essential to determine long term strategy, especially where there is an expectation that a site will be returned to its original pre-construction condition. If an extended period of safe-enclosure is considered as a strategy, location and hydro-geological factors will have greater importance. The proximity to large current or projected residential and commercial conurbations must also be considered. There are instances where nuclear facilities were located remotely but are now encompassed in a commercial and/or residential area. Watercourses and rivers should also be considered if liquid discharges are necessary especially as regulation in this respect may become more restrictive. Tidal and coastal flows need also to be characterized and understood before siting. An unfortunate example was the contamination of the Maine-Yankee outfall in the US from tidal backwash after shutdown, thus presenting a site clearance problem. There are also instances where facilities were located in very remote areas sometimes for perceived safety issues. However, attracting and maintaining experienced staff for decommissioning activities after shutdown becomes very difficult and high salaries may be the only incentive. This adds to the costs and project management difficulties in taking decommissioning to a final conclusion. An example of this is the decommissioning of the remote Dounreay site in Northern Scotland. Some remote sites also become environmentally protected areas which can also add to the decommissioning and waste management challenges.

It is clear that many factors must be taken into account in optimum site location and decommissioning considerations can play a large part. This applies equally to nuclear research centres, fuel cycle facilities and nuclear and radiochemical laboratories.

Radiological characterization of any new site must be done in detail. This was not always done, or done adequately in the past, but it is now established practice and would be a normal part of the comprehensive environmental and hydro-geological surveys constituting the pre-project environmental impact study.

TABLE 1

FACILITY DESIGN AND OPERATIONAL DESIGN FACTORS

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
1	**Facility Design**			
1.1.	The facility design should maximize the ability to use conventional dismantling techniques.	Conventional experience and practice in non radioactive dismantling and demolition is well tried and tested.	Designers, Policy Makers	4.2 (iii), (iv), (v) & (vi)
1.2.	It should be recognised that some construction features such as modular construction may prove beneficial for decommissioning.	Make increases use of such features and record them in the decommissioning plan. The modular construction concept can be applied to the smaller nuclear facilities as well as the large reactors.	Designers, Planners	4.2 generally 4.2 (iv) & (vi)
1.3.	Provisions should be made in the design for easy and safe access for final dismantling.	Adequate access should be provided not only for maintenance but also for eventual dismantling	Designers	4.2 (iii), (iv), (vi) & (viii)
1.4.	The design should provide for access for intact removal of very large items of the contaminated plant.	This refers to items like steam generators, large pumps etc. for which access for removal intact should be considered.	Designers	4.2 (iii), (iv), (v) & (vi)
1.5.	The option to segment large contaminated or activated items “in-situ” for easy removal should be retained.	Experience has revealed significant problems in the need to segment large items in confined spaces and enough access is needed.	Designers	4.2 (iii), (v) & (vi)

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
1.6.	Designs should limit embedding pipework, ducts, tanks and equipment in floors and walls.	Removal of contaminated and embedded items present problems during dismantling. The use of sleeved pipe penetrations and removable tanks may be an alternative.	Designers	4.2 generally 4.2 (ii), (vii) & (viii)
1.7.	Design and installation of pipes and ductwork should minimize the holdup and deposition of liquids, crud and active dust.	Systems should be designed to avoid low points, bends and pockets where activity can collect. Sufficient access and provision for removal should be provided.	Designers	4.2 (v), (vii), (viii), (ix) & (x)
1.8.	Where necessary, consider the use of remote handling techniques to remove active items and allow provisions in the design for this application.	There may be instances where the judicious use of remote equipment may be the best solution and this should be planned for in the design.	Designers, Planners, Policy Makers	4.2 (iii), (iv) & (vi)
1.9.	Limit the use of potentially radioactive underground tunnels, ducts and drains.	These items can be a serious source of contamination accumulation and present difficulties in removal.	Designers	4.2 (ii), (vii) & (viii)
1.10.	Designs should consider corrosion resistant tanks, containments and sumps with provision for early leak detection.	Tanks and sumps that hold active liquids should not be permitted without these provisions.	Designers, Regulators	4.2 (ii), (viii) & (ix)
1.11.	Designs should provide for ease of chemical decontamination of primary circuits and other contaminated piping systems.	For reactors and radiochemical plants, this will greatly facilitate access for dismantling and reduce dose to workers.	Designers, Operators	4.2 (i), (ii), (iii), & (ix)

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
1.12.	Wherever possible, contaminated and non-contaminated systems should be segregated.	It is realized that in some cases segregation may not be practicable and for these cross contamination should be avoided.	Designers, Regulators	4.2 (i), (ii), (v) & (vi)
1.13.	The design should minimize the number of systems and equipment that will need eventual dismantling.	The reduction of equipment and systems will reduce waste volume, dismantling time and cost. (It may also improve plant availability).	Designers	4.2 (i), (ii), (iv), (ix) & (x)
1.14.	The design should consider, to the extent practical, the ability to adapt the capacity and configuration of auxiliary systems that may be required during the decommissioning period.	The design should consider the extent to which this is feasible and economical. Specifically, electrical, service-water & ventilation systems etc. will need consideration.	Designers, Operators	4.2 (ix), (iv), (v), (ix) & (xi)
1.15.	Ensure design and operating life of selected plant and equipment are sufficiently long to be useful for decommissioning.	It will be beneficial to select materials and to design systems such as piping & ventilation for the whole life cycle, i.e. including safe-enclosure (where applicable) and decommissioning.	Designers	4.2 (i), (ii) & (ix)
2	**Design for Optimization of Waste Management and Contamination Control**			
2.1.	Avoid “ad hoc” on-site disposal of waste.	Disposal requires a properly designed and authorised facility. Interim on-site storage should be strategically located for decommissioning access.	Operators, Regulators, Policy Makers	4.2 (ii), (x) & (xi)
2.2.	Minimize waste volume and total activity.	Good working practices and controls must be instituted using proper zones and barriers. Plant complexity should be avoided.	Operators, Regulators, Policy Makers	4.2 (ii), (iv), (v), (ix) & (x)

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
2.3.	Consider dismantling and structural segmentation in terms of waste generation.	The optimum size of waste components and package sizes should be considered in design and construction	Designers	4.2 (ii), (iii), (v) & (viii)
2.4.	Seek to simplify waste management operations.	Provided easy-to-follow waste segregation procedures to facilitate waste treatment and management.	Operators, Regulators	4.2 (i), (ii), (ix), (x) & (xi)
2.5.	Provide for waste conditioning during operation and decommissioning and condition the waste for disposal, if possible.	Waste should be conditioned for disposal or interim storage using agreed waste acceptance criteria, (e.g. via early preparation of the disposal WAC). Suitable facilities should be provided.	Operators, Regulators, Designers	4.2 (ii), (x) & (xi)
2.6.	Provide expandable waste storage facilities based on life cycle considerations.	All necessary waste storage facilities should be identified in the design and provided for during construction.	Designers, Policy Makers, Regulators	4.2 (x), (xi) & (xii)
2.7.	Decommissioning requirements of all waste conditioning and interim storage facilities must be adequately considered.	The design criteria and proposals for these facilities do not always consider their future decommissioning.	Policy Makers , Designers	4.2 (ii), (ix), (x), (xi) & (xii)
2.8.	Provide on-site storage for spent fuel meeting, or expandable to address, the entire facility life.	These should be designed for ease of decontamination and for easy dismantling and removal of such facilities.	Designers, Regulators, Policy Makers	4.2 (x), (xi) & (xii)
2.9.	Minimize the generation of mixed and hazardous wastes such as radioactive chemical waste.	Care should be taken in design, construction, operation and maintenance to avoid producing mixed wastes.	Designers, Operators and Regulators	4.2 (v), (ix), (x) & (xi)

No.	**Feature**	**Description/Comment**	**Responsibility (organizations and persons)**	**Section Reference**
2.10.	The designs should, as far as possible, consider the segregation of materials to facilitate future waste management.	Barriers and separating partitions should be considered where different materials and levels of activity are in proximity.	Designers	4.2 (ii), (v)& (x)
2.11.	Provide on-site decontamination facilities and equipment for all foreseen operations as well as decommissioning.	This will allow the good practice of dealing immediately with contamination from spills, leakage and maintenance work.	Operators, Designers	4.2 (ii), (v), (x) & (ix)
2.12.	Seal or line all porous surfaces against ingress of activity.	Provide impervious materials and use protective covers, as appropriate. Lining of sumps and reactor pits with durable materials will avoid spread of contaminated liquids.	Designers, operators	4.2 (ii) & (x)
2.13.	Seal openings created during operations and maintenance to avoid penetration of contamination.	Such openings should be sealed as soon as possible (when not required) with durable material.		4.2 (ii) & (x)
2.14.	Designs should ensure that facilities and equipment such as evaporators for liquid waste (that create high dose areas) are not located in inaccessible or congested areas.	There are cases of serious contamination of these facilities which are often located in very inaccessible areas.	Designers, Operators	4.2 (iii), (iv) & (v)
2.15.	Plant personnel should be trained to recognize the contamination potential at certain facilities and equipment and avoid unnecessary contamination or cross contamination.	Inadequate training and poor operating practices in contamination control can add to decommissioning costs and difficulties.	Operators	4.2 (ii), (v), (ix) & (x)

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
3	**Design Interface with Decommissioning Planning**			
3.1.	Facility design processes should have an iterative interface with the Decommissioning Plan development and associated cost estimates.	There is a need to ensure that the Decommissioning Plan accurately records the developing design and yields reliable decommissioning costs. A dismantling process will need to be developed.	Designers and Decommissioning Experts	4.2 General 4.3 (ii)
3.2.	Estimate future decommissioning costs regularly during design and operation.	Decommissioning costs should be reviewed and updated at regular intervals.	Policy Makers, Owners, Regulators	4.2 General 4.3 (ii)
3.3.	Design planning may be needed to resolve the interdependence between an operating facility and an adjacent shut down facility.	This can apply to power plants and nuclear processing facilities which are interlinked with safety systems and services.	Designer, Regulators, Policy Makers	4.2 (ix) 4.3 (i)
4	**Design Interface with Licensing and Safety**			
4.1.	The entire facility life cycle including decommissioning planning should be considered in the design.	It should be recognised that regulatory requirements and facility economics will focus designs on operational safety and system efficiencies. However, decommissioning should be an important consideration along with the other factors.	Policy Makers, Owners, Regulators	4.2 General 4.3 (i), (ii) & (iii)
4.2.	It should be recognized that safety during the transition and dismantling period after shutdown may be different from the operating period.	Safety in decommissioning is largely achieved by good working practices.	Designers, Regulators, Operators	4.3 General

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
5	**Design Interface with Radiation Protection**			
5.1.	Initial Characterization of construction materials to minimize generation of activated and contaminated materials.	Careful selection of materials to minimize the production of activation radionuclide. The baseline inventory of trace elements will be useful in this regard. Minimize the potential for contamination from fission products.	Designers and Materials Specialists, Nuclear Physicists	4.2 (i)
5.2.	Overdesign of biological shielding should be avoided especially if it involves poured, reinforced concrete.	Design for average source levels. Use temporary shielding for peak levels. Design measures to reduce radiation during operation will also benefit decommissioning.	Shielding Designers, Radiation Physicists	4.2 (i), (iv) & (vi)
5.3.	The design should consider the use of shielding constructed of removable panels.	Consider modular, prefabricated concrete for shielding. This will facilitate the removal of these items.	Designer	4.2 (i), (iv) & (x)
5.4.	Modular or temporary shielding.	Design for use of modular or temporary shielding to simplify removal (see above).	Shielding Designers	4.2 (i) & (iv)
5.5.	Plan for regular and comprehensive site and groundwater monitoring and the rectifying of any leakage problems detected .	This should be conducted throughout the operating period to avoid seriously contaminated sites left for decommissioning. All spills should be characterised and recorded.	Operators, Regulators	4.2 (ii) & (x)

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
6	**Design Interface with Project Management**			
6.1.	The design organization should establish a procedure for identifying, evaluating and incorporating desirable design features.	Unless a formal procedure is set up within a design organization many beneficial features are likely to be overlooked. The principle of Design for Decommissioning (DfD) should be adopted. Training will be needed.	Policy Makers, Design Organizations	4.2 General 4.3 General
6.2.	Maintenance and retrofit procedures and a complete record of activities are useful during decommissioning.	These procedures and their associated records should be identified and preserved where relevant to decommissioning (See below).	Designers, Decommissioning Planners	4.2 (xii)
7	**Design Interface with Documentation and Records**			
7.1.	Records specifically needed for dismantling and decommissioning should be identified during design and construction.	It is suggested that within the existing and permanent plant data base, some procedure should be defined to identify the records (drawings, change packages, modifications etc) that are necessary for decommissioning.	Designers, Operators, Policy Makers	4.2 General 4.2 (vi) & (xii)
7.2.	Decommissioning related records must be carefully preserved for the entire operating life of the facility in an appropriate storage medium.	It will be important to identity the storage medium, location and the long term responsibilities for records management.	Owners, Operators, Policy Makers, Regulators	4.2 General 4.2 (xii)
7.3.	Provision should be made to obtain and retain representative samples of selected plant and construction materials for future analysis.	Very often there are difficulties in obtaining robust data for future safety and technical analysis during decommissioning and samples of materials are invaluable for this.	Designers, Regulators	4.2 (xii) 4.3 (iii)

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
7.4.	Provision should be made to facilitate an accurate inventory and location of radioactive material at the end of the operational life.	Operational records of all events with radiological consequences should be carefully preserved. Access for characterization should also be considered.	Operators, Designers	4.2 (ii), (v), (x) & (xii) 4.3 (iii) & (iv)
7.5.	Appropriate Quality Assurance should be applied to control and record the inclusion of beneficial features for decommissioning.	This will ensure that all features are adequately considered and that records are identified.	Designers, Policy Makers	4.2 General 4.3 General 4.2 (xii)

TABLE 2

POLICY, PROJECT AND REGULATORY FACTORS

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
1	**Policy & Strategy**			
1.1.	Define decommissioning strategy early.	Need to decide on immediate or deferred dismantling, or other strategies.	Policy Makers and Licensees	4.2 General 4.3 (i)
1.2.	Consider the socioeconomic impact of final shutdown of a nuclear facility.	Policy makers should have contingency plans available to minimize the impact of sudden or planned final shut down of a facility. Funds for regional economic transition and incentives for companies to alter their market focus and labour force training are needed.	Policy Makers, Regulators	4.3 General 4.3 (i), (ii) & (iii)
1.3.	There is a need to consider the special case of new users of nuclear facilities.	In some countries acquiring new facilities there may be less appreciation of future decommissioning liabilities. Training is available from many international organizations to give assistance.	Policy Makers, Future Owners	4.2 General 4.3 General

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
1.4.	Secure Decommissioning funds.	Need to establish provisions for adequate decommissioning funding with appropriate oversight.	Owners/licensees Regulator, Gov. Policy Makers	4.3 (ii)
1.5.	Future reuse of the facilities and site.	Consideration should be given, if possible, to eventual reuse of the site.	Owners and Policy Makers	4.3 (iii) & (iv)
1.6.	Attention to planning for the transition period between end of operation and start of decommissioning.	Advance planning and training for the transition period is necessary to avoid decommissioning delays.	Policy Makers, Licensees and Operators	4.2 (ii), (ix) & (xi) 4.3 (i)
1.7.	There is a specific need to ensure lessons learned are recorded and passed on to avoid future problems.	Lessons learned are from past and on-going decommissioning projects should be considered on a regular basis.	Policy Makers, Regulators, Designers	See Section 3 above 4.2 (xii) 4.3 (i)
1.8.	For ISD, consider the ability to place grout within below ground structures.	A vent path is required to ensure complete filling with pumped grout. If such spaces have a roof without openings, review the ability to place a core drilling machine above the space.	Designers	4.3 (i)
1.9.	For ISD, consider the ability to place grout within large tanks, vessels and pipes.	Tanks, vessels and large pipes below grade within the structure or buried in close proximity to the facility should be reviewed for the ability to fill with grout.	Designers	4.3 (i)

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
2	**Licensing and Safety**			
2.1.	Licensing procedures for Decommissioning.	Endeavour to simplify licensing issues to minimize complications, delays and costs.	Regulator and Licensee	4.3 (iii)
2.2.	Site release and licence termination.	Recognise difficulty of terminating licence and achieving stages and types of site release.	Regulator, Licensee, Owner	4.3 (iii)
2.3.	Baseline site Characterization prior to construction.	Complete comprehensive site Characterization is needed to facilitate licence termination after decommissioning.	Owner, Designer, Environmental Agencies	4.3 (iii) & (iv)
2.4.	Site reuse after decommissioning.	Consideration must be given to safety issues, environmental issues and amenities in the potential reuse of the site or facilities.	Designers, Policy Makers	4.3 (i) & (iii)

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
3	**Project Management**			
3.1.	Justify provisions of design features specifically needed for decommissioning.	The additional cost to the design versus the benefits of more simple and economic decommissioning need to be evaluated.	Designers and Policy Makers	4.3 (i)
3.2.	The design organization should have decommissioning engineers on the reactor design team.	This will ensure input to design on factors that are important to eventual decontamination and decommissioning.	Policy Makers, Design Organizations	4.2 General 4.3 (i)
3.3.	It should be recognised by operators and owners that life extension or output enhancement may increase the cost and complexity of dismantling.	Increased activation, waste volumes and additional plant are likely to increase the cost and extent of dismantling work. Decommissioning costs will need to be adjusted.	Operators, Owners and Policy Makers	4.2 (i), (x), (xi) & (xii) 4.3 (i) & (ii)
3.4.	Avoid tendency towards unnecessary over design especially for structural and shielding concrete.	The selection of construction structures should be based on engineering calculations and the requirements of regulators or the standards. Practices in the past generally lead to very thick concrete structures which may not have been optimized.	Designers, Constructors	4.2 General 4.3 (i)
3.5.	For research facilities all contaminated equipment should be decontaminated and removed after use.	It should be incumbent on the research team or organisation to remove all residual contaminated items.	Researchers, Operators	4.2 (ii), (v) & (x)

No.	Feature	Description/Comment	Responsibility (organizations and persons)	Section Reference
4	**Management of Waste and Contamination Control**			
4.1.	A national waste management strategy is needed that includes the decommissioning waste.	This will facilitate decommissioning waste to be conditioned to appropriate disposal criteria.	Policy makers, regulators, environmental agencies	4.2 (x) & (xi) 4.3 (i)
4.2.	Recycling of material from dismantling and maintenance.	Designs should consider the eventual recycling possibility of materials.	Designers and Policy makers	See Section 3.5 4.2 (v) & (x)
4.3.	Continued development of decontamination techniques.	The development of more effective techniques should be continually promoted.	Operator, Policy Makers	4.2 (ii) & (x)
4.4.	There is a need to consider the case of countries with very small quantities of radioactive waste.	There is a need to develop a suitable national waste management strategy and policy no matter how small waste volumes are.	Policy Makers, Government Authorities	4.2 (ii), (x) & (xi) 4.3 (i)

5. OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS

5.1 Observations

- Decommissioning has been on-going for a number of decades and a large number of research reactors and fuel cycle facilities and a smaller number of power reactors have been decommissioned or partially dismantled.
- There has been extensive reporting of experience and lessons learned for completed and on-going decommissioning projects.
- A number of publications exist from international organizations and authorities (e.g. IAEA, USNRC, OECD/NEA and the IAEA) and individual authors that identify beneficial features to be incorporated in new designs of nuclear facilities.
- The main designers/suppliers of nuclear power plants have produced documents that identify such beneficial design features.
- Designers of small facilities have not issued significant information on beneficial features for decommissioning.
- Some features beneficial to decommissioning require little justification since they offer reductions in construction cost and improved safety and operation. Most require justification due to additional costs and/or perceived impacts on design optimization for normal operation.
- Features provided to facilitate decommissioning can also benefit retrofit and life extension activities – an important consideration as the design-life of facilities continues to increase, with the incumbent need to replace aging/obsolescent components and systems at least once during the facility life.
- Waste volume minimization and avoiding contamination and access problems (both for removal activities and decontamination activities) have been some of the most reported problems associated with decommissioning projects.
- The lack of national waste disposal strategy and associated waste acceptance criteria makes it difficult to plan for appropriate segregation and conditioning of decommissioning waste.
- Much of the waste from decommissioning is being placed in interim storage pending the availability of disposal facilities. This can lead to additional future handling and conditioning of the wastes.

5.2 Conclusions and Recommendations

Design-for-Decommissioning is an important concept for a broad range of stakeholders including policy makers, designers, vendors, constructors, prospective owners, operators and regulators. Planning which addresses the entire lifetime of a facility is strongly recommended

A key element of this planning is the preliminary decommissioning plan (PDP), which should be prepared at the commencement of design work to record the outline strategy and all relevant design aspects and features beneficial to decommissioning.
This preliminary plan should evolve into a detailed plan (DP) through design completion, manufacture, construction and operation, with increasing detail being incorporated in subsequent revisions as the facility approaches its shut-down and decommissioning phases. A dismantling plan and procedures should be proposed at the outset, even if these are provisional. While a preferred decommissioning strategy should be selected during design, it needs to remain flexible to adapt to changing circumstances. The decommissioning plan should also address the transition phase between shutdown and the commencement of

decommissioning to avoid long delays in the latter. Release from regulatory control, site clearance and site reuse should also be considered at the design stage. Guidance from IAEA publications WS-G-2.1 [50], WS-R5, SRS -45 and SRS-50 provide an effective framework for this [93-95].

For future facilities, especially on new sites, the goal of design-for decommissioning should be to permit dismantlement without protracted safe enclosure and the ultimate free release of the site.

The inclusion of decommissioning experts and expertise in design and procurement teams and/or access to this expertise, is a method of ensuring that beneficial features are incorporated in new designs. The features highlighted in Tables 1 and 2 of this document provide an important tool for this process. Additionally, training on decommissioning concepts of key participants in the process such as designers and policy-makers is essential. Countries investing in nuclear facilities for the first time especially need such training and access to experts to ensure all aspects of decommissioning and its associated waste management are properly considered. Such training is available from international organizations such as the IAEA.

It will often be difficult to ensure that all features beneficial for decommissioning are incorporated in a new facility due to the complex nature of designing a large facility. Such features will need justification especially if they are mainly of benefit to decommissioning and there are cost and programme implications. Tracking the disposition of all such features is an important part of the engineering discipline to be applied in the design process. Appropriate quality assurance is needed to control the recording of this process.

An integral part of the decommissioning planning is the preparation of reliable cost estimates. The estimated cost of decommissioning based on the proposed dismantling procedures should be established for the preferred strategy and funds accumulated and held securely in a fund segregated from other financial assets. The adequacy of this fund should be reviewed on a regular basis and amended as required.

Throughout the planning and execution of decommissioning, decommissioning-related records need to be specifically identified and preserved. A template for detailed materials and radiological inventory should be prepared early in the decommissioning planning process, as it will contribute to the process of identification of such records.

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ANNEX I

CASE STUDIES FROM DECOMMISSIONING EXPERIENCE

I-1 RPV Removal at Big Rock Point

I-1.1 Issue

Intact removal of a RPV has specific advantage in terms of reduced occupational dose and limiting the issues related to internals. However, the intact removal requires a large opening in the structures and use of heavy lift equipment.

I-1.2 Analysis

At Big Rock Point the RPV was removed intact. This required the use of heavy lift equipment, use of a large Type B cask weighing over 100 tonnes and creation of a large opening in the sphere. The packaged RPV in Type B cask was transported in a special rig to a rail line. The package was transported by rail to the Barnwell site for disposal. See Figures I-1.1 and I-1.2.

Figure I-1.1 BRP Transfer Cask

Figure I-1.2 BRP RPV Removal

I-1.3 Lessons Learned

During decommissioning, it may be possible to remove intact the RPV or other large components such as steam generators. New reactor facilities being planned should consider the possibility for the large component removal.

I-2 Segmentation of RPV Internals at Maine Yankee

I-2.1 Description of the Issue

Segmentation of Reactor Pressure Vessel (RPV) internals poses technical and logistical challenges because of the high radiation environment.

I-2.2 Analysis

At Maine Yankee decommissioning project, the segmentation of RPV internals was performed in the flooded refueling cavity. Cavity penetrations were sealed to confine the cutting debris to the reactor cavity and strict controls were put in place for potential air and water contamination.

I-2.3 Lessons Learned

Remotely operated filling and capping of containment for high radiation waste may be important considerations in future designs. Modular and quick disconnect features may be desirable. Depending on the technique employed, various design features could facilitate such action at the end of the plant lifecycle

I-3 Rubblization and Release – Issues at Maine Yankee

I-3.1 Description of the Issue

Rubblization (crushing concrete into rubble) has been tried as an approach to manage large concrete debris from the plant structures. The regulatory issues related to overlapping jurisdictions and/or changing regulatory requirements for material release can make the process inapplicable or cost-prohibitive. Also, the site release criteria may be subject to additional constraints.

I-3.2 Analysis

For Maine Yankee, the State of Maine defined concrete as "special waste" and imposed a state limit of 0.5 μSv/y (0.05 mrem/y) for any residual radioactivity on site. This was far more restrictive than the 0.1 mSv/y (10 mrem/y) through all pathways and 40 μSv/y (4 mrem/y) through the groundwater pathway. that Maine Yankee had agreed to and based on other stakeholder interactions. This enhanced criterion was well below the criterion noted in the License Termination Plan and submitted to the NRC, which was the NRC requirements of 0.25 mSv/y (25 mrem/y) through all pathways and a demonstration of ALARA application. The net result was that the rubblization approach was abandoned.

Additionally, it should be noted that for unrestricted site release, the criteria from NRC has a dose limit of 25 mrem/y (0.25 mSv/y) through all pathways and the demonstration of ALARA requirements. Lessons from Maine Yankee are again worth noting which started with the intent to conduct remediation sufficient to meet the NRC requirements. However, based on the long interactions with stakeholders including the State, the final criteria ultimately used was substantially more restrictive. The criteria used were the enhanced radiological cleanup criteria of 10 mrem/y for all pathways and 4 mrem/y for the groundwater pathway.

I-3.3 Lessons Learned

A single set of criteria and a clear agreement from all relevant and interested regulatory jurisdictions is necessary. In terms of design planning, the lesson learned is that designers be cognizant of such intricate issues that may occur in future. In practical terms, minimizing the potential volume of materials to be released is advisable.

I-4 Explosive Demolition at Maine Yankee

I-4.1 Description of the Issue

Explosive demolition can be a viable technique for large containments but only after ensuring that all radioactivity has been removed.

I-4.2 Analysis

In Maine Yankee's case, explosive demolition was considered a viable option to recover project schedule time. It could only be applied after almost all radioactivity had been removed. With the removal of the RPV, other equipment and piping and the containment concrete interior, about 99% of activity had been removed. This allowed much less risk with the use of explosives. This reduced the demolition time substantially.

I-4.3 Lessons Learned

Explosive demolition can be a viable technique for large structures and can reduce the demolition time substantially. However, this has to be balanced against the cost, security oversight and other factors such as proximity to other structures. It can be a reasonable choice for uncontaminated buildings or where the remaining activity has been almost completely removed.

I-5 Spent Nuclear Fuel (SNF) Storage Issues in US

I-5.1 Description of the Issue

Spent nuclear fuel storage or disposition is a significant issue for reactor decommissioning.

I-5.2 Analysis

Spent nuclear fuel is national issue in every country with a nuclear power reactor program. In the Unites States, spent nuclear fuel is a federal responsibility and the Department of Energy (DOE) was obligated to start accepting SNF from commercial reactors in early 1990s. There is no realistic chance of federal disposition facilities being ready to accept SNF for years to come.

Because of the long term uncertainty, the decommissioning projects have little choice except to construct on-site dry storage facilities. This requires significant cost, security, monitoring in the long term (until national disposition of SNF is actually available). These storage sites will also be licensed facilities that will have to be maintained under regulatory jurisdiction. Such facilities (Independent Spent Fuel Storage Installations, ISFSIs) have been constructed at Big Rock Point site and at the Maine Yankee site, where the reactor decommissioning is complete and sites have been released. The ISFSIs are maintained under separate regulatory license. Similar facilities have been constructed at several other decommissioning sites and at operating reactor sites.

I-5.3 Lessons Learned

SNF management is national issue. Different countries may have different regulations and approaches to managing SNF. In the US the Department of Energy is ultimately responsible for the SNF but has not started accepting anything from utilities. This has necessitated the construction of on-site storage facilities. Such facilities may be needed for operating reactors (where the spent fuel pool capacity is reaching the limits) but they are also imperative for the decommissioning projects in the US. The Independent Spent Fuel Storage Installations, can cost anywhere between 50 to 100 million dollars which can be a significant cost for decommissioning project.

I-6 Lifting Equipment at HDR Karlstein in Germany

I-6.1 Description of the problem

Project delays may result in considerable increases in the cost of decommissioning. In certain cases, extending the project duration even just for days can result in considerable cost increases.

I-6.2 Analysis

During decommissioning the transport of material to be segmented and of the subsequent canisters of waste is an important project activity, for which limitations in lifting capabilities and/or capacity will automatically result in delay. In most cases the reactors are equipped with only one crane and therefore all lifts need to be performed with this. Lifting limitations in compartments where heavy components are installed is often a problem that can only be solved by cutting the components on site in transportable pieces for further segmentation or treatment. This has to be done usually in small caverns, compartments under severe space conditions. An example is at HDR Karlstein in Germany.(Superheated Steam Reactor/*Heissdampf Reaktor),* see Figures I-6.1 to I-6.3.

Figure I-6.1 Removal of Steam Converter for further treatment

I-6.3 Lessons Learned

The removal of large components, such as the steam generator and large pumps, requires sufficient lifting capacity to facilitate transportation in one piece for further treatment and segmentation, preferably outside the reactor building. This implies a clear pathway to take the components out of the building, especially through doorways hatches, etc. All this should have been considered at an early stage of the design. During design a sufficiently large cutting area should either be provided in the reactor building or plans should be made for immediate use of another building after shutdown, e.g. the generator building. This will impose a separate waste treatment building for the operational waste as well as for decommissioning waste. Special consideration should also be given to the treatment of resins.

Figure I-6.2 Removal and segmentation of RVP lid.

Figures I-6.3 Removal and segmentation of RPV.

I-7 Limited Access Provision at MZFR facility in Germany

I-7.1 Description of the Issue

The layout of the MZFR provides only very limited space for the installation of remote handling equipment required for dismantling, as illustrated by Figures I-7.1 to I-7.3.

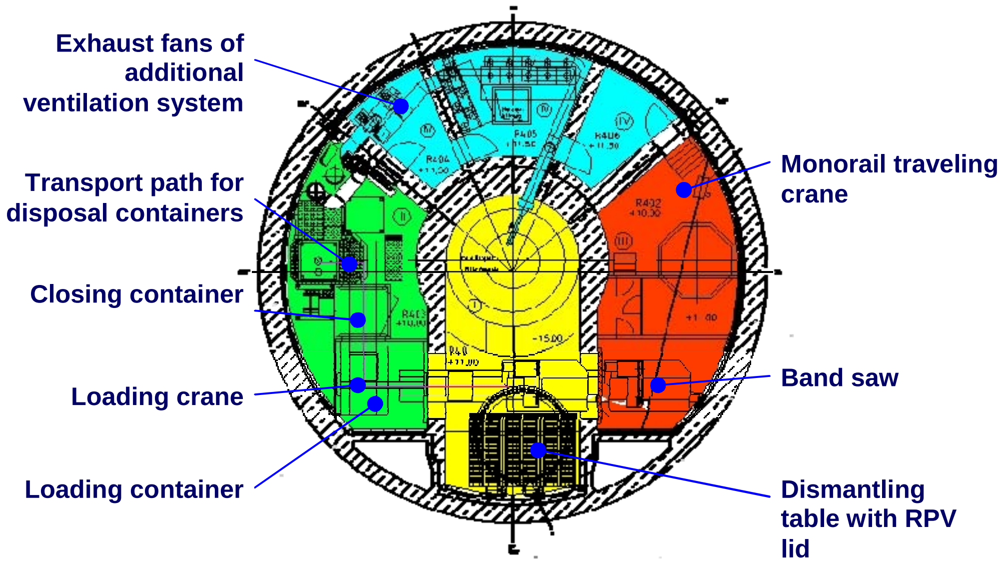
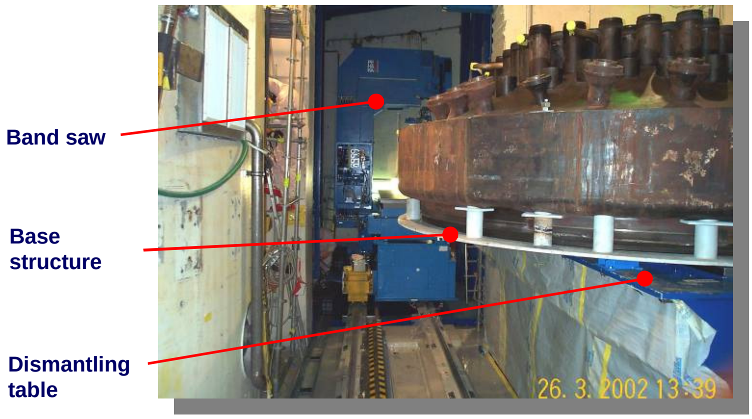


Figure I-7.1 Facilities for MZFR RPV dismantling.



Figures I-7.2 Segmentation of the RPV lid.

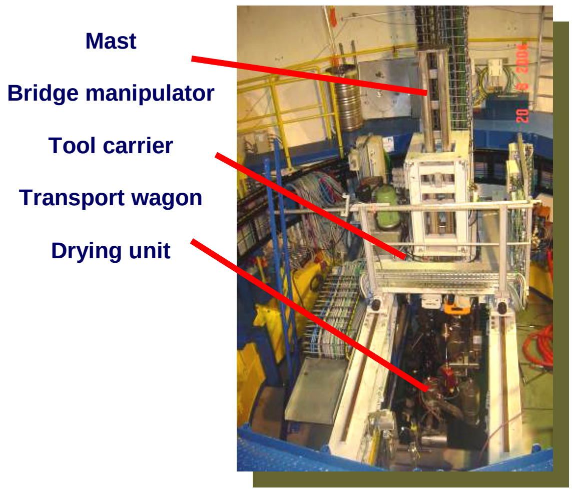


Figure I-7.3 View into the remote dismantling area at MZFR.

I-7.2 Analysis

As can be seen from the equipment layout (see Figures above) the whole upper plenum and the compartments below is being used for provision of supplementary ventilation, additional crane, cutting tool carrier, transport systems, treatment and packaging stations.

I-7.3 Lessons Learned

This situation could have been avoided if at the design stage provisions for the equipment needed had been considered.

I-8 Removal of the Biological Shield and Concrete Structures at KKN and HDR Reactors and Concrete Blocks with Pipe Penetrations at Reprocessing Plant WAK in Germany

I-8.1 Description of the Issue

Besides the removal of large and heavy components including the reactor pressure vessel, the demolition of the biological shield can represent a very time consuming decommissioning task when adequate provisions are not made at the design stage.

I-8.2 Analysis

To save time soft explosions were used to crack the heavy concrete for easier removal (see Figures I-8.1 and I-8.2), or diamond wire sawing was used to cut the bio shield or other concrete structures (e.g. pipe penetrations in reprocessing plants) in large pieces then to be placed directly into disposal containers. (see Figure I-8.3). It took more than a year to remove around 120 blocks with pipe penetrations. This was the quickest way to remove the embedded pipes. To cut out pipes separately and directly on site would have resulted result in delays of the order of a few years delay, with an associated high risk for severe contamination if pipes are damaged during demolition and removal from the wall. Several cutting machines were operated in parallel to save time (see Figures I-8.1 to 3).

Figure I-8.1 Removal of the KKN biological shield by soft explosions.

Figure I-8.2 Biological shield removal at HDR using soft explosions.

Figures I-8.3 Removal of cut concrete blocks from the WAK reprocessing plant for further treatment at the central waste treatment facility HDB.

I-8.3 Lessons Learned

To facilitate such work and reduce radiation exposure to the workers, openings to insert the diamond wire could be installed during construction and sealed, if necessary by lead wool, to avoid additional exposures during operation. Structures with 2m thickness are not easy to drill perpendicularly (deviations of a few mm may result in deviations in several cm or tens of cm after 2m). Soft explosive techniques can be used successfully for removing bioshield concrete.

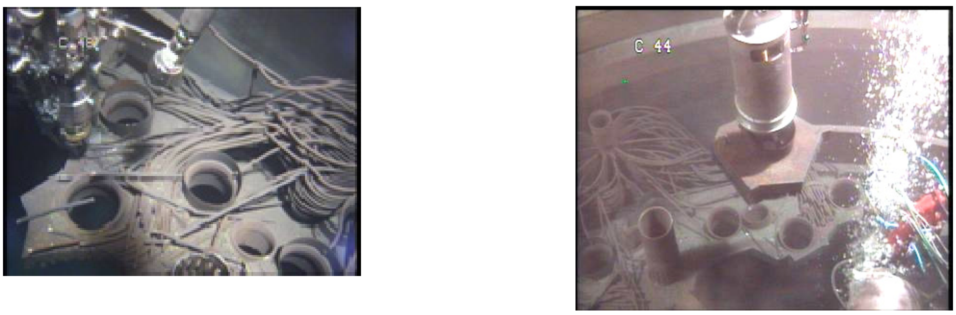
I-9 Modular Design of Instrument Lines and Auxiliary Systems in the RPV

I-9.1 Description of the Issue

At the MZFR decommissioning project in Germany, issues related to the removal of instrument lines caused significant delays in work because of the necessity to remove these one at a time.

I-9.2 Analysis

The use of remote handling techniques takes 10-15 times longer for a single action than manual. Figures I-9.1 depicts a view of these lines at MZFR. Because these lines were not built modular, it turned out be a complex task in identifying removal sequence and the actual removal with remote handling techniques



Figures I-9.1 (a) and (b): Arrangement of measurement lines at MZFR.

I-9.3 Lessons Learned

A modular design of the measurement lines and auxiliary system to guide and control the reactor should be constructed in a way that allows for easy removal with few grabs, since this type of work usually needs to be remotely controlled.

I-10 Facilities for Decontamination of Stainless Steel Components

I-10.1 Description of the Issue and Lessons Learned

In older nuclear facilities, generally there are no decontamination and waste treatment facilities. This experience was reported from Japan, Korea, China and the US.

I-10.2 Analysis

The waste treatment facilities would be required for use during decommissioning and these facilities need to be constructed prior to dismantling operations. The facilities required may include the following.

- Segregation, dismantling and decontamination caisson;
- Cutting caissons;
- Acid decontamination baths;
- Supercompactors;
- Incinerators;
- Evaporators.

I-10.3 Lessons Learned

Centralized facilities for on-site waste treatment have been already constructed for new projects in Japan. Other countries such as Korea, China and USA are also pursuing this in their new facility designs.

I-11 Provision of an Adequate System for Measurement of Radiochemistry properties

I-11.1 Description of the Issue

The extent of activation of materials due to neutron flux can, in principle, be determined accurately even in the case of composite materials such as graphite or concrete. The level of accuracy that may be achieved depends crucially on the number of sampling measurements and there is an associated risk that insufficient numbers of samples are taken.

I-11.2 Analysis

The global dismantling strategy should take account of the need to get adequate samples in sufficient numbers and at the right time. It is very important to set aside time and funds for this and to anticipate the need for laboratory facilities to undertake the necessary analysis and especially radiochemical analysis. In some cases and in some countries there may not be an adequate number of specialized accredited laboratory facilities and the time to do the analysis could therefore be very long. This situation presents risks for all dismantling projects. One possible outcome is that the lack of an accurate radiological inventory will hamper project definition and the analysis of health and waste management risks.

I-11.3 Lessons Learned

It should be remembered that neutron and activation calculations are obligatory and therefore radiochemical measurements must be undertaken. At the initial design stage, it is necessary to make provision for taking sufficient irradiated samples of concrete, steel and other structures surrounding the reactor internals.

I-12 Decommissioning Planning Prior to Final Shutdown of a Nuclear Power Plant

I-12.1 Description of the Issue

In France, the decision on the decommissioning strategy for PWR units must be taken 10 years before the estimated final shutdown date., This is to allow planning for the last loading of fuel, calculating the last burnup cycles and preparation and treatment for removal of items (spent fuel) in the pools of the fuel storage buildings.

I-12.2 Analysis

In accordance with the French Nuclear Safety Authority guide on final shutdown and dismantling (*Mise en arrêt définitif/Démantèlement*, MAD/DEM) a number of actions must be carried out, which are allowed under the operating safety guidelines:

Once the fuel has been unloaded from the vessel, the decommissioning of the circuits of the reactor may be undertaken. The first operation is to decontaminate the primary circuits. Radiological and material inventories are then undertaken in preparation for dismantling. Systems are modified and adapted for decommissioning.

I-12.3 Lessons Learned

The following lessons can be drawn from this analysis:

- The importance of a project organization that is optimized and engaged at a very early stage.
- The need to anticipate some preparatory work before final shutdown.
- Accurate identification of tasks for which the plant operator is responsible and which are established with the agreement and in accordance with the French Safety Authority guide referred to above.
- Existing installations and equipment need to be quickly adapted, whilst maintaining others that are still required.
- An improvement in the cost estimates for current operating PWRs which were initially based on feedback from Chooz A and Creys-Malville experience.

I-13 Removal of Steam Generators at Latina Magnox Reactor Site in Italy

I-13.1 Description of the Issue and Lessons Learned

The Latina steam generators had been installed, at the beginning of the 1960s, using a huge crane called GOLIA (Figure 1). After the installation the crane had been moved to a corner of the site where it remained unused for more than 20 years. When the local amenity near to the plant started to develop there was pressure on the Electric Company to remove the crane that was actually visible over a long distance on the landscape. The crane was subsequently removed from the site.

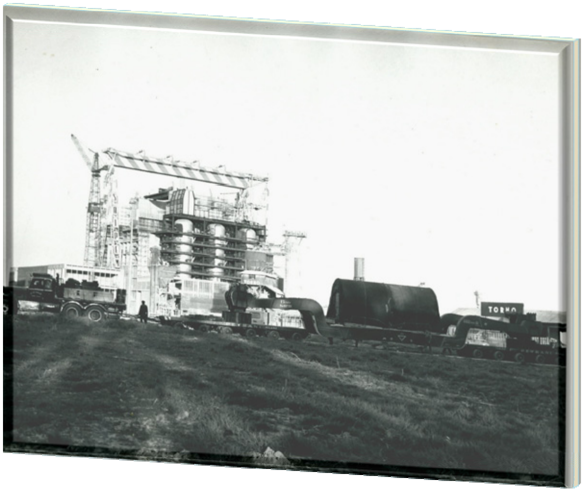


Figure I -13.1 GOLIA Crane.

I-13.2 Analysis

At that time the Utility did not consider the possible future need of the crane for the eventual operation of dismantling of steam generators and agreed to removal of the crane and the rails. Since the beginning of 2000, the Italian decommissioning company has been facing the problem of dismantling the steam generators and of cutting them into pieces acceptable to a melting company for recycling. The problem was shown to be more complicated than expected. A great difficulty was caused by the intended use of a modern new crane being the only type available today. These modern cranes are able to take a cylindrical sector of the steam generators and then transport it across the site to a suitable cutting facility. The route would pass over redundant imbedded condenser cooling water discharge ducts and some effluent piping. The structural strength of the piping and ducts was not sufficient to bear the weight of the crane. The decommissioning company then had to submit a project to remove the large piping and to route the liquid effluents in a different way. This project, for many reasons, encountered many difficulties with the Safety Authority

I-13.3 Lessons Learned

Future dismantling needs must be taken into account in the initial designs and recorded in the decommissioning plan. Only then would the required equipment on site be considered for retention during the decommissioning phase.

I-14 Example for decommissioning procedures required at the design stage in Germany

I-14.1 Description of the issue

As part of the licensing procedure for a vitrification facility (VEK) in Germany, decommissioning procedures were requested by regulators based on the current atomic law as well as specific requirements of the regulator. This is an example how past lessons learned are now been applied in a ongoing licensing procedure. It was required to give a detailed decommissioning sequence together with equipment needed, an inventory of the expected radioactive waste, waste treatment procedures and storage capabilities.

I-14.2 Analysis: remote controlled dismantling of VEK process equipment

After shutdown of the plant it will be decontaminated (rinsed). The intermediate level waste (LLW) resulting from this operation will also be vitrified. Within the framework of the shut down procedure, the melter will be charged again with clean glass to decontaminate it and reduce the radiation level. The melted glass is discharged into a canister. After termination of this, the first decommissioning step will be the segmentation of the melter and the removal of brick lining. The consequent dismantling steps are dependant on the radiological survey. Based on the expected dose rates, further dismantling of the VEK cells will be done in a sequence: Remotely controlled equipment will be used. The dismantling of VEK will be accomplished to a large extent with the already existing operational equipment. The following figures show the facility in illustration and views of the melter in the cell.

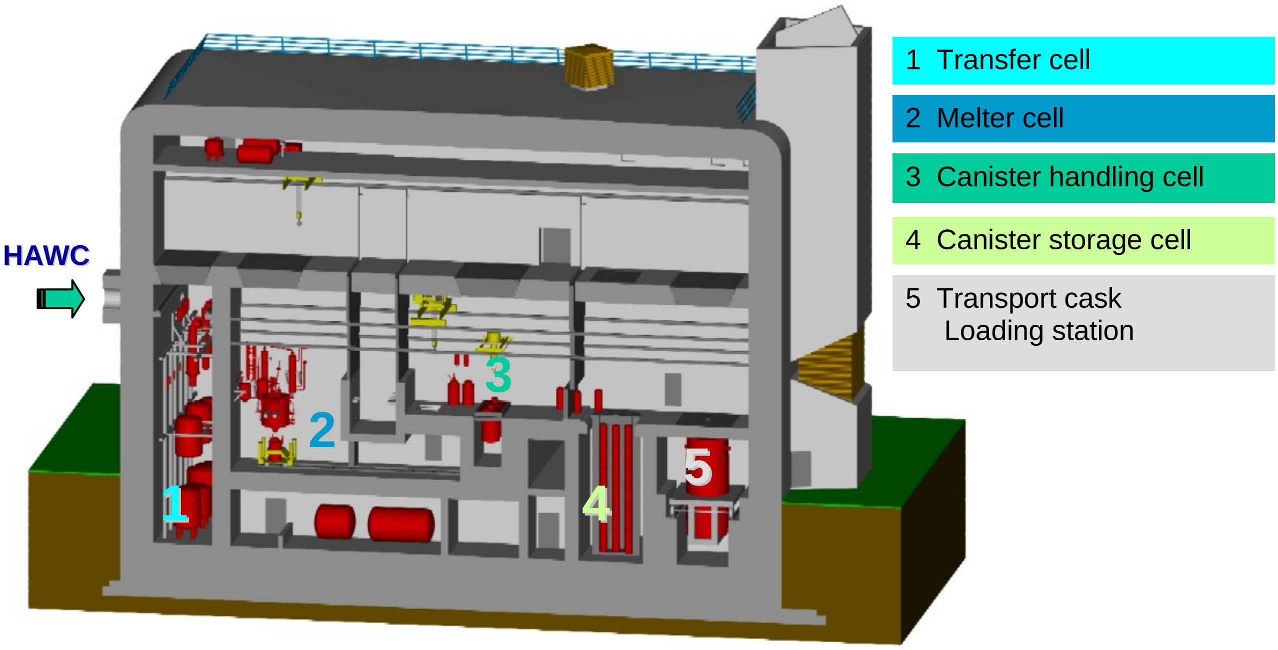
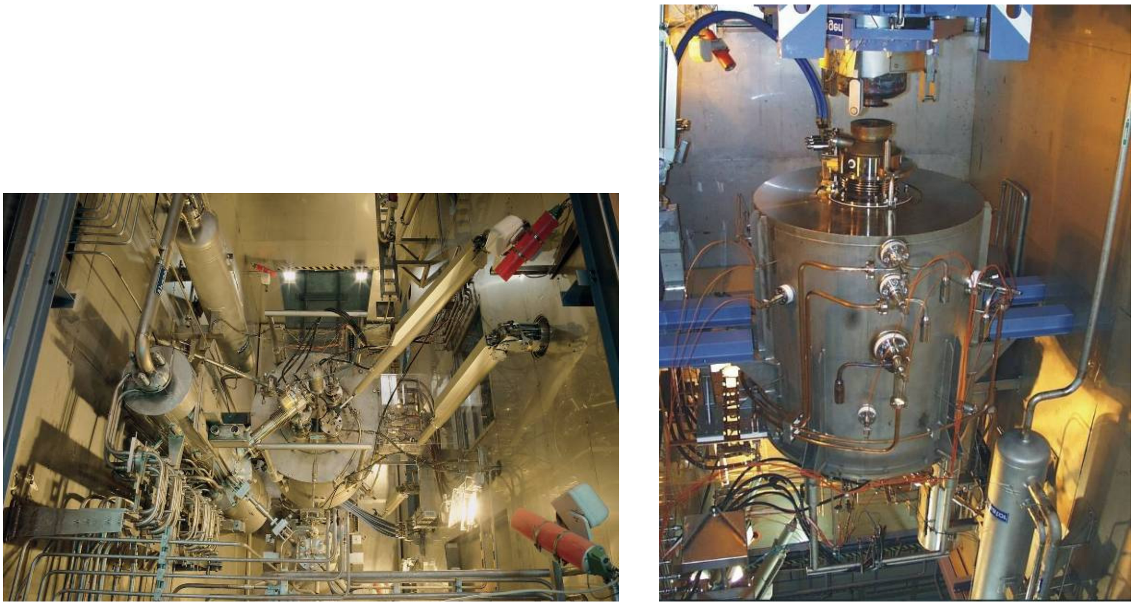


Figure. I-14.1 Layout of the vitrification facility, longitudinal cut.



Figures. I-14.2 Top and front view of *the* melter in cell V2.

I-14.3 Lessons Learned

As described in the analysis section, the procedures and requirements for new nuclear facilities require that detailed decommissioning planning be considered at the design stage of the facility. This facility was successfully decommissioned according to detailed planning and procedures developed during licensing.

ANNEX II

OVERVIEW NOTES FROM PUBLISHED REPORTS

These notes and extracts were taken from numerable sources covering background material, extracts from publications on lessons learned where beneficial design features were identified or were alluded to and also publications where design features are specifically identified and discussed. The material has been loosely grouped into four categories. Not all the material in this annex was included in the main body of the report especially where items were repeated or identical or only of background interest. All identified design features from all sources have been included in Tables 1 & 2. The complete list of references for the whole document including this Annex is given in the References.

II-1 General Lessons Learned

An IAEA paper presented at a training workshop in Cambridge UK in 2007 gives a current situation on the number of decommissioning projects completed worldwide [1]. As early as 1986 the IAEA published a Technical Report (TRS No. 267) which recorded methodology and technology of decommissioning nuclear facilities [21]. At this time it was clear that attention was being given to the special problems that decommissioning of the earlier designs of facility were revealing.

The IAEA published a comprehensive technical report (TRS No. 382) in 1997 [14] in which it concluded that means to facilitate decommissioning should be seriously considered during the design and construction phase of new nuclear facilities. Numerous reports and studies had highlighted the costs and complexities of decommissioning the earlier generation of Power Plants and other large facilities. The report lists 69 references to earlier publications on a wide range of decommissioning experience.

The objective was to provide recommendations for selecting suitable new sites and to highlight beneficial features that might facilitate decommissioning for those involved in planning and designing, constructing and operating future facilities. In some detail it dealt with policy and strategy, waste management and basic design aspects such as plant layout and access, shielding, materials, materials handling, surface conditioning and decontamination and post shutdown requirements. It also emphasised the need for good record keeping. Particular design features were highlighted such as reducing radiation exposure, shortening the time for dismantling, simplifying waste management and consideration of alternative strategies such as safe enclosure and deferred dismantling.

In 1995 an additional contribution to TRS No. 382 was offered by a nuclear contractor [42] and an amended version was included as annex 1.2 of TRS No. 382. The conclusions from the original contribution maintained that the cost of resolving waste problems did not add significantly to the overall decommissioning cost burden. It was also recommended that more attention should be given in future reactor designs to trace elements in materials that might become activated. It also recommended that fuel cladding integrity be improved and fuel assemblies be simplified (e.g. no steel grids). It added that attention should also be given to the reduced use of cobalt and nickel and that primary circuit water quality control should be improved to reduce corrosion.

In the UK a significant study was done in 1984 which identified some design features could be beneficial to decommissioning and some were incorporated in the designs of advanced gas cooled reactors to minimize possible decommissioning problems [15]. Important features were highlighted and the study was referred to in TRS No. 382. It largely confirms the observations in other publications.

A joint publication from the OECD/NEA and IAEA in 2010 [59] reiterated many of the topics mentioned in related reports and confirmed that the important design features that needed attention were plant layout and access, biological shielding, material handling provisions, material specifications, surface conditioning and contamination control and numerous post shutdown requirements. Attention to these design features can reduce radiation sources, shorten dismantling time, simplify waste management and allow adequate safe enclosure of residual structures.

In order to assist designers and policy makers involved in designing and developing new large nuclear facilities or even smaller research reactors, it may be useful for them to consult publications that deal with broad decommissioning issues. Among these are two IAEA publications on techniques, organization and management [32], [33]. There is also a report in the IAEA Bulletin which emphasises the importance of sharing experience and working together in the world nuclear community as a notable lesson to be learned [34]. It deals particularly with waste management, training, regulation and worldwide collaboration and gives examples of environmental restoration and contract strategy used in the UKAEA.

Since 1997, there has been considerable reporting of lessons learned from decommissioning projects and some authors have made recommendations to avoid the often unnecessary problems that have arisen. Among these recommendations, particularly in two US publications [48], [60], there have been specific design features such as; allowing sufficient space and access for dismantling work; avoiding underground tunnels and vaults that can be come contaminated; improved pipework and system designs to avoid crud build-up; attention to detailed glovebox and hot cell designs and encouraging the inclusion of experienced decommissioning engineers in design teams. A detailed proforma check list/questionnaire is included in one report [48] and is intended to be filled in as a systematic review of the design as it develops.

Another report [3] looks particularly at a future Nuclear Power Plant design (Westinghouse AP-1000) and shows how the basic design has been extensively simplified e.g. only 2 primary loops instead of 4. This leads to a substantial reduction of large components, systems and cabling as well as building size and volume. A more recent publication from a conference in the UK [4] presented a decommissioning strategy for the new AP1000 Westinghouse reactor. Particular design features to be included are a much simplified plant design and layout, a common integral basemat for the reactor containment building, modularisation of many large components including shielding walls, attention to leakage containment especially for spent fuel pools, ample space for work in radiological areas, facilities for major component replacement e.g. steam generators and particular attention to waste management and contamination control.

Lessons learned in recent years have been extensively reported on at international conferences and seminars. A useful list of 13 items from lessons learned has been given in tabular form [18]. The items are intended for power reactors but have relevance to other nuclear facilities and are:

- Adequate site Characterization before construction and regular monitoring there afterwards;
- Design features to meet ALARA principles particularly on improving access;
- Design for intact removal of large active components e.g. steam generators;
- Adequate measurement facilities for radiological monitoring;
- On site installed decontamination facilities;
- Adequate records management specifically for decommissioning;
- Implementing of a comprehensive site characterization plan;
- Implementing of comprehensive ground water monitoring programme;
- Tanks and pools to be corrosion resistant and have inbuilt leak detection;
- A quality assurance inspection programme to monitor for leakage and releases;
- A floor and wall inspection procedure to monitor for trapped contamination;
- Ensuring that block shielding walls are sealed against penetration and all surfaces are sealed against contamination;
- Surveillance and monitoring and upgrading as necessary of non- radioactive zones. This should include liquid and airborne monitoring.

The OECD has indicated that new nuclear power plant designs (GEN-III & GEN-III+) are being developed against clear objectives of improved safety, increased availability, extended life, reduced dose and shortened construction time [5]. It maintains however that lessons learned from decommissioning are not readily available to plant operators, designers and regulators in general and systematic analysis and databases aimed at designers and operators do not exist. It is suggested that utilities may be able to allocate reduced funding for final decommissioning if account of experience from past dismantling projects are taken into account in new designs. It adds that public awareness that past experience from decommissioning is being taken into account in new designs could increase acceptance. The OECD plans to assess and document the current status of lessons learned in a systematic detailed manner and to relate these to the expectations of regulators and utilities. If the expectations are favourable, they intend to document recommendations for existing operators and future plant designs. The intention is to produce a list of design aspects that are expected to be amenable to improvement of design and practice. A final report is expected in 2009. Designers and regulators will be involved. It has been reported that this may be delayed.

A detailed technical manual for public use was produced by the US department of the Army [16] which addressed general design criteria to facilitate decommissioning of nuclear facilities. It covered a wide range of facilities such as power reactors, research reactors and accelerators, radiographic facilities, depleted uranium and various research laboratories. Reference material is restricted to US regulatory and related documents. It was not referred to in compiling TRS No. 382. It deals extensively with decommissioning planning and strategy and the regulatory regime. There is a detailed chapter on general criteria and design features to enhance decommissioning. In particular, it deals with site planning and access provisions for waste management. The structural and architectural design criteria are somewhat specific and deal with pipework, drains, wall penetrations, floors, contamination control measures etc. In addition there is a detailed section on mechanical, electrical and HVAC system design criteria. This includes many prescriptive details on tanks, sumps, ventilation, cabling and electrical equipment etc. There are then separate sections on waste handling, decontamination specifying numerous techniques available and safety services such a fire protection.

The text concludes with a chapter giving specific guidance on criteria for power reactors and separately for research reactors, accelerators and various research, testing and medical laboratories. It suggests that strategies for power reactors may consider DECON, SAFSTOR or ENTOMB but research facilities should be dismantled. Glove boxes are dealt with in some detail. There are included some appendices on radiological hazards and source materials. The document is an excellent summary of all aspects of decommissioning.

An international conference was held in Athens in 2007 on lessons learned from decommissioning and the safe termination of activities [20]. The aim of the conference was to share experience and knowledge and to identify areas of international harmonisation in decommissioning. An important conclusion relevant to future designs of nuclear facilities was to increase the awareness, through a Joint Convention on Safety, for governments and policy makers of the need for early planning, adequate funding, government support and establishing long term strategies for decommissioning and waste management. Other outcomes were the support for an IAEA proposal to establish a Decommissioning Network to feedback decommissioning experience, a need to reflect the accumulating decommissioning experience in revised IAEA Safety Guides and a strong recommendation that lessons learned from decommissioning to date be used as an input for design, operation and maintenance of all new nuclear facilities. It also noted that lack of waste disposal facilities should not be a reason for delaying decommissioning. There was also reemphasis on the need to preserve and maintain knowledge and records.

The US NRC has compiled a comprehensive list of 24 documents available on a CD-ROM which report on lessons learned from decommissioning in the US [19]

A publication by the US NRC identified some practical solutions to difficult decommissioning issues from feedback from various decommissioning sites [60]. Some recommendations were made for considering in future designs. These are to avoid the burying or imbedding pipes underground or in walls, establishing a comprehensive ground water monitoring programme from the outset and locating buildings on sites so the spills can be more easily managed. The NRC also published information from UC power plant sites (Braidwood, Byron, Dresden, Haddam Neck/Connecticut Yankee and Indian Point) where ground water contamination has occurred. [62] This reinforces the need for future facilities to give particular attention to undetected releases to the environment and to implement stringent monitoring systems.

A presentation from an implementer of decommissioning in Belgium (SCK-CEN) raised the question why external contractors (implementers) in 15 years of work have never been asked for any feedback of their experiences [63]. The suggested answers are:

- For a research organization the major interest is always on the next research project with little concern for the past or learning from a decommissioning project. There is little interest in bad experience.
- It is also assumed that modern facilities will automatically take into account record keeping, QA inventory databases, optimal waste management etc.
- External implementers (contractors) are in an open market and may be reluctant to offer beneficial design changes that may cost more and make them less competitive.
- It is also recognised that the cost of decommissioning a nuclear power plant may only be ~10% of the build cost and hence this cost discounted into the future is negligible.
- Regulatory bodies are more focused on safety and not enough on decommissioning.
- It is likely that operators may become concerned that, when major plant revisions are done to extend operating licences, this may increase decommissioning costs. This however may

not be so if there is good design to facilitate decommissioning, agreed justification and consideration of whole cycle costs.

- The owners of new facilities (internal implementers) are much more interested in commissioning new facilities to cost and programme and less interested in long term issues.
- There are, however, controls within SCK-CEN from a waste management group to get authorisation for anything that will be used in a radiologically controlled area.
- There are also obligations within SCK-CEN to take account of future decommissioning costs.

It is concluded that designers and implementers of new facilities must be encouraged and even obliged to take account of future decommissioning liabilities otherwise there will be lack of interest.

The US Electric Power Research Institute (EPRI) has produced a comprehensive report on lessons learned from decommissioning [64]. It covers all the main lessons learned that are being reported internationally over the last few years. The main emphasis has been on:

- Ground monitoring programmes that should be in force throughout the operating period;
- The ability to achieve good chemical decontamination of primary systems;
- Enhancing the ability to segment activated reactor vessel internals for removal including the use of mockups;
- Avoiding the problems of removing contaminated embedded piping as far as possible;
- Attention to the timely provision of interim spent fuel storage facilities separate from the reactor;
- Attention to low-level waste management facilities and volume reduction;
- Provision of interim storage for greater than class C waste;
- The application of robotics to decommissioning.

II-2 Decommissioning Strategy, Planning, Licensing and Cost Estimation

The importance of a preliminary decommissioning plan (PDP) leading to a detailed decommissioning plan (DP) is emphasised in many IAEA and other documents. The suggested contents of a plan are listed in the paper given the training workshop referred to above [1].

The choice of an appropriate decommissioning strategy or a selection of options should be done at the planning and design stage of a new facility and be included in the preliminary decommissioning plan required in the licence application. Many new facilities, especially power reactors, may be designed for an operating life of up to 60 years. It may be difficult to define a detailed strategy at the early stage of design but some outline and costing on decommissioning will be required to satisfy the licence and to enable some cost estimates to be made. These estimates with appropriate contingency allowance will be required as a basis for financial provisions for future decommissioning projects. The issues and factors associated with selection a strategy have been dealt with in numerous earlier publications by the Agency and others but pertinent summary of factors is given in a recent IAEA publication which has useful references [51]. In particular, it gives a table of factors and related “good practice” attributes to consider. Interest was generated in the option of in situ decommissioning as a strategy for some facilities in certain situations and the IAEA accepted this as a viable option provided a safety case could be made. An IAEA technical document was published to highlight and record aspects of this option in 1999 [28]. Although it is believed that safety and environmental issues could be acceptable, this strategy has not received much attention.

As a result of decommissioning the Rancho Seco nuclear power plant in California and other plants in the US, two publications were issued recommending a number of minimal changes in plant design that could result in significant cost savings in decommissioning [35], [36]. This experience also reflected on improvements in the way documents and records are kept. It was observed that earlier designs were so robust in construction and over designed that it appeared doubtful that dismantling was ever contemplated. Cost of decommissioning has doubled since 1987. In particular, the excessive embedding of piping and conduit in concrete and the placing of many systems underground, resulted in very difficult cutting and removal problems. A list of 7 design related recommendations was given and include improved location, more access, contamination control especially concerning penetration into concrete, improved separation of radioactive and non-radioactive systems and areas, more use of modular items, avoidance of mixed wastes, more photographic records from construction etc.

Recommendations relating to the design process for shielding have been made in a publication applicable to new plants and decommissioning [43]. The application is for shielding to meet dose targets for operators mainly involved in process activities including decommissioning activities and is not relevant to reactor biological shields. Three factors are considered viz. location where shielding is required, the source material and the nature of the process. It suggests 7 criteria for making decisions on the amount of shielding required to meet dose targets:

- Minimize the amount of shielding;
- Minimize the construction time and operator occupancy;
- Use realistic source dose levels i.e. averages not maxima;
- Avoid using dose sharing;
- Use safe distance from sources & remote operation if possible;
- Use local or temporary shielding for high or abnormal doses;
- Have the ability to remove high level sources when maintenance is required.

This approach is intended to save costs and avoid excessive shielding which is easy to install but much more costly to remove.

In 2001 the European Utility Requirements Group (EUR) issued Terms of Reference for future designs of LWR nuclear power plants for the EU [25]. Chapter 2.16 dealt with decommissioning. It recommended that experience gained from maintenance, overhaul, backfitting, current and previous decommissioning and radiological measurements should be taken into account. It was aimed at giving guidance on design/decommissioning issues. At a EUR coordination group meeting in 2007 Areva NP gave a response to a Questionnaire on features incorporated in their design for the EPR reactor [24]. There has also been a fundamental safety review of the EPR design for the UK which was included in Chapter T: Decommissioning and Dismantling Volume 2 of the Safety Overview document [38].

Westinghouse gave a presentation of the design features of their AP1000 reactor to meet EUR requirements at an EU Seminar in Brussels in 2007 [23]. There is also a UK safety and environmental assessment report for the UK on the Westinghouse AP1000 reactor [22]. To supplement the attention to safety in the design, the UK HSE has issued a Design Safety

Assurance document which includes specific reference to quality assurance (QA) relating to design changes and the design/decommissioning interface [39].

In the UK, the chief design organization for a new generation of nuclear submarines (Rools Royce) is addressing design features that will facilitate decommissioning of the Nuclear Steam Raising Plant (NSRP) [65]. In particular, disposal is to be integrated with the UK MOD decommissioning and disposal policy. The overall design process is described.

In Canada, the nuclear safety commission (CNSC) has produced a detailed document setting out the regulator's expectations for the design of new nuclear plant [40]. There is a small section on decommissioning covering three basic principles. The designer of a new generation of Candu reactors (AECL) has produced a technical summary of the new Candu ACR 1000 reactor [41]. The document gives a brief outline of desirable features beneficial to decommissioning. AECL are members of the OECD/NEA cooperative programme on decommissioning.

Reported and indicated cost estimates for decommissioning in some countries have shown significant differences even for similar facilities. It is realised that economic practices and approaches vary in different countries but a need to harmonise and standardise cost models was recognised. The OECD/NEA published a proposed standardised list of items for costing purposes in 1999 [52] and there was a discussion paper presented at a workshop in Rome in 1999 [53]. There also exists a computerised costing model for decommissioning estimates developed by the UKAEA. A private company in the US has also published a useful study done on trends in decommissioning cost estimates [54].

A recent publication under the IAEA Safety Standards Series has been published as a guide for designers of new power plants to ensure adequate radiation protection for workers and the public [44]. It gives guidance on all aspects of the facility where radiation exposure could arise. It covers all aspects and features outlined in TRS No. 460 [27] but is more prescriptive on radiation protection matters. There is also a more general IAEA safety guide which deals with important aspects for licensing decommissioning projects for large power reactors and research reactors [50].

A comprehensive study has been completed on the redevelopment of nuclear facilities after decommissioning [66]. Although the future use of a facility and/or the site might not have a significant influence on the immediate design of a new facility there should be some awareness of the potential value of a site and its facility whether for financial or amenity potential. Clearly the future potential has not always been foreseen until many facilities have been completely decommissioned and opportunities may have been lost. Some locations have been in potentially desirable areas but severe contamination of the site has precluded meaningful reuse. The value of this document is particularly for policy makers and planners who should at least be aware of the future potential of a site and should take note of what has currently been achieved on reclaimed and reused sites after decommissioning. Certainly the reuse of a site for renewed nuclear activities will be a consideration if it cannot reach green field release status. Sites for many existing nuclear power plants are likely to be well located as electrical load centres and for cooling water supplies and other services.

A major project was undertaken to completely dismantle the Trojan Nuclear Plant in the US and to ship all waste for storage site at Hanford [67]. This was a successful project completed in about 10 years (licence terminated in 2005) and costing over $400m. It has been extensively reported and documented. No particular original design features were reported that had or would have facilitated the dismantling activities.

Reference has been made to a publication by the Institution of Chemical Engineer s, London on addressing feedback from the closure of chemical sites in the design of new plant [68]. There is no nuclear radiation or radioactive waste involved but there are toxic chemical and substances. The document describes a new methodology for integrating features into the design of new chemical plants to make them easier, cheaper and cleaner to decommission. They use the terminology "Design for Decommissioning" (DfD). The main activities they highlight for decommissioning are:

- Process plant decontamination
- Dismantling
- Site decontamination
- Site remediation

They cite several methodologies that are used to reduce the whole life impact of industrial products but propose a new design approach that has the specific aim of reducing the impact of future decommissioning activities. In essence the approach proposes 8 stages with checklists to be applied alongside the normal design process. Each stage is described in some detail to allow designers to take relevant decommissioning factors and features into account. The method has relevance to future design features for nuclear facilities and are:

- Justifying the decommissioning design features;
- Estimating the discount rates for decommissioning costs;
- Assessing staff and organizational awareness;
- Identifying closure scenarios;
- Deriving decommissioning costs and impacts;
- Identifying design associations and principles;
- Assessing cost implications on future designs;
- Closure planning of the proposed facility.

A company in the UK has produced a paper on design for decommissioning (DfD) which emphasises the importance of planning and designing for decommissioning. The huge cost of decommissioning a large facility can be minimized by considering whole lifecycle design and cost [30]. It recognises that decommissioning requires new facilities which, in turn need decommissioning and the aim should be to minimize the self perpetuating cycle. A number of long term benefits from DfD are listed. Among these are improved public perception, reduced costs, improved safety, reduction in waste arisings, shorter programmes and optimizeduse of on-site resources. It maintains that the layout development process should involve all stake holders. An example is given of a flow diagram for integrating a new waste treatment facility into the existing site infrastructure.

Another publication highlights attention to end of cycle issues because of the extended operating lives of numerous new facilities being planned. [29]. It discusses issues at reactor, National and International levels and, in particular, the need to incorporate whole life cycle planning.

There is an additional paper on design for decommissioning issued by an organization called Integrated Design Management Ltd, which emphasises the multi-faceted nature of engineering design in an attempt to satisfy many competing objectives. It refers, in particular, to the huge task to clean up the waste storage facilities at the UK Sellafield site where little or no attention had been paid to decommissioning during the original design. It highlights the conflict between the regulatory requirements for minimal risk, the need for a minimum cost option and the public demand for hazard reduction and removal of the facilities. [83] The decommissioning of the waste storage facility is needing another large facility which will in turn need decommissioning thus suggesting a decommissioning cycle. Designs are needed to eliminate this perpetuating cycle.

A lesson learned from the decommissioning activities reported from the multiple facility Kerr-McGee site in the US [69] was that, whereas it was advantageous to divide the site into discrete sectors or units for planning, management and reporting, this approach required separate licensing which put greater demands on the NRC. A balance must be reached in offsetting the additional licensing costs against gains in decommissioning operations. They also reported two problems associated with the management of radiological and non-radiological mixed waste which indicates the need for segregating these wastes as far as possible in future designs. A lesson learned and emphasised is the need for an adequate and complete radiological Characterization of any proposed site during the design phase to facilitate final site release conditions even though this may be well into the future.

The importance of a well planned transition and deactivation (shutdown) process is raised in two US DOE guidance documents [70], [71]. These are processes of placing a facility into a safe shutdown condition and the transition to decommissioning that ensure that it is economic to monitor and maintain all necessary systems until eventual decommissioning takes place. These processes should be considered in the design of a facility especially where there are other facilities like an adjacent operational power or processing unit that are linked with the facility that is to be shutdown. Very often safety systems and other services are shared and prudent design of systems that can be separated when required in the future is an important design feature.

A companion document to the above two US DOE guidance reports is the Decommissioning Implementation Guide [72]. This highlights the need for adequate decommissioning planning to ensure a smooth uninterrupted decommissioning process.

It has been recognised in recent years that the final shutdown of a nuclear facility has a significant socioeconomic impact on the local and national community and economy. There are many examples of the effects and proposals on how to address the problem given in an IAEA technical report [31]. The immediate affect is low staff morale which can have many adverse implications. These can affect safety and cause costly delays in starting and progressing with decommissioning. The most adverse impact is the sudden shut down of a facility without sufficient planning or preparation. Most significant effects have been major nuclear accidents which have caused policy changes in many countries and the severe consequences that result from changes in government or political regimes. Planning to minimize the effects on the local community and the economy at large site needs to be considered by policy makers. Very often safety of nuclear facilities may be at risk if contingency plans are not available.

A paper presented at a Nuclear Forum in the UK gave a number of simple principles that should be taken into account in establishing a decommissioning funding scheme [55]. These were, in particular, knowing the real costs, recognising robust costs, fixing the rules, secure the fund against dispersal of funds, establishing a funding arrangement plan.

A publication reported in an IAEA Bulletin [34] recognises the lack of skills needed for decommissioning and for nuclear technology in general and identifies a number of international organizations that are giving support or providing training.

II-3 Waste Management and Contamination Control

There is also a publication from a specialist employed by Framatome (now Areva) in France that addressed the problems of activation and contamination [6] and included recommendations for future designs. The recommendations also highlighted the need for improved plant layout in new designs. This document was published in 1992 but remains valid and was referred to in TRS No. 382 [1].

A US NRC Regulatory Guide drafted published in July 2007 provides guidance on the minimization of contamination and radioactive waste generation [49]. It states that specific design considerations are drawn from nuclear industry experience and lessons learned. It restates that, from August 1997, there has been a US requirement for any new facility to demonstrate how it will minimize contamination and waste generation. Three principles were embodied in contamination management viz. prevention, detection and aggressive cleanup. The US NRC receives annually license applications for over 100 different types of nuclear activities. There are 9 specific guidelines such as early planning to minimize contamination, providing adequate containment, prompt detection, avoiding releases, reducing the need for decontamination, review of procedures, record keeping and site confinement where necessary. The document then gives an extensive list (26 items listed) of specific measures and actions that must be considered to minimize contamination of the facility itself. There is a similar list covering avoiding contamination of the environment.

There is a shorter list of 5 measures to minimize the generation of waste. These cover volume reduction, defining waste streams, avoiding on-site disposal, on-site decontamination and modular construction of large concrete structures. There are finally some suggestions on the application of the guide for different facilities.

An established measure to reduce and facilitate surface contamination is to make use of fixed or removable coatings to allow ease of cleaning and to prevent sub surface penetration. New techniques are being continually developed and designers and constructers should be aware of these. A particular development reported recently is using epoxy enamels [45]. Epoxy enamels have been shown to have good adhesion properties to most materials, radiation resistance and ease of decontamination. They also do not contain flammable or explosive solvents so avoiding fire hazards. It is claimed that the particular product, which has been developed in Russia, meets the requirement of a regulation GOST R51102-97. Tests have shown that there is no change in protective properties in a steam/air environment for 10 hours at 0.5 atm overpressure. The coating also meets fire test safety requirements. There are also good hardness characteristics. The long term design life of the coatings was not mentioned.

Important considerations have been addressed and recommendations made in an attempt to minimize the generation of waste from decommissioning of future facilities. The IAEA has recently published a comprehensive technical report (TRS No. 460) on waste minimization to give guidance to future and current planners, facility designers and policy makers [27]. It explains that the concept of waste minimization can be interpreted in two ways: in terms of volume (sometimes mass) or in terms of radioactivity. There is usually a trade off between benefits accrued and the cost of achieving waste minimization. For example decontamination may not always result in minimization. Costs are associated with processing and interim storage if there is no disposal route. Worker dose and exposure must also be taken into account. The document suggests 4 fundamental principles:

- Control of waste generation.
- Minimization of activation and contamination.
- Reuse and recycling of materials.
- Reduction in overall volumes.

All these should be considered at the design stage. It is recognised that minimization may not always be optimum or even possible when dismantling existing facilities takes place, which is why it is so important to give consideration at the early design stage of any new facility.

Important features that have been identified to minimize waste production are:

- Building and equipment layout with emphasis on zoned areas according to activity levels;
- Layout of ventilation systems;
- Layout of piping systems;
- Design of storage tanks and equipment to minimize leakage and for eventual removal;
- Selection of materials especially to minimize activation and migration of activity. Minimizing undesirable impurities in steel and concrete is important;
- Sealing of porous surfaces with suitable coatings to prevent penetration as activity.
- Limiting corrosion and erosion;
- Designing piping and ducting systems to minimize crud formation;
- General good design practice to facilitate decontamination of surfaces and systems.

There are also provisions that can be made to facilitate dismantling and segmenting activities. Among these are:

- Minimum use of hazardous materials that might give rise to mixed waste;
- Special layout considerations to facilitate dismantling especially regarding access;
- Pre installation of dismantling aids e.g. shielding, lifting fixtures, rails, openings etc.
- Design for intact removal of large items such as steam generators, pumps, vessels and tanks etc.
- Adequate records of equipment including initial installation details and photographs etc.
- Continued development and improvement of decontamination techniques;
- Continued development and improvement of dismantling and demolition techniques;
- Continued development and improvement of measurement techniques;
- Development of ways to simplify waste management including volume reduction, Characterization and assay techniques;
- Considering the use of mobile waste treatment facilities to allow maximum and optimum usage;
- Inclusion of design features and facilities for the selected decommissioning strategy (e.g. for safe enclosure if this is selected).

The document includes two useful tables (Tables 10 and 11) which summarize the factors to consider at the design stage to minimize waste and to evaluate design options. The report concludes that sufficient is now known about the decommissioning and waste management processes to give valuable feedback to designers to avoid unnecessary cost and problems in the future. There are over 100 references used in compiling the document and a description of most of the important types of nuclear facilities that give rise to radioactive waste.

There was an important joint NEA/IAEA/EC workshop in Rome in 1999 on the regulatory aspects of decommissioning and a particular session 3B presented 11 papers reporting experience from various countries on exemption, clearance and authorised release of a site It is important that there is awareness by planners of the potential problems for eventual site release when a new site is being licensed [57].

A topical report [13] from a RWMC meeting in March 2007, addressed decommissioning and waste management issues relating to small users and/or producers of radioactive materials for educational, medical or industrial purposes. The aim is to consider what items are appropriate for inclusion in future work programmes. It was noted that there was a need to develop comprehensive strategies for management of these types of wastes. It was apparent that the approaches were very different in various countries. It was noted that not all problems at the back end of these activities have been recognised or resolved or that funding is readily available. The .OECD/NEA and IAEA has also recognised this and published a number of documents to give guidance [10], [11], [13]. Clearly for future and ongoing activities there is a need to feed back experience to enhance any future designs or initiatives. A specific safety guide was also issued by the IAEA to encourage safe practices [12].

The State of Kansas Department of Health and Environment issued a document on the prevention of problems arising from decommissioning with particular relevance to liquid and airborne releases and some aspects of design [73]. Adequate inspections and environmental sampling were most important. In future the following should be recognised:

- Cleanup is a major contribution to cost;
- Need more competition for disposal options;
- Minimize volume;
- Better characterization for better control;
- Avoid unnecessary disposals;
- Decommissioning planning must start right at the beginning of a project.

There is a particular report related to the above on the decommissioning of a large Thorium Mantle production facility in a multi story building in a downtown area in Kansas [74]. The site and numerous facilities had been in continuous use from about 1909 to the 1980s with very little attention to the spread of contamination. Earlier attempts at decommissioning and decontamination in the 1990s were unsuccessful. Although radiation effects were small the accumulated effect is large. There were many surprise findings and even a disposal site under the building and other chemical hazards. There was a complete lack of historical records.

Another example of where lack of records and monitoring is giving rise decommissioning problems is the attempts to characterise a uranium enrichment site (Hematite and Windsor) where samples ranging from depleted to fully enriched uranium are being found [75]. Characterization work is still ongoing.

A report from the US Fuel Cycle Facilities Forum [76] indicates that, in spite of cleanup efforts and meeting all NRC criteria, some sites may never achieve finality and be released. This should be borne in mind when future fuel manufacturing facilities are being planned that the site may not be reusable.

A publication addressing the huge decommissioning and cleanup problems at the Sellafield reprocessing plant site and elsewhere in the UK stresses the importance of initial engineering design and the challenge for design teams [30]. Waste management is a particular problem to address.

The serious implications for decommissioning a site that is contaminated with carcinogenic chemicals and low level uranium presents a special problem in obtaining authorised and accepted waste disposal sanction [77]. This illustrates the need to avoid mixed wastes in future facilities where ever possible. The problem is still not resolved at the 600 acre site and a number of agencies and authorities are involved.

The design of waste storage facilities has received attention and consideration needs to be given to decommissioning of these when they are no longer required. It is clear that little consideration had been given to decommissioning in the past and a number of difficult problems had been encountered when decontamination and dismantling is undertaken. There are many instances of solid waste bunkers becoming extremely contaminated due to storing unsealed, untreated waste and deteriorating conditions were exacerbated by ingress of water. There have also been difficult problems associated with access and the absence of any or adequate records. Storage of liquid waste has also been problematic due to sludge, leakage and lack of suitable treatment facilities. Resultant ground contamination has been a difficult problem to resolve.

Most of the documentation published has concentrated on the management of the waste itself and not specifically on the decommissioning of redundant waste storage facilities. An IAEA TECDOC published in 1994 promoted a typical reference design for a centralised waste processing and storage facility [51]. It covered design features for waste processing and storage in some detail. It was specified that the waste had to be properly conditioned and packaged before storage and that the facility should be straightforward to decommission as it should be largely uncontaminated and could be used for other industrial purposes. The plant and equipment in the waste processing and conditioning facilities however are likely to become contaminated. No mention is made however in that TECDOC concerning design features to facilitate decommissioning. For example, the waste from dismantling this facility will, in itself, need some additional facilities or measures to process it for storage. A mobile waste processing unit may be of use.

In 1999 the IAEA published IAEA-TECDOC-1096 which reviewed factors affecting the selection of waste management technologies [78]. The IAEA also published a TECDOC in 2003 to give guidance for waste management in countries with small amounts of waste [79]. The document gives guidance on the technical factors affecting the selection of waste management technologies. It emphasises the need to consider the waste properties and characteristics, the scale of the operation, the maturity, robustness and flexibility of available technology and the site characteristics. A list of design criteria for a storage facility was given. These briefly include defining acceptance criteria, proper waste segregation, provision of adequate handling equipment, prevention of degradation of waste packages, hazard protection of the facility including fire and water ingress, proper record keeping, waste and facility inspection regimes, waste retrieval provisions and adequate security against unauthorised intrusion.

II-4 Miscellaneous Issues, Legacy and Research Sites

In the US the DOE has proposed some initiatives for a task to identify design and operating features with respect to improving Generation IV reactors (the current designs under review) by facilitating their decommissioning [7]. The current high cost and timescales for decommissioning the previous generation of facilities has resulted in criticism and reservation concerning the building of a new generation of power reactors. In particular, the DOE document maintains that facilities should be designed to simplify decontamination and decommissioning and/or increase the potential sites for reuse. It recognises that both the DOE Order 6430.1 and IAEA TRS No. 382 publications should contribute to guidance on new design and construction.

A detailed report was issued in 1990 concerning the decommissioning of the large sodium cooled fact breeder reactor in France [17]. It revealed that activation products were a significant problem. Consideration was given determine whether Co-60 could be substituted with an alternative such as nitrate coating in future designs. It was also found that insufficient attention had been given to the ability to drain out all liquid sodium due to pockets and traps in the structure particularly in the diagrid. Over all plant layout was also far from optimum to facilitate easier dismantling. This report was issued for the use of future designers although no new fast breeder reactor is being planned at present.

Feedback from lessons learned into new designs is not restricted to power reactors. In 1998 a paper was published by the Atomic Weapons Establishment in Britain (AWE) which included a section on design features to facilitate decommissioning when planning for future construction [26]. It highlighted a need for awareness of decommissioning at all stages of design. A series of value engineering workshops for staff are conducted at the beginning of a project which includes decommissioning aspects, maintenance, design authority, health physics etc. Features such as materials of construction, simplified modular design, easily decontaminable surfaces, optimization of pipework systems and accessibility are included. Records are kept of all design features which are of value and relevance to future decommissioning. There will be rigorous design and document control regarding records. An illustrative chart giving the procedure and interfaces between all those involved shows how decommissioning features will be integrated.

The Hanford site in Richland, US, has been keeping a record of lessons learned from their on-going operations since 1995 [80]. There have been up to 50 incidents or reportable events per year. Many of the activities are decommissioning or related to site operations related to decommissioning but there is no reporting that the lessons learned have specifically led to feedback into the design process. Although the published information is detailed and a useful record, there does not appear to be any meaningful feedback for reporting in this TECDOC.

A US NRC document issued in 2004 had highlighted some of the problems that have been experienced in the US in attempting to meet license termination rules [81]. Much of it has been associated with long lived isotopes of uranium and thorium and it is all to do with residual levels from cleanup. Some aspects are concerned with on-site disposal. There are also issues concerning the provision of funds to control or monitor future legacy sites. There are also difficult rules about the mixing of contaminated soils. The lesson learned to feed back to future designers and site owners is the difficulty in achieving free release status and the extreme care that must be taken to avoid site contamination.

The Atomic Weapons Establishment (AWE) in the UK have recognised the value and importance of including decommissioning requirements in all stages of a facility’s lifecycle from the initial concept through detailed design, construction, commissioning, operation, maintenance, mid-life upgrades and eventual final shutdown [26].They run value engineering workshops which address all basic requirements of a new facility including decommissioning and is supported by all relevant sections in the organization. In particular detailed design will address materials of construction, simplified modular design, surfaces easy to decontaminate, optimum pipe and service runs and accessibility to all major items of plant and equipment. Special attention will be given to comprehensive record keeping. There will be rigorous control of changes and modifications.

In the UK studies to resolve the difficult problem of decommissioning the severely damaged air cooled reactor pile 1 has been on going for many years. The two reactors (Piles 1 & 2) were shut down after a fire in 1957. A review has shown that some original design features have made decommissioning more difficult but some, fortuitously, are facilitating access and the potential for dismantling [82]. For example, large air ducts have allowed good access and, being horizontal, have allowed easier removal of debris and the horizontal water ducts have even allowed man access. Direct fuel removal to ponds will eliminate the need for transfer casks. The bioshield is not pressured, has no steel reinforcing. and has an inner steel liner and neutron absorber which has reduced concrete activation and contamination. Access is available to all surfaces of the bioshield. Air filters were located some distance from the core and are not damaged. The cooling system is located in a separate building and is not damaged. The control rods are of stainless steel with only short billets of hard boron steel which make cutting easier. Fuel and the graphite moderator are in small component sizes and can be removed horizontally with a remote handling device.

Design aspects that are making dismantling difficult are the stored Wigner energy in the graphite which is a fire risk. The extent of annealing that has occurred to remove this energy is not measurable. The fuel was clad in aluminium and both this and exposed uranium fuel is subject to oxidation and hydriding (uranium hydride is pyrogenic and there is s risk of spontaneous combustion). Damage and debris has made Characterization of the facility very difficult. There remains a criticality risk due to disturbance of the core and fuel geometry. There is also a graphite dust explosion hazard. A conclusion reached is that design features exist to facilitate dismantling but the damage caused by the accident is the main cause of difficulties.

A company involved in decommissioning has produced a paper on design-for-decommissioning (DfD) which emphasises the importance of planning and designing for decommissioning. The term DfD (design-for-decommissioning) is used for this activity and is similar to Defence-in-Depth (DiD) for safety systems. It claims that the huge cost of decommissioning a large facility can be minimized by considering whole lifecycle design and cost and recognises that decommissioning requires new facilities which, in turn need decommissioning and the aim should be to minimize this self perpetuating cycle [30]. There is also a similar proposal introducing the concept of DfD made in a publication relating to design of waste decommissioning facilities at the UK Sellafield site [83].

In Brazil at the IPEN facility, a number of design and construction features that have an impact on decommissioning, have been reported [84]. Most of the facilities were constructed in the 1960/70s as pilot plants with little consideration for decommissioning. The features which allowed flexibility for construction, modification and operation gave rise to particular decommissioning problems. The situation was exacerbated by a prolonged shutdown period of 12 – 15 years. Decontamination had been superficial and, although activity levels are not high, a very large volume of radioactive waste was generated. Another problem was the unfortunate choice of materials, in particular, perforated, corrodible steels, painted surfaces that impeded attempts at decontamination and the use of glass fibre and asbestos. Floors and walls were of porous material which absorbed contamination and there was ill-advised use of ceramic or polymeric tiles. Corners were also not sealed against ingress of activity. It was concluded that the problems for decommissioning were made worse because of the specific attention given to research and development with no consideration given to waste management or future dismantling.

At the Rez site in the Czech Republic, there are a number of obsolete radioactive facilities being decommissioned and considerable quantities of waste to deal with [85]. The objective is to reduce all environmental liabilities. Many problems were encountered which were made worse by the lack of reliable records and information. A special problem was a large underground tank which included heavy internal steel shielding for unknown reasons and was very contaminated. There were also many problems with pipes in tunnels due to access and contamination. There were also many difficulties associated with a contaminated site sewage system. There were extreme access and removal problems associated with an obsolete liquid waste evaporator which had been concreted into a pit. Many floors and surfaces were of porous material. There were also underground tanks that contained both solid and liquid waste. At times, ground penetrating radar was used to locate waste due to lack of any records.

The ASTRA-MTR research reactor in Austria was finally decommissioned in 2006 and the site released for re-use. [86]. The experienced decommissioning team had been deeply engaged with the facility throughout the operating life. All historic records were available in good condition. A new company was formed (Nuclear Engineering Seibersdorf GmbH) to take responsibility for final decommissioning. A particular beneficial design feature was the use of removable lead shielding blocks in the reactor vessel to protect the concrete. It was also presumed that the lead protected the internal alumina components from corrosion by galvanic action. The lead also allowed remote access for dismantling with minimal exposure to operators. The extensive use of Alumina also minimized activation radiation levels. The ability to take Characterization samples from concrete within the vessel prevented spread of contamination. The accurate sampling of the depth of activation, allowed waste to be separated in terms of activity and minimized the quantities for disposal. The design and construction of the main ventilation systems allowed these to be used during the dismantling activities.

The successful demolition of the DR2 research reactor bioshield in Denmark was reported. [87]. Good practices were employed and these were essentially considered to be the lessons learned. They included essential planning, dry cutting methods to reduce contamination and good waste management. No suggestions for design features to facilitate decommissioning were offered.

The expected completion of decommissioning of the Korean KRR- 2 research reactor was reported to during 2008 [88]. It is a small reactor of 2MWtr and it was concluded that the layout of the facility greatly facilitated the work. They concluded that clear separation of the reactor hall from all other facilities was beneficial and they adopted a flow of waste material from simple to more complex contamination.

Design features were identified during the decommissioning planning of the ET/RR-1 2MW research reactor at the Nuclear Research Reactor in Egypt and was reported in IAEA-TECDOC 1273 [89]. There was particular emphasis on the handling and storage facilities for spent fuel and the need to retain services for these long after the reactor systems are shut down. It was also recommended that designs should avoid difficult areas for decontamination, e.g. to minimize penetrations through the reactor walls for piping systems. Future designs should consider clear and short routes for the removal of contaminated items. It included provision for engineered barriers as containment systems. Documentation needed for decommissioning, as called for in the decommissioning plan, should always be kept up to date. It was also desirable to maximise the ability to use conventional demolition techniques for reactor equipment and system dismantling which is largely achieved by simple designs and layout.

In period 1972–77 the 150MWe reactor A-1 in Slovakia had two accidents and was shutdown. The prolonged decommissioning programme is underway and extends to 2033. Feedback from the project has been reported for the benefit of future design, construction and operation [90]. The beneficial factors to be considered are:

- Avoid complex construction.
- Use standardised components for which material content is known.
- The designer should propose dismantling procedures for major components.
- Dismantling procedures and proposed equipment and tools should be part of the initial delivery.
- Training for dismantling should be part of the supply package.
- The design should exclude non-predictable leakage i.e. leak monitoring must be provided.
- Areas designated for decommissioning should be identified.
- Waste handling facilities for operational waste should be readily extendable to decommissioning waste.
- Proposals for conversion or use of installed handling equipment in the reactor hall to be readily usable for decommissioning.
- The reactor hall space and equipment should take account of any need to dismantle large items for packaging or transport.
- Provide training for operators to avoid and minimize leakages.
- Facility information system should include specific modules for decommissioning records.
- Educate and train personnel before the final shutdown transition period.
- Develop precise procedures for a smooth transition from operation to decommissioning.
- Continuous processing, conditioning and storage of operational waste and its retrieval.

The document also gave many examples of good dismantling practice.

A report from the Russian Federation covers extensive decommissioning and waste management that has been conducted as a result of cleanup activities at many facilities and buildings on numerous historic sites [91]. Approximately 400 M^3 of waste was recovered, processed and sent for interim storage. No specific lessons were reported that can be fed back to future designs as the sites were so diverse.

The IAEA published two comprehensive TECDOCs in 2006 and 2007 on the status of designs for small and medium reactors systems with and without on-site refuelling [8], [9]. It was in recognition of the ongoing interest in Member States in the development and application of small and medium sized reactors (SMR) in the output range of about 300 – 700 MW(e). Reactors of below 300 MW(e) were generally of the non on-site refuelling types [9].

It was noted that some designs were for modular reactor cores that could be transported intact from the site. There was a particular need to furnish information to those Member States that were contemplating nuclear power programmes or wished to engage in development and research. Detailed information on an extensive number of designs was given ranging from water and gas cooled, liquid metal cooled to more unconventional and exotic designs. It was noted that there were 146 SMRs in operation in 2005.

Reference to design features to facilitate decommissioning is referred to and there are about 25 references in IAEA-TECDOC-1485 [8]. These design features include reduction in activation to reduce doses during decommissioning and in depth plant simplification to reduce maintenance and dismantling and to make decommissioning easy and cheap. Of interest is the MARS design (Multi purpose advanced inherently safe reactor) [8]. It was claimed that decommissioning costs could be reduced to 10% of construction costs. There are a number of other designs from other countries e.g. SMART (Korea), IRIS (Westinghouse consortium US), CAREM (Argentina), AHWR (India) and PBWR (South Africa) but few specific beneficial design features are mentioned. In Japan, for the GTHTR design [8] (page 318), the reduction in the number of reactor components is said to reduce eventual decommissioning waste volumes. The PBWR design in South Africa also claims a reduction in decommissioning waste volume [8].

In Germany a small firm (Temme AG) backed by Eastern European investors, is moving into the test phase of a research project that ultimately aims to set up a small underground high temperature geothermal reactor following similar initiatives in Japan, Russia and the US where developers are exploring niche markets in some developing countries [46]. The power rating is expected to be in the range 10 – 100 MWe. The applications are stabilising wind generation plant by provision of base load, production of process heat and hydrogen/oxygen production by electrolysis. An interesting concept is the return of the reactor to the country of origin after, say, a 30 year operating life. No other mention has been made about inclusion of design features to facilitate decommissioning.

In the Russian Federation the design of a rail transportable fast reactor module has been proposed. This is able to connect to fixed facilities for cooling and services. This obviously allows the reactor itself to be taken elsewhere for refuelling and decommissioning as required. It is reported in the IAEA-TECDOC-1536 [9]. The feasibility of this is in question however and no particular design features have been mentioned. There is also a design in the US for a transportable modular fast reactor called STAR [9]. Some applications of the non on-site refuelling reactor designs are for large desalination facilities. The information being put forward on the more unconventional designs concentrates mainly on safety, fuel design and performance. Little mention is made of decommissioning.

In Russia it was reported that a contract has been agreed to complete the construction by 2011 of a floating nuclear power plant of 2 x 35 MWe capacity. The reactors are similar to those used for ice-breakers [92]. It will be able to be towed to different locations and supply a city of up to 200,000 people. Nothing is mentioned about decommissioning but it is expected to be a good example of where modular intact removal of the reactor can be done. A first application is expected to be a city in far eastern Russia. A second plant may be started in 2011.

GLOSSARY AND ABBREVIATIONS

AECL	Atomic Energy of Canada Limited
ALARA	As Low As Reasonably Achievable
CNSC	Canadian Nuclear Safety Commission
DfF	Design for Decommissioning
D&D	Dismantling and Decontamination
DP	Decommissioning Plan
ENTOMB	Sealing up a nuclear facility for an indefinite period (see also ISD)
EPR	European Power Reactor
EU	European Union
EUR	European Utilities Requirements
GNB	German Regulatory Authority
HVAC	Heating, Ventilation and Air Conditioning
ILW	Intermediate Level Waste
ISD	in-situ decommissioning (see also ENTOMB)
ISFSI	Independent Spent Fuel Storage Installation
LLW	Low Level Waste
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Cooperation and Development
PDP	Preliminary Decommissioning Plan
POCO	Post Operational Clean Out
PWR	Pressurised Water Reactor
RPV	Reactor Pressure Vessel
RWMC	Radioactive Waste Management Commission
SAFSTOR	Safe Enclosure of a nuclear facility followed by deferred dismantling
SMR	Small and Medium sized Reactors
SNF	Spent Nuclear Fuel
UKAEA	United Kingdom Atomic Energy Agency
UK HSE	United Kingdom Health and Safety Executive (Regulator)
UK MOD	United Kingdom Ministry of Defence
VLLW	Very Low Level Waste

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IAEA
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