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Decommissioning of Small Medical, Industrial and Research Facilities: A Simplified Stepwise Approach

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DECOMMISSIONING OF SMALL MEDICAL, INDUSTRIAL AND RESEARCH FACILITIES: A SIMPLIFIED STEPWISE APPROACH

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IAEA NUCLEAR ENERGY SERIES No. NW-T-2.3

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FOREWORD

Most of the existing literature on decommissioning addresses technological and other aspects of decontaminating and dismantling large nuclear facilities; such as nuclear power plants, reprocessing plants and relatively large prototype, research and test reactors. However, the majority of nuclear and radiological facilities are smaller in size and complexity and may present a lower radiological risk in their decommissioning. Facilities such as zero-power reactors and critical assemblies, radiodiagnostic and radiotherapy hospital departments or laboratories, factories using radioactive material, etc., are often associated with the erroneous perception that their decommissioning is a trivial, low priority activity. Under these circumstances, even the minimum requirements and strategies may be disregarded in decommissioning, resulting in unnecessary costs, delays and, possibly, safety issues such as the loss of radiation sources.

This report provides hands-on guidance in the selection and implementation of decontamination and dismantling strategies/techniques for small nuclear facilities. It is written as a simplified, stepwise approach for the guidance of nuclear operators and those carrying out decommissioning with little or no experience in decommissioning. It is a follow-up to Technical Reports Series No. 414. The latter provided a more conceptual framework (factors and criteria) for the planning and execution of decommissioning activities, whereas this report responds to practical needs and provides ‘how-to’ hints supported by case studies and lessons learned. The IAEA officer responsible for this publication was M. Laraia of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

SUMMARY

This report provides practical information, experience and assistance to practitioners who are faced with decommissioning of a small nuclear facility, yet have limited or no previous experience. In such circumstances, it is also conceivable that newcomers to decommissioning may be faced with inadequate financial and scientific resources to complete the task; making it all the more important to avoid costly errors. Furthermore, it is also possible that a worker may need some guidance in starting the process of obtaining finance and resources to progress with the task of decommissioning. The aim of this report is to provide useful practical advice to newcomers to decommissioning to aid them in the planning and management of hands-on decommissioning technologies for small nuclear facilities, using a step wise approach, through to facility and site release.

This report breaks down the process of decommissioning into a number of manageable stages, such that the inexperienced practitioner has the opportunity to build confidence as they progress with each stage. Whilst acknowledging that there may be a wide diversity of regulatory licence termination conditions throughout the world, the generic stages of decommissioning will broadly be the same, such that this report should be a basic handbook of use in all instances of small facility decommissioning. This text emphasizes, at each stage, the importance of appropriate interface and dialogue with the Regulatory Body and other stakeholders, not only as a means of advancing any regulatory permission required for decommissioning and licence termination, but also for the many benefits gained by early and ongoing dialogue.

This report covers the practical aspects of decommissioning of small nuclear facilities typically found in medical, research and industrial applications. Power reactors, prototype and demonstration reactors, larger research reactors, fuel processing and reprocessing plants and their associated large chemical facilities, and all forms of waste disposal are outside the scope of this report and have been covered adequately elsewhere. Typical facilities covered by this report include:

- Medical facilities with radiography and radiotherapy units and those using radioisotopes;
- Industrial facilities, such as those producing radioisotopes, using irradiation and radiography devices, and manufacturing products incorporating radioactive materials;
- Research facilities such as particle accelerators, and those associated with the nuclear industry (e.g. critical assemblies or zero-power reactors), pharmaceuticals and medicine;
- Laboratories in universities and hospitals.

This publication has been structured as a series of sequential actions, and is supported by tables identifying lessons learned during decommissioning of small facilities. This should assist the inexperienced worker in following a logical stepwise approach to decommissioning. Whereas it is not possible to include all the specific detail of every aspect of decommissioning in this report, a number of useful references are included at each stage, thereby directing the reader to further information. This report is structured as a number of practical stages, some of which can be initiated in parallel rather than sequentially, taking note that many factors under consideration may change throughout the decommissioning process up to achievement of release conditions. This report also includes a range of practical examples of decommissioning projects from around the world in the annexes, specifically providing details of project planning and implementation, along with lessons learned.

1. INTRODUCTION

1.1. BACKGROUND

There are a number of readily available technical publications that address the regulatory, organizational, technical and other aspects for the decommissioning of large facilities such as nuclear power plants, reprocessing plants and relatively large prototype, research and test reactors [1, 2]. There are, however, a much larger number of licensed users of radioactive materials in the fields of medicine, research and industry, where the facilities are much smaller in size and complexity, yet all of these facilities will require decommissioning at some point in time. Typically these facilities present a lower radiological risk during their decommissioning, and full decommissioning through to release for unrestricted use should be the objective [3, 4]. Such facilities are located at research establishments, biological and medical laboratories, universities, medical centres, and industrial and manufacturing sites.

The workers employed in these facilities typically have little or no experience of decommissioning, waste management and associated safety aspects of these types of facility at the end of their operational life. Furthermore, for many of these workers, the occasional use of a radiation source may only be a minor part of their overall job, yet the focus of their employment might have to change considerably once decommissioning activities begin. Sometimes the task becomes more onerous when a worker is faced with the relocation of their nuclear laboratory, and they are required to simultaneously deal with decommissioning of the existing laboratory and relocation of the services to the new facility, whilst trying to provide continuity of the laboratory routine services in the interim. Even this is achievable with careful planning, using the stepwise practical approach endorsed in this report.

Given that inexperienced workers may not consider decommissioning a task they should be required to undertake, concern exists that even the minimum requirements of decommissioning may be disregarded, resulting in avoidable delays, risks and safety implications; e.g. loss of radioactive material and a loss of all records. Incidents have occurred in which persons have been injured or put at risk.

It is recognized that the strategies and specific requirements for decommissioning of small facilities will be much less than for larger facilities but many of the same principles apply. There has been considerable attention given to nuclear facilities and many IAEA publications are complementary to this report [3, 4]. This report, however, gives specific practical guidance for small facilities. It should be noted that the use of the term ‘small’ in the context of this report does not necessarily mean small in size, but identifies a facility that is generally modest in terms of complexity, safety risk and radiological inventory.

1.2. OBJECTIVES

The key objective of this report is to provide practical information, experience and assistance aimed at a broad spectrum of practitioners who are faced with decommissioning of a small nuclear facility, including those who have limited or no previous experience. The decommissioning organization may be faced with limited financial and scientific resources, making efficient and effective decommissioning planning essential. Furthermore, it is also possible that the organization may need more guidance in starting the process of obtaining financial and other resources required for decommissioning. This report provides useful practical advice to newcomers to decommissioning to aid them in the planning and management of hands-on decommissioning technologies for small nuclear facilities, using a step wise approach, through to unrestricted release or as required for an intended reuse. This report promotes timely and cost effective decommissioning and waste management at the end of life of a facility. No statements in this report are intended to be prescriptive.

The objective of this report is to break down the process of decommissioning into a number of manageable stages, such that the inexperienced practitioner has the opportunity to build confidence as they progress with each stage. Whilst acknowledging that there may be a wide diversity of regulatory licence conditions throughout the world, the generic stages of decommissioning will be broadly the same, such that this report should be a basic source of information for use in all cases of small facility decommissioning. This report emphasizes the importance of interface and dialogue with the Regulatory Body and other stakeholders as appropriate, not only as a means of progressing any regulatory permissions required for decommissioning and licence termination, but for the many benefits to be gained by early and ongoing dialogue with relevant stakeholders.

In the past, operators of small facilities have stated that they have been overwhelmed by reading publications aimed at decommissioning of larger nuclear facilities. If operators of small facilities only have published information for large complex facilities, then there may be a tendency to overreact and engage in elaborate or unnecessary studies and actions. They may also shy away from important issues and do too little, either because they are not trained or advised properly, or they do not have a decommissioning plan or adequate personnel and financial resources. In some very small organizations, a single person may be responsible for a range of decommissioning actions. This report brings together much of the information they will require for decommissioning.

1.3. SCOPE

This publication is intended to cover the practical aspects of decommissioning of small nuclear facilities typically found in medical, research and industrial applications. The focus of the report is principally aimed at laboratory decommissioning, focussing on operators with little or no previous experience in decommissioning. This report is not intended for contractors doing the decommissioning work, since they are assumed to be well experienced. This report is for newcomers to decommissioning carrying out decommissioning in their workplace.

Power reactors, prototype and demonstration reactors, larger research reactors, fuel processing and reprocessing plants and their associated large chemical facilities, and all forms of waste disposal are outside the scope of this report and have been covered adequately elsewhere [1, 4]. A summary list of the type of facilities covered by this report may include:

— Medical facilities with radiography and radiotherapy units and those using radioisotopes;
— Research and teaching laboratories in universities and hospitals;
— Industrial facilities, such as those producing radioisotopes, using nuclear density gauges, using irradiation and radiography devices, and manufacturing products incorporating radioactive materials;
— Research facilities such as particle accelerators, and those associated with the nuclear industry (critical assemblies, and small research reactors up to 10 kW; e.g. Slowpokes and small Argonauts).

Application of a graded approach to decommissioning commensurate with the complexity of the facility to be decommissioned is essential. It is assumed that technological difficulties in decommissioning of any of the above facilities will be relatively minor, and mostly limited to contamination of surfaces. However, certain requirements and strategies should be in place to prevent undesirable incidents and ensure safe and cost effective decommissioning. These are highlighted in this report.

The IAEA safety standards that are relevant to the subject addressed in the present report are IAEA Safety Standards Series No. WS-R-5 and IAEA Safety Standards Series No. WS-G-2.2 entitled IAEA Safety Guide on Decommissioning of Medical, Industrial and Research Facilities [3]. These standards provide the foundation for the aspects of the present report that pertain to safety.

1.4. STRUCTURE

This publication has been structured as a series of sequential actions, and is supported by tables identifying lessons learned during decommissioning of small facilities. This should assist the inexperienced worker in following a logical stepwise approach to decommissioning. Whereas it is not possible to include all the specific detail of every aspect of decommissioning in this report, a number of useful references are included at each stage, thereby directing the reader to further information. This report is structured as a number of practical stages, some of which can be initiated in parallel rather than sequentially, taking note that many factors under consideration may change throughout the decommissioning process. This report is deliberately written in a colloquial style. Guidance is given to those responsible for decommissioning, and academic statements are reduced to a minimum. In many sections, a table has been included detailing the potential consequences if certain aspects of the project have been overlooked or inadequately addressed. This guidance is there to assist the reader to avoid these same mistakes which could detract from the successful, within budget, delivery of a decommissioning project.

The CD-ROM that accompanies this publication contains practical information in two annexes. Annex I provides a range of practical national examples of decommissioning projects, specifically providing details of the project planning and implementation, along with conclusions and recommendations. Annex II provides brief insights into specific problems encountered during decommissioning. It is set out in the format of problem encountered, solution and analysis and lessons learned.

2. SETTING THE SCENE

2.1. GETTING STARTED — THE FIRST STEPS

Decommissioning requires specific knowledge and experience. As an aid to getting started, the following pre-requisites are essential:

— Identification of the owner/operator;
— Identification of appropriate staff for decommissioning, including management competence and technical expertise;
— Knowledge of the prevailing radiological characteristics;
— Knowledge of facility history;
— Definition of decommissioning objectives.

Consider the position of a laboratory manager suddenly faced with an instruction that the laboratory is to be closed and must be decommissioned to permit unrestricted future use. The owner/operator giving the instruction perceives this worker as his on-site expert. The manager is very experienced in the day to day running of the laboratory, but has no knowledge or previous experience as a project manager for laboratory decommissioning. A lack of available resources to take this task forward may further add to the growing concern of the manager in respect of his abilities to embark on this task. Meanwhile, the owner/operator of the facility will be waiting for the laboratory manager to inform him if there are any specific resources required to take this task forward, as he has done so many times in the past when new laboratory services have been introduced. Moving into decommissioning brings with it a host of other social concerns in respect to long term employment; therefore it is helpful to approach the task in the same logical step wise way that you would progress with any new laboratory development.

An initial discussion with the owner/operator is necessary at the earliest opportunity to establish exactly what is to happen, in what timeframe and to establish at what point the existing work carried out by the laboratory is to cease. It could be that the facility will no longer carry out work involving the use of radiation sources and therefore total decommissioning for future unrestricted use of the laboratory must be achieved. Consider also the possibility that the business may be expanding. The existing laboratory is too small, so the owner/operator has decided that all work involving radioactive materials is to be relocated to another branch of the business in a separate building some distance away. In this case, not only is the manager to maintain the routine work of the laboratory, until one month prior to the transfer into the new modified building, but he is also to liaise with architects and builders in respect of modification of the new laboratory. In addition, taking forward the decommissioning of the existing laboratory, which is required for another use, as soon as possible after the existing laboratory services have been relocated. Whilst it is all too easy for the manager to acknowledge that he has no skills, knowledge or experience to take forward laboratory decommissioning, the many generic techniques employed throughout his working career can readily be modified into specific actions for decommissioning. Furthermore, many laboratory workers might readily be trained in new skills, building on existing expertise, to be able to actively participate in the decommissioning project. It should be noted that typically facility managers may be very experienced in their normal operations, but have no relevant experience in project management or implementation of large scale configuration changes on a nuclear facility. A useful report for the newcomer to decommissioning, which provides guidance on staying ahead during the challenging process of decommissioning is provided in [5].

2.2. THE PATH TO IDENTIFICATION OF RESOURCE REQUIREMENTS

Consider the following scenario: if a new scientific development was reported in the literature and the owner/operator of the facility required a manager to implement this technique in the laboratory, consider the logical steps that would have to be taken to put together a business case to take this action forward. A typical laboratory manager already has these skills, and they are all readily transferable to the role of decommissioning. A logical start would be to review available literature to help scope the work project that has to be taken forward. It is essential to ensure that the relevant publications are read [3, 4, 6, 7] , rather than reports detailing decommissioning of larger nuclear facilities [1]. The IAEA has published a large number of reports which are available on-line on the IAEA web site, many of which have been referenced in this report. If the laboratory has difficulty accessing these publications on line, they can be purchased directly from IAEA or delegated national bookstores. Numerous publications are referenced in this report and specific examples are provided at the end of sections and in Annexes I and II, which provide information on consequences of failure to adopt good working practices and lessons learned from decommissioning of specific types of facilities. This information should help the newcomer to decommissioning to avoid making the same mistakes.

Facility operators might consider contacting colleagues at other facilities who have had experience of decommissioning and discuss their experience and any lessons learned from the work that they undertook. Although no specific resources in terms of staff or financial resources have as yet been identified, yet alone been secured, there are positive actions that can be undertaken at an early stage that will make the process easier later on. Early communication with all relevant regulatory bodies is essential. The regulatory bodies should be informed of the outline plans of the owner/operator to decommission the facility and regulatory advice should be sought on making an early application for any licenses that may be required to facilitate taking forward the task. It may be helpful to compile a list of all the requirements identified by each of the regulatory bodies, as it may be necessary to resolve any differences and discrepancies amongst them before the decommissioning project can move forward. Furthermore, all regulatory bodies must be kept appropriately informed as the project proceeds. If the facility is to be relocated, it is important to coordinate license termination at one site with issue of permissions for the new laboratory, or future business may face delays in starting up again. Communication with the regulatory bodies should occur as prescribed or agreed during the decommissioning project. The key stages for interaction with the regulator for a decommissioning project are approval of the decommissioning plan, periodic inspection as the work proceeds (which may or may not be required, especially for very simple projects), receipt and acceptance of the final survey and termination of the license.

Faced with laboratory decommissioning, the inexperienced project manager may embark immediately on clearing out shelves, drawers and cupboards of surplus material to make the final task of packing up the laboratory easier. It is essential that all laboratory records, equipment manuals and technical drawings are retained, even if it is not immediately apparent what use they will be. For example, the handbook of a laboratory counter that is to be disposed of as scrap may be needed as a future reference to identify if the equipment has an in-built radioactive calibration standard. This manual might also provide essential information when compiling the radioactive inventory as it may provide information that facilitates understanding of historical laboratory records of measurements made using this equipment. A useful task would be to list and review the relevance of all laboratory records and information so that specific items are readily retrievable. Old measurement equipment, if still functional, might usefully be retained as its measurement characteristics might assist in the interpretation of historical data. The IAEA has published a number of reports that provide advice on record retrieval and maintenance [8, 9].

Once the decision to decommission a laboratory has been made, this decision should be communicated as soon as possible to all staff that will be affected by the decision, and any other stakeholders [10]. To withhold this information could be detrimental in securing future cooperation of the staff in taking forward decommissioning, as it could result in loss of trust. The information in many cases is best communicated verbally to the staff by their immediate line manager rather than the owner/operator of the facility, who may be unfamiliar to them. Staff members are likely to welcome the opportunity to ask questions, even if the answers are not yet available. The laboratory manager could meet with all staff members individually, at an early stage, to listen to their concerns, but also to ascertain what skills they may have but are not currently using in their existing job. It could be that some of the existing staff have previous decommissioning experience or have a specific desire to expand their current range of skills, making them ideal candidates to nominate for training courses to learn the skills necessary to take forward decommissioning.

2.3. DECOMMISSIONING FLOW CHART

When planning a project, it is often helpful to break it down into a number of discrete phases for ease of planning. For decommissioning projects, it might be helpful to consider the project under three distinct activities:

- Development;
- Implementation;
- Termination.

The following schematic provides details of what is involved at each stage under these three headings and details inputs and processes involved, and the outputs and outcomes that are expected. The numbers in the boxes relate to the relevant supporting section within this report where further useful information is available to the reader.

3. DEVELOPMENT OF THE DECOMMISSIONING PROJECT

3.1. DEFINITION OF THE PROJECT

The project manager could benefit from an early meeting with the facility owner/operator to identify exactly what is to be achieved in terms of the business as well as the exact extent of the area, systems and connecting facilities that are to be decommissioned; e.g. drainage and ventilation systems may be shared with other facilities still in use or might extend far beyond the rooms intended for decommissioning. Be aware that the point at which the owner/operator would wish to see the project terminate (end state) may not directly correspond to the end point that the regulator is prepared to accept for modification or termination of the license. This issue will require resolution through discussion and the regulatory end point needs to be clearly communicated and agreed to with the owner/operator and any stakeholders at an early stage, as this is likely to influence the resource requirements to complete the project [10].

In general, irrespective of whether the laboratory services are to re-locate and work is to continue into the future, the task of decommissioning the existing facility to unrestricted use is the best option where practicable. Where release for unrestricted use is not achievable or not the desired end point, as occurs in the case where the facility is intended for future radiological use, it is important to agree applicable criteria for decommissioning with the regulator. In such cases, it is important at an early stage to put in place a mechanism to ensure preservation of the records of the remaining radiological inventory. It is not possible to specify the resources required in terms of skilled manpower and finance until the task has been scoped and the physical inventory identified (Table 1).

3.2. DEFINITION OF THE END STATE

The definition of the end state will be one of the significant steps in the planning of a decommissioning project, as it could substantially increase the required cost; e.g. if the desired end point is unrestricted release, it will be more expensive than leaving some contamination in situ. It is essential to closely examine and define the project objectives before starting to plan the project and make certain that the end point is clearly understood and agreed to by the relevant stakeholders.

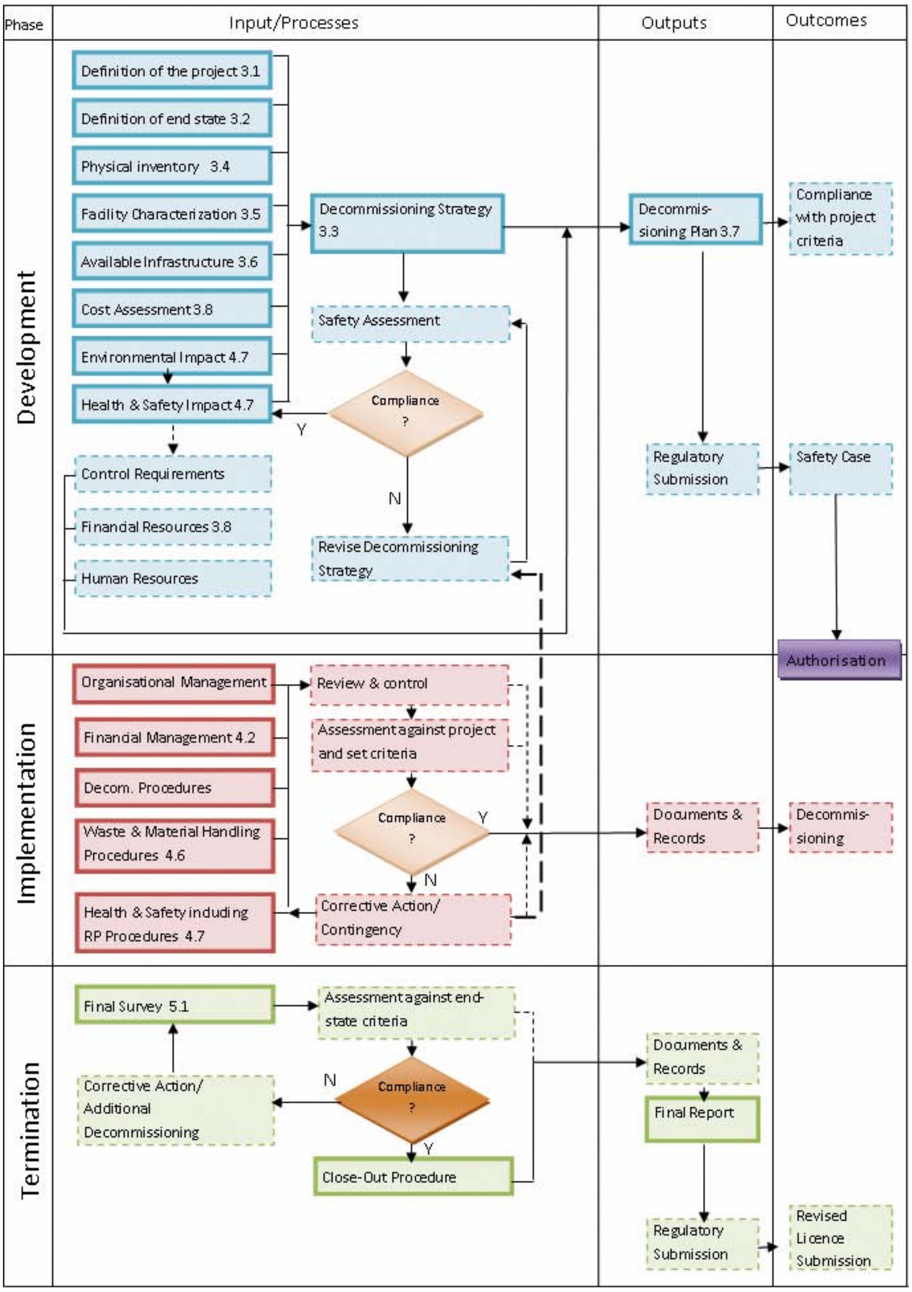

FIG. 1. Schematic of the stages of a decommissioning project.

Specific problems may arise where the required end point of decommissioning of a small nuclear facility is release for unrestricted use but where the inventory is complicated by the presence of naturally occurring radioactive material (NORM). The regulatory body will refer to specific standards that are accepted for return of a facility to unrestricted use, and this is likely to involve the additional costs of NORM removal, which could further add to the waste removal and disposal costs (see Section 6.11.). IAEA guidance — albeit still incomplete — on NORM management can be found in [11, 12]. Currently there are international moves towards greater regulation of NORM wastes, and progress in this area might be kept in mind when defining the end point of a decommissioning project.

Consideration of the following questions might aid the decision making process when identifying the most appropriate end point for a decommissioning project:

— Is it necessary to achieve unrestricted use of the small nuclear facility or might it not be useful to consider at an early stage the possible reuse of the facility for further radionuclide work or another use that does not necessitate achieving unrestricted use status?

TABLE 1. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE WHEN DEFINING THE PROJECT

Inadequate definition of project's end state.	Without a clearly defined end state, the project will face ongoing difficulties due to the uncertainty.
Failure to identify the possibility for reuse of part or all of the facility.	Use of extra resources and increased costs.
Failure to define the total inventory and do the full characterization.	Project will not achieve the desired end state or adequately manage the full inventory. This will result in inadequate waste management. Need to back track and repeat stages of the plan, which will involve additional costs. Possible inadequate budget.
Failure to identify the boundaries of the project (e.g. sewage lines, ventilation ducts, neighbouring rooms, hard-to-access cubicles, etc.).	Late discovery of contaminated areas left behind will inevitably lead to inadequate or incomplete termination of the project, extra costs unplanned, litigation, uncertain transfer of ownership etc.

— If the laboratory will be used for future radionuclide work, will it involve use of the same radioisotopes or totally different isotopes?
— What is feasible within the existing regulatory permission? Does the existing licence provide for such changes in use to occur or would it require a revision of the licence?
— How easy would it be to develop the decommissioning plan if the end point is not unrestricted future use of the facility?
— Would regulatory requirements pose substantial handicaps to delivery of the plan?
— Has it been confirmed that the proposed final end point status of the facility will not conflict with the remaining structures, underground facilities or residual contamination?

In instances where early planning for decommissioning is based upon a proposed reuse of the facility, it is important to learn as many facts as possible about this reuse at an early stage. It is important to always consider the benefits of reuse of a facility for future radiological work. Financial benefits may arise because it may not be necessary to remove some walls and supporting facilities, and decontamination and waste disposal requirements are likely to be less demanding, since release criteria would be less stringent.

Once a definite decision for reuse of a facility has been made, it is important to make provisions to carry out as much decommissioning and decontamination as is necessary to meet the needs for this reuse, taking note of relevant compliance issues such as regulations and license requirements for the new use. If the end point of decommissioning is not unrestricted use, it is crucial to plan and provide for any further future financial liability that may exist when the reused facility (which was handed over for the new use with an identified future radiological liability as the end point of decommissioning) is scheduled for decommissioning.

It is essential not to become discouraged if all of the required information is not available at the start of planning the project. All possible sources of information could be identified and explored as and when they are available.

Communicating with anyone who might have an interest in the reuse of the facility, or any parts of it is also an important component of the project. Once decommissioning of a specific area of a facility is underway, it is possible that another worker on the site will come along and recognize that the area, or part of it, which is currently scheduled for decommissioning would ideally suit their work expansion proposals. In such circumstances, it is important to be flexible and attempt to accommodate this proposed reuse within the decommissioning project. It is essential to communicate freely and openly in respect of the proposed changes with all relevant officials, regulators and authorities to achieve the desired reuse. All of the relevant stakeholders will welcome being promptly and fully informed of the decision to reuse the facility, irrespective of which stage in the decommissioning plan such a decision is made.

It is prudent to put in writing as part of the decommissioning plan, any end points of decommissioning discussed and agreed to with the regulator and issue a copy to the regulator for his records before the decontamination stage of the project gets underway. One decommissioning research facility faced problems that could have been avoided if this approach had been adopted. The original regulator, with whom the project end points had been verbally agreed, died quite unexpectedly. The regulators records did not include information on the agreed end point and the new inspector who took over the regulatory management of the project identified more stringent end point requirements than had originally been agreed, resulting in the entire contingency budget being required to meet these more stringent standards for license termination.

As good practice, it is prudent to document the details of any discussions with the regulator, identifying any points for action or working standards that have been agreed. Ideally this record should be signed off by both the operator and regulator at the time, or should retroactively be submitted in writing to the regulator for his records. Although the operator needs to be largely self-sufficient in delivery of the decommissioning plan, there are essential regulatory milestones that must be satisfied; e.g. approval of the decommissioning plan, periodic inspection as appropriate during decommissioning (although this may not be necessary for very simple projects), submission and approval of the final survey and termination of the licence. Table 2 lists a number of mishaps that may occur if the end state is not properly defined in a timely fashion.

3.3. DECOMMISSIONING STRATEGY (SCOPING THE TASK)

The decommissioning strategy is developed and optimized appropriate to the full physical and radiological inventory for the project. Section 3.4 contains useful information on compiling the physical inventory. Without a comprehensive inventory, it is possible that the best strategy will not be selected for the project and health and safety problems might occur that require corrective action as the project proceeds; e.g. discovery of asbestos not included in the inventory.

As part of our daily lives, we scope tasks that we are required to do. Without particularly focussing on what we do, we break down the actions to break the task into component parts and then follow them in a logical order to complete the task. The same approach is helpful when scoping a decommissioning project. A boundary needs to be applied to the task to gain an understanding of what is included within the project. A cautionary note is to be flexible about expanding the perimeter of the boundary, especially where it is possible that there may have been spread of radioactive material outside of the area currently being considered for decommissioning. This is especially relevant where highly mobile radioisotopes have been in use; such as tritium. Furthermore, the task needs to be all inclusive and consider all pathways for spread of radionuclide activity further afield, such as to the roof of a building from a ventilation exhaust system, or ground contamination from a leaking pipe where radioactive waste has been discharged to the drains.

TABLE 2. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES WHEN DEFINING THE END STATE

Failure to clearly agree and document the desired end state.	Could lead to regulatory conflict, especially due to changes in regulatory personnel; e.g. when interpretation of unclear criteria is required. Could lead to conflict with other stakeholders. Could lead to misunderstandings such that errors are made and the regulator may not agree license termination or revision when the final report is submitted.
Inability to resolve and agree with the regulator a realistically achievable end point for decommissioning at the outset due to uncertainties in the characterization of the facility, such as due to inaccessible areas that will not be reached until dismantling is already underway.	Ensure an adequate contingency budget realistic to the uncertainties. Agree with the regulator if any communication will be required once characterization of inaccessible areas is achieved, and where necessary, seek a revised end point for decommissioning where the original end point is found to no longer be achievable. Maintain appropriate open dialogue with stakeholders to avoid conflict.
Lack of information on proposed reuse of the facility.	Lack of clarity in understanding of the end point for the project. Difficult to cost and fully scope the project. Possibly, more costly than needed.

The previous section specifically deals with the definition of the end state which is the main driver for the development of the decommissioning strategy. This strategy is the route map that will guide you to your end state. The flow chart in Section 2.3 provides a useful schematic to illustrate this point.

Scoping the task will require a number of key activities, to include a data collection phase so as to fully understand the history of the facility and a characterization stage to collate an inventory for further management. In order to fully scope a decommissioning project, it will be necessary to obtain information on the full life history of the radiological operations that have taken place at the facility, and the impacts that these operations may have had on equipment, facilities and the environment. For most facilities, changes in operation and building design have occurred with time, so it can be difficult to ascertain the radiological characteristics of the facility. The older the facility, the more difficult it may be to obtain a full lifetime history. The situation is usually exacerbated if the facility has been used for research and development purposes, as often this has involved frequent introduction of additional radioisotopes and new techniques. In these circumstances, determining the scope of any decontamination efforts will be a critical part of the project.

A useful starting point is to get a drawing of the area to be decommissioned which also details all the adjacent areas and services such as drainage, electricity, pressurized gases, ventilation; etc. It is always wise to check the accuracy of any architect's drawings by direct comparison with a visual inspection of the area. Often it is helpful to take a series of pictures with scale markings so dimensions can be verified away from the area. Aim to obtain drawings and specifications of all alterations to the building or the services in situ that have been made since the building was first constructed. It is advantageous to talk to employees who have worked at the facility for a long time, as they may have knowledge that does not appear in the records that are currently available. Once the area to be decommissioned has been identified, it may be helpful to produce individual floor plan sketches for each room, onto which information can be entered at the time of completion of the characterization survey. Examples of such floor plan sketches are given in Figs 15–18 in Appendix I.

In Member States where a long established and experienced regulatory regime for radioactive materials is in place, a discussion with the regulator might be helpful. The regulator may have knowledge or information in his records of a past incident that occurred at the facility which may have resulted in radioactivity being dispersed. Laboratory records of accidents and incidents might be a useful knowledge source when scoping the boundary of the decommissioning task. Even if there is no direct evidence that radioactivity has spread outside of the boundary being considered for the decommissioning project, the regulator may have a specific requirement that drains or ventilation systems are inspected to rule out spread of contamination, so this is essential to consider when scoping the task. One laboratory failed to consider the possibility of leakage from the drainage system when scoping the decommissioning project and drafting the decommissioning plan. This later resulted in problems when the regulator requested the drainage system be checked by telemetry. The underground drainage pipe was found to be broken and leaking, hence causing unanticipated additional expenditure to remediate the ground. Figure 2 shows the dismantling of underground pipes at Argonne National Laboratory, USA.

Full radiological characterization of the facility is required in order to establish the boundaries as well as to provide information related to waste and materials management and safety assessment of planned decommissioning activities. Reference [13] is intended for larger facilities than those addressed in this report, but the principles and main factors still apply. It may be helpful to discuss and define the methodology for the characterization survey in good time, including information on any calibrated instruments to be used for direct measurement of contamination and any calculations/extrapolations that will be used to assess levels of contamination etc. This action should be completed at the project scoping stage, especially where there is the possibility that additional instrumentation may need to be purchased to be able to take the project forward. Radiological characterization is a field where the potential for mishaps and misunderstandings is high. If in doubt, a suitable expert in the field should be consulted.

The decommissioning strategy will also depend on the time frame for cessation of the work of the existing laboratory, and whether the work is to cease altogether or be relocated to another venue. Where total cessation of the work is to occur with decommissioning to unrestricted use, there will be a larger inventory for disposal. If the work is to be relocated, many of the records from the former laboratory will transfer to the new facility once decommissioning is completed, so the record management system put in place should ideally reflect this and it will affect the way in which the records are archived. The inventory for disposal will be much smaller when the equipment and useful materials are to be transferred to a new laboratory, but the scope of the task will need to build in the requirements for safe packing for shipment, compliance with regulatory transport requirements and licence requirements for work to commence at the new facility. The contractors specializing in cutting and dismantling are

FIG. 2. Dismantling of underground pipes at Argonne National Laboratory, USA.

more likely to be replaced by an engineer where specific aspects of the existing laboratory construction are to be relocated to the new facility, such as glove boxes.

A useful pointer in scoping the task is to compile an outline list of what needs to be done, and then start to add detail at every stage, based on what needs to be achieved as the agreed end point of the task. It is crucial that the list of tasks follows a specific sequence so that essential services are not terminated prematurely. The newcomer to decommissioning will be surprised at how quickly he will start to compile all of the data required to be able to scope the task.

It is essential that early planning is made for removal of radiation sources, especially where engineering works carried out by a contractor may be necessary to retrieve the sealed source (Fig. 3) or transport of the source may require specialist approved packaging to meet current regulatory requirements. It is not unknown for specialist packaging hire companies to require six months advance notice.

Another important issue is the involvement of stakeholders at an early stage of the project. A stakeholder may be any party directly involved or affected by the decommissioning process; e.g. the competent authorities, personnel, the radioactive waste department, the colleagues next door, the general public especially in the neighbourhood and even pressure groups. Be aware, that certain tasks necessary in the decommissioning process may be quite familiar to you and your staff; e.g. working in an isolation suit, but might look peculiar and even frightening to the public. Local stakeholder communication is especially important if the project will involve the need for temporary constructions; e.g. tented enclosures outside of the building. All necessary stakeholder consultation should ideally be carried out and the issue agreed to and resolved well ahead of finalization of the decommissioning plan and its submission to the regulator to secure his agreement with the proposals. The early communication of the intended work to all stakeholders will help to avoid later concerns that could lead to unexpected delays in the project.

If the public becomes an active stakeholder in the decommissioning project, it might be useful at an early stage to identify a named representative of the organization as their contact person for enquiries. Whereas in larger nuclear facilities, the licensee often appoints a community relations specialist, this is unlikely to be necessary for decommissioning of most small nuclear facilities. The key issue when interacting with the public is to ensure the licensee spokesman is speaking their language; e.g. avoid detailed science and jargon. It is important to communicate the decommissioning proposals in plain language, stating what you intend to do, identify how they are going to be protected, ensure you do what you tell them you intend to do, and keep them informed as the project progresses. When a decommissioning project is going to directly cause inconvenience to local people, albeit for a limited time; e.g. a required road closure to move a large sealed source, it would benefit the licensee to negotiate

FIG. 3. Dominican Republic, conditioning of the disused ^{226}Ra radiation sources into stainless steel capsules.

with local residents when this work could be carried out to cause them the minimum of inconvenience, rather than adopt a ‘decide, announce, defend’ strategy of public interaction. Table 3 lists a number of possible occurrences in a poorly defined strategy.

3.4. THE PHYSICAL INVENTORY

A detailed and complete physical inventory is necessary to be able to adequately plan for decommissioning and to ensure that sufficient funding is sought to complete the project. To obtain this information is likely to necessitate compilation of a detailed physical inventory, to include hazardous material inventory and radiological characterization of the area to be decommissioned. The physical inventory includes compiling inventories of all radioactive material and/or radiation sources, associated shielding, equipment, fixtures and fittings, laboratory chemicals, etc. The entire inventory of the project needs to be included, so that predictions can be made on the overall quantities of waste that will arise. When compiling the inventory, it is useful to identify any opportunities that exist for reuse or re-cycling of materials present; e.g. a sealed source may be subject to a return to manufacturer agreement or a laboratory chemical may be suitable for transfer to another authorized user within the organization.

When compiling the inventory, it is essential at an early stage to standardize on a unified way of data collection that will be used throughout the decommissioning project. This is necessary so that the final decommissioning report will clearly demonstrate to the satisfaction of the regulator that the full inventory has been accounted for and has been safely managed through to recycling and/or disposal. See Table 4 for issues resulting from inaccurate physical inventory.

TABLE 3. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES WHEN DEVELOPING THE DECOMMISSIONING STRATEGY

Difficulty in obtaining data to scope the task.	This could have been minimized by having a good record keeping and retrieval system, including for archived records.
Failure to preserve the records under safe storage arrangements.	Records may be damaged by water, fire or insects/rodents making scoping the inventory more difficult.
Failure to identify and adequately communicate with all stakeholders.	Could lead to later problems, including project delays.
Failure to optimize development of the decommissioning plan.	Project will be more costly. May be delays in obtaining regulatory permissions.
Failure to complete a comprehensive options appraisal where a number of options exist for carrying out the work.	The regulator may require the work to be completed using a method that is not as cost effective hence not optimizing use of available resources. This could have been avoided by a comprehensive, fully priced, options appraisal supported by a risk assessment and ALARA appraisal.

TABLE 4. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE WHEN COMPILING THE PHYSICAL INVENTORY

Failure to include all of the hazards present in the inventory; e.g. presence of asbestos.	Likely to be a budget shortfall. Requirement to retrospectively engage specialist contractors for asbestos removal. Likely to result in project delays and possibility for hazard to workers prior to realization of presence of asbestos. Need to review and revise risk assessment and decommissioning plan.
Failure to check the suitability of the transport container when sealed sources can be returned to the vendor or are destined for recycling or disposal.	Inability to remove the sealed source from site early in the decommissioning project as a means to reduce the radionuclide inventory. Additional costs to hire an appropriate container and resolve security issues whilst the source remains on-site. Alternatively the logistics of putting in place special transport arrangements where approved type-tested packaging is not available.
Failure to estimate the total waste inventory and adequately quantify the waste requiring disposal.	More of the budget will be spent on waste disposal than originally envisaged, with possibility of a budget shortfall.
Inadequate detail in the inventory or incomplete data.	The optimized decommissioning option may not be selected. Project may not be adequately priced and there could be health and safety implications with hazardous materials not identified.
Failure to fully utilize all of the characterization survey data when compiling the inventory.	Inventory will be incomplete and likely there will be inadequate financial provision for management of all of the materials and waste. Project delays and possible need to secure further funding or use the contingency budget to cover the financial deficit in financial provision for management of the total inventory.

3.5. RADIOLOGICAL AND HAZARDOUS MATERIAL CHARACTERIZATION

The recording of the inventory is the precursor to the radiological and hazardous materials characterization process. The planning of facility characterization is most cost effective when it is designed to address all of the data needed for license termination or revision. Designing the characterization survey is likely to require consideration of many factors, including determination of background surveys, design of the sampling and analysis programme, data validation, reporting and record keeping. In performing the characterization survey, the associated hazards of any equipment employed could also be considered.

For the newcomers to decommissioning, a useful starting point is the determination of the physical boundaries by a scoping survey. This survey might include contamination and radiation measurements to identify potential lost sealed sources or contamination that has been transferred outside of the radioactive working area. For example, door handles or light switches on the inside and outside of doors of the area under consideration may be measured. If contamination or elevated dose rates are detected, then the area under consideration needs to be expanded. Detection of surface contamination necessitates that the project scope includes the application of suitable decontamination techniques so that as much of the contaminated material as possible can be disposed of at clearance level.

The characterization survey will identify areas of contamination or elevated dose rates and the nature of the contaminant. An objective in any decommissioning project is to achieve radioactive waste minimization, hence all opportunities for gaining knowledge on the application of suitable decontamination methods to permit clearance should be explored [14–17]. Detail on radioactive waste management is given in Section 4.6. Similarly, the characterization survey will serve to plan for personnel access and decontamination and dismantling techniques. Information on decontamination techniques can be found in Section 4.4. A detailed description of health and safety aspects during active decommissioning is given in Section 4.7.

Normally routine operational surveys emphasize accessible surfaces in areas where personnel are working. Typical locations that are often overlooked during characterization for decommissioning include:

— Locations where wastes collect over time; e.g. waste traps beneath sinks and sluices, at the joint to the rear of laboratory benches especially when drip trays have not been in routine use, sumps, bases of elevator shafts or hoists used to transfer materials between laboratories located on different floors of the building.
— Cracks in surfaces; e.g. joints in floors, surface cracks, penetrations through walls.
— Radioactivity in locations where walls used to be, different floor coverings were used and under paint and panelling.
— Radioactivity associated with leakage from the drainage system; e.g. soil contamination from a cracked or broken drain, often associated with tree root growth damaging underground pipes.
— Radioactivity within the drainage system; e.g. storm drains, sanitary sewers, waste overflow sumps.
— Radioactivity associated with ventilation exhaust systems, often found on roof areas or trapped between roof layers, such as when a flat roof has been recovered over with further layers of roofing felt. Figure 4 shows the removal of ventilation ducts at SCK-CEN Centre, Mol, Belgium.
— Quiescent areas where dust can collect, such as on the top of light fixtures and transformers, flat surfaces on structural steel, etc.

FIG. 4. Removal of ventilation ducts at SCK-CEN Centre, Mol, Belgium.

— Vacuum extraction systems used in laboratories, where contaminated liquid may have been drawn back into the vacuum airline due to incorrect connection of the Y piece.
— Cold rooms or refrigerators identified solely for storage of non-radioactive materials. At times when radioactive cold storage was at a premium, consider the possibility that use of alternative non-radiological storage may have occurred resulting in contamination.

Any areas identified in the records where past decontamination activities have occurred might merit special attention during characterization. Past cleanup operations may have reduced residual contamination levels for work in the laboratory to safely continue, but this does not provide any guarantee that the wastes generated from this area during decommissioning will be suitable for free release. It is important to consider the possibility that a previous contamination incident may have been resolved by applying a surface finish over the contamination to seal it in as non-removable surface contamination. Whereas this may have been acceptable whilst the laboratory was operational, this might have to be dealt with in full compliance with regulatory requirements at the time of decommissioning.

Whereas it is normal to plan to have equipment available for the survey to include calibrated instruments, sample bottles, absorbent wipes, plastic bags, permanent marker pens, etc. it is equally important to have the right people in the survey team. For a simple laboratory, it may be that the characterization survey can be carried out by a single staff member, whereas for a more complex facility, it may be necessary to ask a plumber or engineer to join the team for part of the survey to permit access to difficult areas such as drainage pipe work, ventilation ducts, service hatches etc.

Resources may not exist for the site to conduct such a survey itself, so advice might need to be sought on suitable contractors and accredited analytical laboratories for the task. A specific contractor is often a useful starting point for enquiry, as might be colleagues in other establishments that have been involved in decommissioning projects. A clear remit needs to be given to any outside consultant engaged to perform this task, such that the measurement methodology is traceable to a quality standard acceptable to the regulator and any uncertainties in the data are specified along with their magnitude. In some circumstances, independent measurement of a representative number of samples by an independent accredited radiation assessment service may be required to determine or verify the radionuclide fingerprint for a specific waste stream. It is important to ensure sufficient resources are allocated for sample measurement, even when it is to be carried out in-house. Do not underestimate the time and effort that will be required to achieve reliably reproducible results.

Quality assurance is an essential part of the characterization survey so that the operator and the regulator have confidence in the measurements and analytical results; e.g. to verify materials as being suitable for clearance [14, 18]. Some premises may have analytical instrumentation suitable to assay wipe tests and other laboratory samples taken as part of the characterization survey. If such facilities are not available in-house, it is prudent to open dialogue with analytical laboratories and ascertain their capabilities, and ensure that the sampling assay methodology is fit for purpose before commencing the characterization survey. It is wise to make available replicate samples should some independent sample measurement verification be required. Failure to complete any detailed aspects of the characterization survey that were included in the decommissioning plan may result in the need to repeat work.

A basic characterization survey might usefully include use of:

— Data capture sheets with columns to record data on samples collected, etc.;
— Floor plan drawings or sketches which provide space to enter data.

Samples could usefully be marked with both a number and precise description of where it was collected. Examples of such data capture sheets and floor sketches are provided in Appendix 1. The data capture sheets can be used as a useful reminder for recording of all the fundamental information that is required in a consistent way. This is specifically relevant where several workers are to participate in the characterization surveys. Working to a pre-printed data sheet is also a prompt for recording details of the instrument used and background measurements made in each area, as sometimes this is overlooked by the novice. There can be substantial differences in background measurements within a building, especially in basement areas where NORM radioisotopes may be present; e.g. radon. The data capture sheet is also a useful reminder when several workers are conducting the survey, to ensure that they consistently record the survey measurements in the agreed units; e.g. counts per second at a distance of 1 cm. An example of a completed data capture sheet from the characterization survey of a small laboratory using only ^{14}C and ^{3}H is provided in Appendix I. In this example, a sensitive beta contamination monitor was used to scope the presence of contamination, followed by wipe tests assayed using liquid scintillation counting to quantify the radioisotopes and their activities. Note that this data sheet does not include background radiation measurements as they were recorded separately and all of the readings provided are background corrected.

Some laboratories may prefer to retain their floor plan sketches or drawings on computer and produce spreadsheets for their data capture. If this is the chosen data capture method, it is important to ensure that a separate back up copy of the data is stored in a secure, fire proof location and that the backup copy is updated at regular intervals. One laboratory manager was unfortunate enough to have his laptop computer stolen, and he had failed to keep a separate copy of the data he had so far compiled from the characterization survey, necessitating that some of the work was repeated.

When performing a characterization survey, it is important to consider the hazards associated with the environment or characterization actions. It is essential to give some thought to the environment in which the characterization survey is to be carried out — is it humid, cold, are there lots of areas difficult to access, could there be biological hazards or toxic chemical hazards, are there sharp projectiles or are some of the areas to be sampled high up so a ladder will be required? When designing a sample collection survey as part of characterization, one should be sure to consider the environment in which the sampling and labelling of samples is to be performed. If the area is very humid, some pens may not write very well and non-permanent marker pens used to write on plastic bags and bottles may run, making it difficult to read when the samples reach the analytical laboratory. If the area is very cold, permanent marker pens may not write clearly on plastic bags or sample bottles. Appropriate consideration of environmental conditions when planning the characterization survey can avoid the need to repeat sampling at a later date.

If the area is no longer occupied, it is important on health and safety grounds not to send a lone worker to conduct the characterization survey. Whenever use of a ladder is identified as part of sampling, there should always be a colleague at the foot of the ladder to secure it safely in position. A comprehensive safety assessment will be required that identifies all of these issues. The output of the safety assessment will help identify the tools, consumable materials, data capture method and protective clothing that will be required to carry out the radiological and non-radiological characterization, as well as identifying the correct staff to do the work.

Where sealed sources are part of the inventory, characterization requirements will include wipe testing to identify leakage and dose rate measurements for further source management. It is appropriate to consider the necessity for information to facilitate source movement. Table 5 assesses possible occurrences due to improper radiological and hazardous material characterization.

3.6. IDENTIFICATION OF INFRASTRUCTURE AND RESOURCES

Identification of infrastructure related to decommissioning; e.g. waste processing and storage capabilities as well as adequate resources (financial and human) are critical inputs to the establishment of the decommissioning strategy and plan. It is essential to secure a guaranteed provision of any resources required to cover the needs of the full project.

All too often, facilities find themselves in a difficult position when faced with decommissioning in the absence of a decommissioning plan or any resources to take it forward. The issue of finance becomes more difficult when no mechanism exists to ‘ring fence’ a specific portion of a budget to cover the costs of decommissioning or where funds only exist within a defined financial year and cannot be carried forward into the next year, even when the expenditure is already planned. Often educational or medical facilities receive gifts from wealthy benefactors of irradiators, cyclotrons or similar equipment. This in itself can cause problems when decommissioning is required. The item was not purchased by the facility and therefore there may not be any commitment by the organization to fund decommissioning. What at first sight appears to be an impossible situation to the newcomer to decommissioning can be resolved.

It is all too easy in such circumstances to say that no progress can be made because no funds are available. This is not a viable long term solution to the problem, and the longer decommissioning is deferred, generally the more expensive the project becomes. Some progress without an identified decommissioning fund is possible by cooperation of the existing workforce. It may be that limited funds might be required at an early stage to provide additional training to existing staff to help them in their new role of preparing for decommissioning. Existing staff

TABLE 5. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES DURING RADIOLOGICAL AND HAZARDOUS MATERIALS CHARACTERIZATION

Failure to consider work environment where the characterization survey is to be performed.	Will arrive without correct tools to complete the task; i.e. permanent marker pens that will write in a damp environment, screwdriver to remove panel to measure sink pipes. Risk assessment needs to consider the environment and workers need appropriate training and protective clothing for the task to meet health and safety requirements.
Failure to agree the scope of the sampling with interested parties, including the analytical laboratory.	May be a need to repeat sample collection. Sample size/volume may be too small or incorrectly prepared for accredited measurement laboratory to process. Regulator may require duplicate samples for independent measurement for validation purposes. CAUTION — Do not dispose of samples until regulatory agreement has been given, as there may be a need for later independent measurements or verification to be made.
Failure to assess the suitability of instrumentation and its calibration before completing the characterization survey, and/or the methodology to be used for the survey. Note: This may or may not be a regulatory requirement.	The instruments used may not be fit for purpose as they may not be sufficiently sensitive to measure at the limits of detection required for free release of materials. Calibration certificate must be current and identify error margins of measurements if regulator is to agree clearance of materials. Could result in requirement to repeat characterization survey, or requirement to purchase suitable equipment, hence exceeding project budget.
Failure to review licence termination conditions when designing the scope of the characterization survey.	Possible that regulator will request changes to the characterization survey proposals in the decommissioning plan. May need to backtrack at a later stage because not all of the license termination conditions have been met.
Failure to adequately document the scope of the characterization survey, with data capture sheets or a computer data base to record results in all of the areas to be sampled and measured.	Likely to have to repeat part of the characterization survey to obtain the missing measurements or samples. If the error is not realized until a later stage in the project, it could lead to problems in decontamination or unexpected risks being retrospectively identified. Could result in early use of the contingency budget leaving no financial provision to deal with later problems. CAUTION — ensure secure storage of results, including a backup copy of computer records.
Failure to record background measurements and instrument used for each measurement when making the survey.	Problems at a later stage in determining compliance with release criteria. It might be difficult to prove that the survey results are acceptable if all factors (such as the instrument and its calibration) cannot be correctly identified. Need to repeat work at additional cost of time and effort.
Failure to keep adequate records where contamination from accidents/incidents has been fixed in situ with a surface covering.	Failure to include this ‘hidden’ radiation in the characterization inventory could result in contaminated materials being free released or could result in late identification of the problem with the need for additional work and waste disposal costs.
Failure to identify the full extent of the contaminated area; i.e. project scope.	Characterization survey might be inadequate to satisfactorily deliver license surrender. Possible risks of contamination to workers outside of the area under consideration, until it is brought within the scope of the project.
Incomplete knowledge to appropriately scope decommissioning activities in the tender document for which an external contractor bids, or no provision to account for unanticipated changes in the contract.	Inadequate budget to cover the required work both in terms of the time taken for the contractors to complete the work, availability of tools/equipment appropriate to the task and inadequate quantification of the waste arising and disposal costs. Appropriate project change arrangements should be part of the contract.

TABLE 5. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES DURING RADIOLOGICAL AND HAZARDOUS MATERIALS CHARACTERIZATION (cont.)

Failure to identify the full extent of the area to be decontaminated and decommissioned.	Possible need to backtrack and extend the boundaries of the task. Need to repeat earlier tasks to include the new area, and modify the decommissioning plan in liaison with the regulator. Potential that the project will require additional budget due to inadequacy to scope the project at the outset.
Failure to standardize units of measurements.	Likely to require some repetition of decommissioning activities. Unlikely to prove in final survey report that then end point has been reached.
Failure to take account of a humid work environment when selecting the sample collection and storage method. Samples were placed in plastic bags and labelled with self-adhesive labels.	Some labels became detached so it was not possible to identify the sample collection point. Had to repeat sample collection.
Failure to identify potential waste streams without disposal options during the characterization survey.	Failure to have identified wastes for which no known disposal route exists might lead to project delays and the need for additional storage arrangements pending a solution for further management of the waste being identified.

are best placed to collect and sort the records of the facility, retrieving historical records from the archives. Often international assistance is more readily available to organizations that show a willingness to try to help themselves within the bounds of the difficulties that they face.

It is important to understand the management infrastructure of the organization so that correct procedures can be followed in taking forward early proposals for resources required for decommissioning. Commercial companies generally face fewer problems in securing funds for decommissioning, especially where the company is still active in the business market and can offset decommissioning costs across the income it receives from its business. The greatest difficulties usually arise in Government funded establishments, where it is often difficult to persuade the relevant government department to accept ownership of the problem or it may be difficult to identify which government department is legitimately responsible.

In educational or research facilities where space in the laboratories may be leased to external commercial interests, it is always possible that part of the inventory for decommissioning belongs to one of these clients. It is important to make the necessary contact within the infrastructure of the host organization to secure information on the client leasing agreement, with a view to securing funds in respect of their liabilities as part of the decommissioning project.

A useful starting point when seeking resources is to apply initially to the owner/operator or the governing body of the facility. This contact should be made as soon as possible after the decision to decommission the facility has been made. Early contact is only to establish the lines of communication and to identify any formal procedures or documentation that must be drafted once information has been gathered, such that a formal bid for funding and staffing resources can be made.

At an early stage it is crucial to compile a list of all potential agencies and stakeholders that will be interested in the decommissioning project, and to establish a contact person at each organization for ongoing communication. Not only will communication internal to the organization need to be established, but all relevant national governmental agencies might need to be contacted to obtain latest advice on their statutory requirements and standards for legislative compliance. Operators with little experience in waste management and decommissioning may find it useful to consult IAEA standards and technical reports to seek technical advice. It may be helpful at the time of first contact with regulatory agencies to seek advice on timescales, costs and requirements for any regulatory permissions/licenses that may be required. Proportionate to the expected impact on stakeholders, public dialogue may be desirable as part of the overall communication of the decommissioning strategy and should be considered.

At an early stage, it is essential to consider relevant aspects of health and safety planning for decommissioning, especially for more complex projects where some communication with external emergency response organizations may be required. The local police, fire department, regional ambulance service and even local hospitals may have a role to play in the event of an accident or emergency occurring during decommissioning activities and in particular during transport operations. Early discussion with the local hospital might identify that they are unwilling to receive casualties that may be contaminated with radioactivity unless their medical condition is so serious that they might die before reaching the regional hospital that is designated to receive contaminated casualties, which is equipped with a decontamination bathroom and suitably trained staff. Where large sealed sources are to be moved by road as part of early decommissioning, it may be necessary to liaise many months in advance with the police, nuclear security agency and the highways authority or other bodies relevant to the requirements of the Member State, to secure their cooperation for the movement. These authorities are likely to want to see the detailed proposals for the movement and the contingency arrangements covering accidents in transit. It may be that the highways authority will place movement restrictions on the operation to minimize the possibility of the shipment occurring during peak traffic flow periods. Table 6 reviews the impacts from lack of infrastructure and resources in a decommissioning project.

3.7. DECOMMISSIONING PLAN

The decommissioning plan sets out the detailed arrangements for the implementation of the selected decommissioning strategy. The decommissioning plan forms the basis of the submission to the regulator to obtain the necessary authorization to implement the project. A summary of typical contents of a decommissioning plan is given in Appendix 2, although the reader is also encouraged to read a reference IAEA Safety Report [19].

The prospect of writing a decommissioning plan sometimes frightens the newcomer to decommissioning. There is a wealth of comprehensive published guidance on the format and anticipated content of a decommissioning plan [3, 4, 19]. It should be noted that the regulatory requirements of many countries include detailed requirements for the content of a decommissioning plan, so where such requirements exist, this is the template for a decommissioning plan that should be followed when making a submission to the regulator. The key point is to ensure that the plan is tailored to the requirements and complexity of the project under consideration. It is essential that what is written in the decommissioning plan, which may be modified by agreement with the regulator as the project proceeds, reflects the work that is actually performed. The regulator is likely to closely scrutinize the final report for evidence that all of the activities from the decommissioning plan have been fully and satisfactorily completed.

For small facilities, such as decommissioning of a radiotracer laboratory, the decommissioning plan may be as simple as a ten page document that references existing work procedures, such as waste disposal arrangements or decontamination of surfaces. Where there are a number of options to carry out specific decommissioning tasks, the regulator will expect the facility to have carried out an options appraisal with justification for the selected working methodology, taking account of demonstrably good practice consistent with the infrastructure and resources of the country. This should incorporate minimization of risks, worker and public exposures, environmental impact and generation of wastes. The IAEA has published a number of helpful publications that detail the specifics of a decommissioning strategy, along with planning and management for a range of different types of facilities, such as nuclear medicine and radiotherapy departments, industrial and research facilities, including hot cells, small research

TABLE 6. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE WHEN IDENTIFYING THE INFRASTRUCTURE AND RESOURCES TO TAKE FORWARD DECOMMISSIONING

Failure to understand the organizational structure.	Delays in contacting the right people to secure funding to take forward decommissioning. Demoralization of the worker whilst trying to secure funding when those contacted appear disinterested. Overall project delays.
Lack of ownership of the task.	Likely to occur with government funded establishments or when more than one establishment has responsibility for the financial liability. Avoid protracted delays by securing participation of all interested parties in a meeting so individual financial responsibilities can be identified and a timescale for their delivery agreed.
Failure to secure sufficient resources.	Inability to fully complete the project. Possible safety issues and escalating decommissioning costs due to the delay. Lack of funding should not be an excuse for no action.

reactors and particle accelerators [4, 20]. When drafting the decommissioning plan, it not only needs to include the specific detail of all the tasks associated with decommissioning, but might usefully incorporate a sound safety case that addresses both radiological and non-radiological hazards, environmental issues and concerns as well as the waste management programme.

The plan will also include specific details of the expected radiation dose to the workers and how this has been optimized consistent with the ALARA principle. Where an adequate financial provision has not been secured to complete the entire project in a single phase, or where the hazard assessment identifies a phased approach to reduce the radiation burden to the workers is the optimized decommissioning solution, the decommissioning plan might include a justification for the proposed timetable to bring the project to completion and also identify how further funds will be made available as the project proceeds. In circumstances of a phased approach to decommissioning, it is important for the decommissioning plan to clearly identify the safety case for each holding phase in the project, identifying how hazards have been minimized. Whereas the decommissioning strategy should ideally be in place whilst the facility is still operational, the detailed decommissioning plan is unlikely to be finalized until closer to the time that decommissioning is to occur. The decommissioning strategy will have considered issues such as regulatory requirements, financial provision, human resources requirements and technical issues. The detailed decommissioning plan considers the health and safety of the workers and of the public, technical issues associated with decontamination and dismantling, environmental protection, waste and material management and human resource requirements. It is important that the plan includes a comprehensive assessment of both the radiological and non-radiological consequences to the workforce and the public during the implementation of the decommissioning plan using a probabilistic and deterministic risk assessment methodology, as needed [21, 22]. It may be useful to stress here that the safety assessment should be subject to a graded approach depending on hazards and risks associated with the decommissioning work.

It is essential that particular consideration is given in the decommissioning plan for waste and material accumulation and management for recycling and disposal as the decommissioning project progresses [23, 24]. Early attention might be paid to any new regulatory permission or written quality system for waste management that will be required [18]. This is one aspect of a decommissioning plan that can go wrong because the existing staff fail to recognize the larger quantities and types of waste that might arise during decommissioning, having assumed (incorrectly) that the wastes would be the same as those produced during normal operation. For small facilities, space is often at a premium and existing waste accumulation space might be totally inadequate once full dismantling of the facility is underway. It is easy to assume that most of the dismantled facility will be suitable for clearance following completion of any required decontamination. Whereas this may be correct, it takes time to complete the documented monitoring regime to be satisfied that the material meets clearance criteria [14]. This may necessitate a new requirement for a storage holding area for dismantled materials such as cupboards, bench tops, laboratory equipment, sinks and drainage pipes, etc. This area needs to be large enough to provide facilities for staff to work and carry out essential monitoring and movement of waste into and out of the area, which might include use of mechanical lifting equipment such as a fork-lift truck. The area also needs to have a low background radiation level, as measurements are likely to be performed at close to the limits of detection of the measuring equipment. Often former office or workshop accommodation is suitable to be assigned as a temporary waste store or for measurement of waste packages. This option should only be considered if the space can be fully protected; e.g. by adherent plastic sheeting on floors and walls. Where further cutting of dismantled items is to occur, consideration needs to be given both to the safety of the cutting operation, to include fire safety, and to minimization of airborne contamination (this includes dusts as well as very low level radiological contamination). Once declared as cleared, the dismantled items may require cutting into more manageable sizes to facilitate recycling or disposal from site, or space may be needed to locate a 40 m^3 skip for periods of days or weeks to facilitate accumulation of cleared material/waste prior to removal from site. Figure 5 shows conditions inside the solid waste storage vault at Paldiski Nuclear Centre, Estonia. Some high activity items had been disposed of there, making manned access impossible. Eventually the facility was decommissioned by remote operation.

It is important to make provisions for additional activities, such as storage and transport and temporary structures that may be required for waste management. This also includes liaising with all relevant regulators when considering waste storage, further management, transport and disposal. If there are regulatory conflicts or jurisdictional overlaps between the requirements of multiple regulatory agencies; e.g. transport regulators, health and safety regulators, environmental regulators and nuclear regulators, these must be discussed with all relevant

FIG. 5. Solid waste storage vault at Paldiski Nuclear Centre, Estonia before decommissioning.

parties and a memorandum of understanding be drafted and signed by all regulators on how this aspect of the decommissioning plan will proceed.

It is important that the detailed decommissioning plan identifies the members of the project management team and provides details of both their roles and responsibilities. When decommissioning small facilities, use of existing human resources could usefully be considered first, even if these staff will require some retraining. Whilst it is accepted that for some small facilities, it will be necessary to employ the services of an external project management consultant with extensive relevant experience in decommissioning of facilities of the type under consideration, most of the work on decontamination and waste sorting, measurement and packaging can probably be carried out by existing staff. Do not forget to consider using the services of plumbers, engineers and maintenance staff employed routinely at the facility where dismantling requirements are minimal and the material is expected to be largely cleared following completion of decontamination procedures. Such workers tend to require fairly minimal levels of additional training when required to participate in a simple decommissioning project, but it is prudent to only get them involved once it has been made clear to them that appropriate additional training will be provided, hence securing their confidence to participate in the project.

Where the dismantling phase is likely to involve complex or heavy work such as removing contaminated concrete walls or cutting up contaminated hot cells, specialized equipment and experienced dismantling workers are likely to be required for that aspect of the project. Where a combination of existing human resources and external contractors are to be employed for delivery of the various stages of the decommissioning plan, it is essential to ensure an integrated approach to the health and safety management of the project to minimize both radiological and non-radiological hazards. It is also essential to ensure timely provision of training of staff and to facilitate constant communication between the workers, so that each clearly understands the roles and responsibilities and work timescales of the other parties involved. Clear communication might be managed by holding a short site meeting every morning with the key players from the project team, with these people cascading the relevant information to all the other workers. It is essential that any holding points in the decommissioning plan where the regulator wishes to inspect the site before the project proceeds any further are adhered to, so a mechanism should be instigated to achieve this. See also Table 7.

TABLE 7. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE IN PLANNING FOR DECOMMISSIONING

Failure to retain records to facilitate drafting of the decommissioning plan [25].	The task will be more difficult to take forward. The vital lesson is to consider retention and suitable archiving for retrieval of records, early capture of knowledge of the workers, and dialogue with other stakeholders (regulator, builders, designers, maintenance companies, etc.) to obtain information from their records. Possibility the decommissioning plan will be inadequate for the task, with a need to back track to include additional work at a later stage.
Failure to identify adequate lines of communication and clearly assign roles and responsibilities within the decommissioning plan.	Making good progress with the project will be more difficult than it needs to be. Possibility that aspects may be overlooked, safety could be compromised, and costly delays and mistakes.
Drafting a decommissioning plan that is unnecessarily complex for the project.	More time and effort than necessary in writing the plan. Will not be cost effective in delivery. Workers may be concerned that they do not have the skills and knowledge to take the task forward.
Poorly drafted decommissioning plan containing inadequate detail of the proposed strategy for decommissioning.	Decommissioning plan will be rejected and will require revision before the project can proceed. If cost estimates have been based on a badly drafted plan, there may be inadequate funding and resources available to complete the project.

3.8. COST ESTIMATION

Cost estimation is done throughout the decommissioning project planning stage and is used to arrive at a decision on the viability and relative desirability of the various options. The decommissioning plan forms the basis of the input of the cost estimation of the project, with cost estimation increasing in depth and precision as the plan matures. There may be a qualitative difference in early versus late stage costing in the plan preparation, as the approach evolves from simple comparisons to a bottom up costing based on unit operations. For any decommissioning project, the funding sought will need to be closely aligned with the plan, but be sufficiently robust to accommodate uncertainties that might arise as the project gets underway.

Cost estimation can be one of the most difficult aspects of the project for the newcomer to decommissioning to get to grips with. Whereas a laboratory manager is all too familiar with the day to day running costs of the laboratory and the costs of support services, such as waste management and disposal, he may not have the confidence to make a cost assessment for a decommissioning project for fear that he will underestimate the costs and the project will be inadequately funded to reach completion. One option might be to provide excessive cost estimates to guarantee sufficient funds are available. The problem in this case will be securing the projected costs — if the costs are perceived to be too high, this might prevent the decommissioning project from being funded. If the cost estimate appears to have too much uncertainty built into it; e.g. a 60% contingency fund, again the cost estimate may be rejected because it has too much uncertainty and as much of this uncertainty as possible will need to be resolved prior to submitting a revised cost estimate.

The easiest way for the operator lacking specific experience in decommissioning to pull together a provisional budget is to break the project down into component tasks and then cost each of these by seeking cost projections from external service providers or from existing service providers to the operational facility. Labour costs should ideally be based on the unit cost for hire of local labour where possible. Where specialist contractors or project management workers are required and such expertise is not available locally, the salary rates of the relevant country from which these workers will be hired will need to be used for the cost assessment. Breaking the project down into smaller component parts facilitates comparison of the charges that an external contractor would make versus costs to re-train existing staff and complete the work ‘in-house’ for that aspect of the project. An example of the individual components to be priced as part of putting together a cost estimation for decommissioning is included in Appendix 4.

It is important at the outset to ensure that sufficient funds will be available to complete the project, even if all the funds are not available at the start. It is crucial to ensure that the final budget projection includes a contingency fund of a minimum of 10–20% of the overall projected budget to cover any uncertainties or price increases that will inevitably arise as the project gets underway. Where there are a lot of uncertainties in a decommissioning budget, it may be wise to increase the contingency aspect to 25–30% of the overall project costs, provided such an approach can be justified based on the available supporting data. The IAEA has published guidance on the financial aspects of decommissioning [26].

For commercial organizations, such as industrial facilities producing saleable products with a regular cash flow, carrying forward of ring fenced funds between financial years is generally not a problem. Early planning for decommissioning and submitting provisional decommissioning costs at an early stage into a long term financial plan is possibly the best way to ensure funds are available when actually required. It is not unusual for commercial establishments to operate a 5 or 10 year forward financial planning projection, so this might necessitate a projected sum being identified for decommissioning long before decommissioning may even be considered to be likely to take place. There is no harm in this sum being a ‘best guess’ at the time it is inserted into the financial plan. The key thing is to get the organization thinking about future decommissioning costs. The best guess figure could usefully be revisited at suitable intervals (perhaps every 1–2 years) and updated to meet current cost projections, adding further refinements to the cost projection to improve its accuracy once decommissioning is actually scheduled to occur. Financial planning for decommissioning at an early stage does not commit the organization to decommission at that time. In fact, one commercial organization in the UK utilized the provisional budget assigned for decommissioning to upgrade the radioactive facilities when work was projected to continue for a further twenty years instead of ceasing after another 3 years.

Although some uncertainty is inevitable in any costing methods used for a particular project; it is useful to avoid key uncertainties. The greater the unknowns; i.e. presence of asbestos or ground contamination from underground waste pipes, the larger the contingency fund might need to be. Even where it is thought that all the costs have been accurately quantified and no uncertainties exist, as an absolute minimum, a 10% contingency fund should still be allowed, so at least some provision for unexpected findings or cost increases can be accommodated. Where the project is expected to extend over longer periods, it is wise to include an allowance for annual inflation increases.

In 1999, a joint publication of OECD/IAEA/EC [27] provided a standardized list of items for costing purposes for decommissioning. Cost considerations in this publication were broken down into eleven sections:

— Pre-decommissioning actions;
— Facility shutdown activities;
— Procurement of general equipment and material;
— Dismantling activities;
— Waste treatment and disposal;
— Security, surveillance and maintenance;
— Site cleanup and landscaping;
— Project management, engineering and site support;
— Research and development;
— Fuel;
— Other costs.

When first examining this list of eleven generic groups for cost consideration, it might be easy for the small laboratory facility to say that not many aspects will be relevant to consider when arriving at a cost assessment for their decommissioning project. Perhaps this is a correct assumption in respect of the many sub-groupings of costs associated with each section, but it is likely that all eleven sections will be relevant for decommissioning of a 10 kW research reactor. For decommissioning of a simple radionuclide laboratory, the costing exercise will be much simpler as there will be fewer individual cost items to consider under each of the eleven generic cost groups. Many workers may find it easiest to set-up an Excel spreadsheet to add in all the monetary values against each cost source as data becomes available.

Every facility will need to allow some finance for pre-decommissioning activities to cover the fees involved with the licence applications or revisions submitted to the regulatory bodies. During this stage, decommissioning planning costs will be incurred, and any costs associated with the need to complete surveys or to involve stakeholders could usefully be considered. At this early stage, assessment of any hazardous materials might be carried out and selection of any specialist contractors might be made so that these costs can be included.

It is essential to consider the proposed reuse of the site or facility, as this will impact substantially the decommissioning strategy and costs. It is uneconomic to demolish a wall that could be useful for the future use of the facility, just as it is costly to decontaminate to remove the entire radionuclide inventory when the laboratory is again to be used as a radionuclide facility (Fig. 6). The potential for asset recovery should also be considered; i.e. the recovery of large volumes of copper piping from a medical cyclotron that has a commercial resale value once decontaminated and released from regulatory control (Fig. 7), or surplus inventory equipment that has a viable resale market. These items for resale should show as an income stream in the financial spreadsheet for the project. All decommissioning facilities should budget for radiological characterization and plant shutdown during this phase of the project. For small radionuclide laboratories, the costs of radiological characterization may be relatively low if all the sampling and measurements can be done in-house using existing staff and resources. It is essential not to overlook the costs of any equipment traceability calibrations or the costs for external measurement of duplicate samples from the characterization survey that might be required by the regulator. For small research reactors, this is the stage in the project when it is appropriate to budget for removal of the fuel.

Procurement of general equipment and material might not at first glance appear relevant as a cost consideration when decommissioning a simple radionuclide laboratory, but it is possible that this assumption is incorrect. It may be that the laboratory already has at its disposal relevant dismantling equipment, tools and materials to carry out decontamination and sufficient health physics equipment to be able to complete this aspect of the decommissioning plan. If not, these costs must be quantified and built into the project cost assessment. This stage of cost assessment does not include labour costs to actually do the tasks for which the equipment and materials are required. Table 8 highlights numerous issues in inadequate assessment of decommissioning costs.

A wide range of costs are included under the generic heading of dismantling activities in the above mentioned publication of items for costing purposes [27]. For this reason, it will have cost implications for every decommissioning plan. Dismantling activities will be a substantial aspect of the budget when decommissioning a more complex radionuclide site or a 10 kW research reactor, whereas in a small radionuclide laboratory, it is possible that dismantling activities may be carried out using existing staff and facility resources, hence limiting additional cost implications. Where decommissioning is to be staged over a protracted time period, dismantling activities may be focussed on achieving a safe state for long term storage, or alternatively the strategy may be focussed on a strategy of entombment, although this should only be the selected strategy under exceptional circumstances. The generic aspect of dismantling cost assessment requires inclusion of cost estimates for the

FIG. 6. The DR-1 reactor room after dismantling (Risø Nuclear Centre, Denmark). The small reactor DR-1 was fully dismantled and its premises converted to an experimental station for storage of Aeolian energy.

FIG. 7. Minneapolis VA MC-40 cyclotron — put up for auction and purchased by University of Birmingham in the UK.

TABLE 8. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE IN COST ESTIMATION

Failure to adequately communicate regulatory end point requirements to the facility owner/operator, where these conflict with his perceived end points.	May face difficulties in securing sufficient funds to complete the decommissioning project.
Inability to put together an adequate budget requirement for the project.	Failure to recognize lack of skill in the field and seek the necessary training or employ the services of an external consultant. Possible difficulties in delivering the project if underfunded or cash flow does not match work progression.
Failure to understand the financial planning arrangements of the organization.	Delays in securing the funding to take the project forward. Likely to result in project increased costs, additional maintenance costs prior to dismantling and possible safety issues. May result in pressure from regulator, donors or other stakeholders to progress decommissioning.
Failure to establish adequate cost projections.	Insufficient funds to complete the project. Likely to result in regulatory action, especially if holding point presents additional safety issues. Delays whilst additional funds are secured. Budget cost likely to increase with time.
Identifying an inflated cost projection to avoid being underfunded.	Management reject the data and require a re-submission resulting in delay in funding provision. Overall project inertia as management are unable to fund the over inflated cost projection.

workforce and any other requirements to carry out a whole range of tasks of decontamination prior to dismantling, transfer of contaminated equipment and materials to storage, sampling for radiological inventory characterization as part of safe store arrangements or for decommissioning and decontamination, providing for temporary waste storage areas, dismantling of reactor vessels and internals, removal of biological/thermal shield, removal and disposal of asbestos, environmental cleanup, decontamination for recycling and reuse, personnel training, asset recovery and final radioactivity survey.

Section five of the cost assessment process as recommended above [27] covers the field of waste/materials processing, storage and disposal. This aspect of the budget must meet the costs of preparing any dismantled components either for final disposal as radioactive waste, or for restricted or unrestricted recycling or reuse. All of the waste materials in any physical form either contaminated with radioactivity or not, need to be assessed for the costs of processing, packaging and transport. Costs of disposal of non-radioactive waste to incineration or landfill should ideally also be included, as well as costs of waste containers and fees levied by a waste storage facility.

Site security, surveillance and maintenance will have a greater financial impact where decommissioning only to the status of safe store is the selected strategy. This aspect of the cost assessment focuses on site protection, control and maintenance activities. This cost aspect would include finance to pay for dismantling of structures, such as stacks, and for final cleanup and landscaping of a site. There may be a need to finance independent verification of cleanup standards where sites are to be reused so this cost should be included here. Any perpetuity funding for restricted release of a building or site should be included as part of this cost.

Project management, engineering and site support costs will increase in proportion to the complexity of the decommissioning project. This aspect relates to costs associated with the implementation phase of the decommissioning project. The requirement to employ a suitably experienced project manager, specialist engineering services or demolition expert will depend on the type and complexity of the facility to be decommissioned. For smaller facilities, more relevance might be given to the costs to set-up arrangements, such as a temporary decontamination facility for personnel, a tented facility for waste characterization and packaging for disposal or for additional laundry facilities. Quality assurance and quality surveillance costs are included within this generic group of cost assessment and although it may not be immediately apparent that this will have a cost implication for your project, it is wise to consider the cost requirement for additional staff training to meet this aspect of the decommissioning plan. Document and record control may also have long term cost implications for record storage, maintenance and retention. Computer hardware and software costs need to be considered along with costs for management of changing technology. For larger projects where public stakeholder engagement is necessary, the costs of public relations might be included in this aspect of the cost assessment. Health and safety costs, to include radiation protection and monitoring costs need to be included, as well as cost implications for industrial safety.

Section nine of Ref. [27] is where a cost assessment of the implications of research and development associated with the decommissioning plan should be considered and included if appropriate. This is unlikely to be required for most small facilities but may be required for untested decommissioning technologies; e.g. for remote decommissioning of hot cells. This aspect of decommissioning is likely to include costs to review available technical options and select (or adapt) the preferred way to complete specific tasks of the project, and any mock up trials as part of ALARA planning.

Section 10 of Ref. [27] covers the costs relating to the evacuation of spent fuel elements and/or nuclear material but excludes costs for reprocessing or final disposal alternatives. This is again likely to impact on very few decommissioning projects typically covered by this report. Figure 8 shows a phase of spent fuel transport from the decommissioned of a Jason reactor (a small reactor located in Greenwich, London). The particular difficulties associated with this project were due to the fact that the reactor was located in an historic building.

Section 11 covers all other costs that cannot be specifically classified in the other ten sections of the cost assessment. It includes costs such as compensation payments for staff reduction, taxes and insurances and overheads of general expenditure. This will also accommodate the contingency aspect of financial assurance for uncertainties occurring throughout the decommissioning project. It is useful to also consider here any income that may be generated from sale of equipment purchased specifically for use during the project that has a resale value.

3.9. REGULATORY INTERACTION AND AUTHORIZATION

A diverse range of regulatory permission/authorization requirements exists across Member States in respect of decommissioning. Furthermore, the maturity and stage of development of radiation legislation varies widely amongst the Member States. Some Member States have radiation legislation extant and updated over many decades, whereas other Member States may have only published their legislation for the first time in the last decade. Where the regulatory bodies to enforce the legislation have been in existence for many decades, both the knowledge of the regulatory inspectors and the requirement to communicate with them during decommissioning might be well

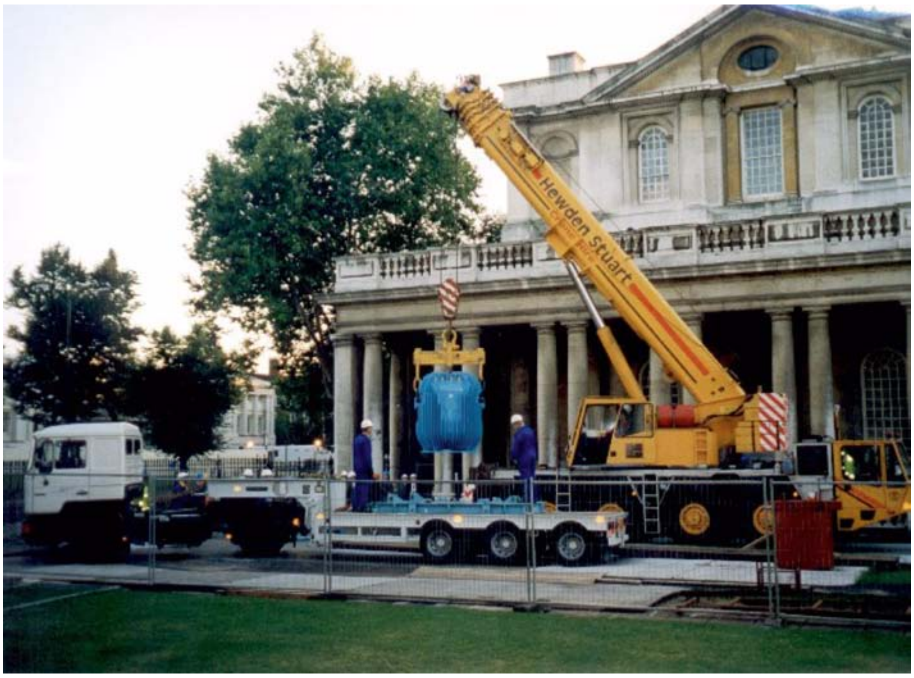

FIG. 8. Spent fuel transport from the decommissioned Jason reactor, UK.

established. In developing Member States, recruitment and development of the expertise of the regulatory body might still be in its infancy, and in such circumstances, the operator will need to be self-sufficient in his knowledge to take forward decommissioning. Self-sufficiency in decommissioning should not be taken to mean that there is a shortage of published information to support the operator in taking forward the required project.

For some countries, a specific decommissioning licence is required, which sets down all of the standards and permissible activities that can be carried out on the site. Major modifications to the decommissioning plan after it has been approved by the regulatory body may also necessitate a revision to the decommissioning authorization. Some Member States can apply for a revision to their existing operational licence to accommodate a move from the operational phase of business to decommissioning. In the UK, for non-nuclear power licensed sites or facilities; i.e. those not regulated by the Nuclear Installations Inspectorate, there is no requirement to apply for a licence revision or a new licence to undertake decommissioning. This does not relieve the responsible person from the requirement to communicate the decommissioning proposals to the regulator at an early stage, and to subsequently submit a comprehensive plan for his consideration and approval before decommissioning activities progress to the operational phase. In the UK, once the final decommissioning report has been agreed by the regulator, the operational authorization under which the site has formerly operated will be revoked, or revised if only part of a site or facility has been decommissioned.

No matter what regulatory arrangements are required for decommissioning, the owner/operator needs to communicate with the appropriate regulatory bodies at an early stage and as appropriate during decommissioning, if the regulator has identified a key holding point where he wishes to be consulted further. In some Member States, the regulators may be interested in exploring the options for decommissioning, especially where several options exist and an options appraisal is provided by the operator. In many Member States, the regulator only requires receipt of the completed decommissioning plan for his approval. Some regulators may wish to inspect the site as decommissioning progresses whereas in most Member States, the regulator will only require receipt of the final survey report, provided no major changes have been made to the decommissioning plan.

Regular contact and open cooperation with the workers and relevant stakeholders is essential as decommissioning activities proceed. Often well run small nuclear facilities have minimum contact with the regulator, possibly restricted to a few hours per year when the inspector makes an annual visit. Once decommissioning and license termination or revision is envisaged, more frequent dialogue with the regulator may be necessary, although not essential. The onus is on the project lead for the facility to contact the regulator, not vice versa, as regulators have no statutory requirement to get involved in delivery of the decommissioning plan after it has been approved. Past performance of the licensee can affect the amount of interest the regulator has in a project and whether this interest is positive or negative. If the licensee has identified a proposal for a technically sound and regulatory compliant decommissioning project, supported with the correct documentation, the regulator is likely to have few concerns and will rely on the licensee to contact him if something occurs that requires a major modification to the approved plan. Working well with a regulator necessitates demonstration of an ongoing level of self-sufficiency and professionalism in carrying out the work, with regulatory communication maintained at a minimal level appropriate to the delivery of the decommissioning project.

Effective planning for decommissioning is impossible without a thorough understanding of all relevant regulatory requirements (and any pending changes to these requirements) for each of the regulatory bodies/agencies with an interest. Each regulatory agency may operate to its own specific standards for potential impacts on workers, the general public and the environment and these must be fully considered by the operator in deciding on the work procedures to be adopted. It is essential that a thorough understanding of the requirements of all regulatory bodies is compiled into a single document at the early stages of planning, and any differences reconciled through negotiation. It may be useful to secure a written memorandum of understanding between the different regulatory bodies where conflicting requirements are identified at the outset.

Some important points that it might be useful to define before decommissioning work commences:

- Establish the natural background radiation level for each area to be characterized. Note that this may be different for different rooms within a building; e.g. in one hospital, the natural background radiation level in a basement records area was higher than in the radionuclide laboratory, due to radon gas emanating from the cracked concrete floor.
- Arrangements for the early removal of any sealed sources and other high radiation sources that may be present, so as to reduce the overall radiation burden of the decommissioning project.
- Agreement on the methodology for carrying out the decommissioning tasks, taking care to select the simplest proven technology wherever possible. Where new techniques or tools are to be used, involve the regulator in discussions of the lessons learned from a mock-up trial and seek regulatory support for development of working procedures consistent with the ALARA principle.
- Agreement on the storage arrangements on-site for decommissioning wastes pending their further monitoring and disposal under the appropriate regulatory regime.
- Ask the regulator to specify any holding points that might be required when a site inspection will be made before work proceeds any further and ensure these are incorporated into the work plan. Note that for simpler projects, the regulator may not specify any requirement. Table 9 highlights possible inconveniences as far as regulatory matters are concerned.

TABLE 9. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE RELATING TO REGULATORY PERMISSIONS/AUTHORIZATIONS

Failure to make a timely application for any required regulatory authorization/permission/licence.	The project will be delayed.
Provision of incomplete or inaccurate information when applying to the regulator for authorization/permission/licence.	Application processing will be delayed. May incur additional costs to make a further submission containing all of the correct essential information.
Failure to identify all regulatory permissions that may be required.	Delays in the project. Could be a budget shortfall if these costs have not been included in the budget.

4. IMPLEMENTATION OF THE DECOMMISSIONING PROJECT

4.1. ORGANIZATIONAL MANAGEMENT

It is the function of the project manager to ensure the timely planning, preparation and implementation of the decommissioning tasks paying due regard to the technical, administrative and legal requirements. Flexibility in coping with unforeseen difficulties or delays is another important obligation. Therefore all the technical and administrative skills necessary to plan and execute the tasks must be represented within the project to react and cope immediately with unexpected occurrences. Whilst quality assurance is an essential component of any decommissioning project, compliance with quality assurance standards/codes need only to be commensurate with the complexity of the project.

Management processes systems and responsibilities should be tailored to the complexity of the project, complying with the safety and quality assurance requirements. Management systems and processes are likely to be required to ensure compliance with:

- Project management/resource management/financial management;
- Legal (to cover safety and environmental legislation, labour legislation);
- Licensing/relicensing requirements;
- Quality assurance/roles and responsibilities/resource management/documentation and records/reporting/work procedures/events and non-conformance management (contingency procedures)/management review/work flow.

In this field the reader can consult Refs [1][28]. Table 10 identifies typical mishaps due to poor organizational management in decommissioning.

4.2. FINANCIAL MANAGEMENT

A key point to consider at the outset is how the cash flow of the facility is managed. If funds are allocated in a given financial year (as is common in government funded establishments), and there is no facility to carry forward unspent funds into the next financial year, the decommissioning project might need to be timed to coincide with the financial year — but do bear in mind that the financial accounting year may not coincide with a calendar year. For

TABLE 10. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE IN ORGANIZATIONAL MANAGEMENT

Failure to set-up an adequate communication infrastructure.	Project will not proceed as effectively. Could compromise project success or safety.
Inadequate management systems and processes.	Inefficient project management. Possible implications for health and safety.
Overly complex management organizational arrangements relative to the simplicity of the project.	Confusion amongst the workers. Unnecessary costs and delays whilst workers cope with overly complex managerial arrangements.
Roles and responsibilities inadequately defined and communicated to all stakeholders.	Lack of overall control of the project. Project delays and possible implications for health and safety.
Appointment of an inappropriately experienced project manager.	Project will not be as successful. May need to make a replacement appointment after the project is already underway, leading to delays and additional costs.

example, in the UK, universities have an annual financial year that runs from July to July, whereas most business establishments have a financial year that runs from April to April. Other establishments may operate their financial years consistent with the calendar year. If it is not possible to secure sufficient funds in a single financial year to complete the project, it might be beneficial to consider starting the project in the second half of the year, safe in the knowledge that the further funding allocation has been guaranteed at the start of the next financial year.

When a project spans several years, but decommissioning funds cannot be ring fenced and the allocated funds have to be spent within that financial year otherwise they might be forfeit back to the organization central budget, it is not uncommon for advance payment to be made for future aspects of the work to be done. In such circumstances, it is essential to consider the value of having appropriate bank insurances should the contractor be declared bankrupt before he has completed his aspect of the decommissioning project.

The decommissioning project might be broken down into stages, with funds allocated to each stage of the work, be it task specific or some other suitable arrangement. It is essential to have ongoing monitoring of funds expenditure versus work progress achieved to ensure the project will be delivered within the allocated budget. Where unforeseen difficulties arise as the project proceeds, and additional or modified work is required, it may be necessary to recost an aspect of the project and allocate money from the contingency budget to cover any increased costs. Clear arrangements need to be in place for measuring project progress against funds expenditure versus project plan, with correction and contingency arrangements being implemented when required to ensure the project remains on track. Cash flow can also be influenced by any materials that can be recycled as decommissioning progresses; e.g. copper piping at clearance level that can be resold to provide funds for the next stage of the decommissioning project. Table 11 identifies experiences of poor practices in financial management and their possible impacts.

4.3. ESTABLISHMENT OF WORK PROCEDURES

An essential part of the establishment of the work procedures for a project is integration of health and safety requirements and consideration of the output of the risk assessments, where hazards should be eliminated if possible, and if not, their impacts minimized. Work procedures need to be reviewed and updated in respect of experience of operation, taking into account any incidents occurring in the work place.

Not only is it important to decide on the most efficient and cost effective working methods, but it is also necessary to agree to the order in which specific aspects of the project are to be taken forward. It may be that new techniques have to be learned by existing staff for them to fully participate in that aspect of the decommissioning plan, so timely provision of training and the opportunity to participate in mock-up trials as part of future participation in the work might be essential. It may be that a number of options for carrying out an aspect of the

TABLE 11. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE IN FINANCIAL MANAGEMENT

Failure to establish a timetable for timely financial provision of the project.	Cash flow does not meet project requirements. Insufficient funds to pay external contractors might result in project being delayed or financial penalties for late payment cutting into contingency funds.
Failure to identify possible income possibilities from sale of free release materials during the project.	Management like to see possibilities for revenue generation identified when considering applications for funding of a decommissioning project. Omission may result in a request to review the cost projection leading to delays.
Failure to understanding the financial management structure.	Cash flow may not be available as required. Need to secure information on the timed delivery of the project budget. Need to ensure that any committed timescales when payments must be made; e.g. in applying for regulatory permissions, are communicated to the finance director.
Failure to adequately monitor cash flow against project progress as part of overall project delivery.	May lead to a budget shortfall. Inefficient use of funds.

FIG. 9. Handheld mechanical cutting equipment for small contaminated pipes, SCK-CEN Centre, Mol, Belgium.

work exist. In such circumstances, a fully documented options appraisal of the relevant advantages and disadvantages of each work option might be required, supported by relevant cost projections and an ALARA and generic risk assessment. Failure to provide the regulator with a sufficiently comprehensive decommissioning plan may cause the regulator to suggest a specific method, based on his knowledge from previous decommissioning projects. It is up to the facility submitting the decommissioning plan to ensure it is comprehensive and contains details of the justification for the selected decommissioning option. It is always wise to choose proven tools and the simplest technology suitable for carrying out the task. Figure 9 shows simple tools (such as those available at a hardware store) that were successfully deployed at SCK-CEN Centre, Mol, Belgium. For small facility decommissioning, it is unlikely that robots will need to be specifically designed and constructed to carry out some of the decommissioning tasks, although some suitable remotely operated tools and equipment off the shelf may still find a niche when decommissioning more complex facilities; e.g. hot cells. Table 12 highlights some potential consequences of deficient work procedures.

4.4. DECONTAMINATION

Decontamination may not be required in decommissioning of some small nuclear facilities, such as a laboratory with an irradiator or a medical facility with beam or sealed source radiotherapy treatment facilities. Where the characterization survey has identified the presence of radioactive contamination, this data should be used to design a comprehensive decontamination strategy [1, 20, 29]. Decontamination is an essential component to achieving waste minimization and for reducing the overall costs for waste disposal. It may not be cost effective to remove all of the contamination identified by the characterization survey, especially when the decontamination process may result in unacceptable radiation dose to the workers or result in the production of a mixed waste that will be costly or difficult to dispose of. It will not be possible to remove all of the contamination where there is activation in concrete.

The characterization of the area to be decommissioned is important in identifying areas that are free from contamination so that they can be eliminated from the proposed cleanup operation. The data obtained on the radioisotopes present and their activity level can usefully be used to evaluate decontamination alternatives and formulate a budget for the cost of the total project cleanup effort. A decontamination strategy needs to be drafted, which should include consideration of:

— Data from the characterization survey suitable to evaluate the merits of different decontamination alternatives, having due consideration of depth of penetration of contamination into structural surfaces, the ease of removing the contamination from the surface and the presence of problem materials such as asbestos;
— The types of secondary waste that may be generated from decontamination techniques, especially in relation to what other constituents may be present, and how these wastes might be treated and disposed of;

TABLE 12. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES WHEN ESTABLISHING WORK PROCEDURES

Failure to complete a comprehensive options appraisal as part of the decommissioning plan where a number of options exist for delivery of the project.	The regulator may require the work to be completed using a method that is not as cost effective, hence not optimizing use of available resources. This could have been avoided by the initial submission of a comprehensive, fully priced, options appraisal supported by a risk assessment and ALARA appraisal.
Lack of flexibility of permit to work arrangements.	Unnecessary delays. Over restrictive use of protective clothing when less stringent requirements are actually needed.
Failure to involve the work force in development of work procedures.	Sub-optimal procedures developed. Work will be less efficient. Possible health and safety implications.
Failure to carry out mock-up trials where new tools or techniques are to be used.	Work procedures will not be optimized. Possibility of accidents as risks not fully assessed in advance. Workers may be lacking in confidence to perform the new tasks.
Major deviation from the approved decommissioning plan without reference to the regulator.	Do not include anything in the decommissioning plan unless you intend to do it. The decommissioning plan is a living document that should be regularly reviewed and revised as required. Where a major change is required, this should be discussed with the regulator. Failure to keep to the agreed/revised plan may cause problems for the final survey and license termination.
Failure to select the simplest proven technology to complete the work task.	Staff likely to require additional training. May result in reduced worker confidence and increased possibility of accidents/incidents.
Failure to make consistent use of units when recording data during decommissioning.	Drafting the final survey report will be exceedingly difficult as units will not be comparable. May need to back track and repeat work. License termination or revision may be difficult as the regulator will require consistency of units used throughout the project.
Failure to establish and provide appropriate protective clothing relevant to the work procedure.	Work progress may be delayed. It is essential to integrate appropriate safety requirements into the work procedures.

— The acceptance criteria for the waste disposal routes under consideration, especially in relation to any restricted materials or problems in disposing of wastes with mixed properties;
— Safety impact of decontamination technique.

Successful decontamination programmes typically share three common characteristics:

— The removal of radiation sources (sealed and unsealed) to a safe location;
— Removal of any residual contamination present;
— Minimization of the quantities of low level radioactive and mixed waste generated.

In addition to the IAEA publications indicated above [1, 20, 29] useful texts on decontamination techniques and their application were published by the US Department of Energy [30] and the European Commission [31]. One should note that these publications provide useful information and guidance on many other aspects of decommissioning. Useful practical advice for decontamination at an oncology and radiobiology facility is given in Ref. [32].

The early removal of radiation sources from a decommissioning site has the immediate effect of substantially reducing radiation risks. Furthermore, effective decontamination is easier to achieve when the elevated background attributed to stored radioactive materials has been eliminated. Radioactive materials need to be moved to a secure location or removed from site through disposal or recycling before decontamination of the area is carried out. In planning for the transfer of sources to a secure holding location on-site, or arranging removal from site, it is important to comply with relevant packaging requirements and regulatory conditions, including any license requirements for the site restricting where radioactive materials may be held.

The characterization survey data will facilitate the drawing up of a floor plan of all the areas to be decontaminated, identifying both the location and the level of contamination. Appendix III includes an example of such a floor plan from a laboratory decommissioning project. If the characterization survey is sufficiently comprehensive, it will also provide data on the chemical form of the radioisotopes, their depth of penetration into surfaces, and the presence of any covering materials preventing complete characterization of a specific area. It is essential that appropriate records are kept where covering materials are applied over residual contamination during the operational lifetime of a facility. Failure to keep such records may result in this concealed radionuclide activity not being included in the characterization survey; causing later problems as decommissioning progresses. It is conceivable that the covered contaminated surface item may incorrectly be disposed of at clearance level, which if discovered, might result in regulatory enforcement action. Alternatively, the concealed activity may be discovered once decommissioning is underway and will result in additional work and a potential increase in waste disposal costs.

The choice of a decontamination technique is determined by the following considerations:

- The nature of the radionuclide to be removed (its type and physical and chemical forms);
- The nature of the material to be decontaminated; consider whether there might be a toxic chemical reaction between the chemical and the material;
- The release criteria that must be met;
- The fate of the decontaminated material; i.e. release, recycle, reuse or disposal as waste;
- The location of the decontamination operation; consider ease of access and possibility for unacceptable exposure or contact of the chemical where staff are working in too confined a space;
- The nature, quantity and treatment of the secondary waste;
- The operator exposure and safety; including correct use of all necessary protective equipment;
- Cost.

It might be helpful to perform some small scale experiments using different decontamination or removal techniques in order to determine their effectiveness. The final selection of the most suitable decontamination techniques involves consideration of three variables:

- What techniques are most effective in removing contamination;
- What techniques provide the safest means of removing the contamination;
- What is the volume and waste form generated by the technique.

While it is not possible to anticipate every potential decontamination problem during the project planning phase, the approach adopted needs to be sufficiently flexible to accommodate field conditions. The time period between characterization and full-scale facility decontamination can be used for small scale mock-up trials in areas where the optimized decontamination method is still to be decided. Safety considerations for the various decontamination methods include minimizing both the potential for radiation exposure and for personal injury. Where exposure rates are elevated, appropriate use of shielding and time can usefully be employed to minimize exposure. Where there is depth penetration of radionuclide and the removal technique will generate airborne contamination, it is essential to ensure that this is tightly controlled both in respect of spread of contamination and exposure of the workers.

As a general rule, for small facility decontamination:

- Start with the simplest technique, which might be a dry technique utilizing a vacuum where loose material is present, although it is often wet cleaning with minimization of water/liquid volume; i.e. a damp wipe clean down should ideally be tried before proceeding to wet cleaning techniques.
- Progress on to chemical cleaning agents, ensuring selection of the appropriate chemical or mixture for the task (which relies on good characterization information). There is a range of commercially available chemical solutions for decontamination, and it is essential to read the safety instructions for their use when deciding on

FIG. 10. Floor scabbler, a tool for simple decontamination of concrete surfaces.

their suitability for the task. Start with the least hazardous but appropriate chemical methods first and progress with other chemicals as required. Do take care to clean away residues of one chemical method before progressing to another, as the combination of chemicals may result in unforeseen dangerous gases or increase the possibility of fire or explosion.

- — For persistent contamination, consider the use of abrasive/mechanical methods, starting with the simplest methods such as use of abrasives like steel wool or sand paper. Progress as appropriate to mechanical tools such as scabblers (Fig. 10), hammer and chisel or electrically operated wood planes where contamination requires removal of the surface to a greater depth.
- — Where underground drains may be contaminated, try various flushing techniques. Initially the drain should be flushed with a surfactant suitable to release any slime moulds attached to the inner surface of the pipe that may be retaining residual radionuclide activity. This might be followed by pressure water washing for a prolonged period relevant to the length of the pipes to be decontaminated.
- — If there is any possibility that the drainage pipes may not be intact, it is unwise to attempt decontamination before using telemetry or some similar technique to investigate the integrity of the pipes, as the released radioactivity from decontamination might further add to existing ground contamination.
- — Where concrete or similar surfaces are to be decontaminated, start by dusting/vacuuming prior to wiping/scrubbing, so that any loose material is captured at the outset.
- — Additional containment may be required when alpha contamination is present.

Chemical solutions are generally more effective on non-porous surfaces. The choice of the decontamination agent is based upon the chemistry of the contaminant, the chemistry of the substrate and the ability to manage the waste generated during the process. It is important not to progress to using more complex decontamination methods unless you are certain that the simpler more routine techniques will not prove effective. In many instances, in small facilities, use of a bleaching agent, a de-greasing agent or an ionic surfactant cleaner may be sufficient to remove any surface contamination that may be present.

It is not proposed here to discuss the individual merits of different decontamination techniques, but the reader is referred to further detailed sources of information. The key issue that most inexperienced workers want answered is “where do I start and what type of decontamination technique will be best for my facility?” Whereas there are no hard and fast rules, the information in Table 13 should be sufficient to get started. The information provided in Table 13 is not intended to be prescriptive, and more experienced workers may have their own preference in the most effective techniques to use.

It is not unreasonable to assume that staff working in a laboratory will be conversant with surface decontamination techniques for the radioisotopes they routinely work with in the event that a spill should occur during work operations. The situation might not be quite so clear cut when a whole range of radioisotopes have been used during the lifetime of a laboratory, with many of which current workers are unfamiliar. Routine decontamination techniques instigated soon after a minor spill in a laboratory might necessitate simply soaking up the excess liquid with absorbent material, followed by washing of the area with an ionic surfactant chemical to remove residual radioactivity. The situation might not be so straight forward when decontamination of the laboratory as part of decommissioning is required, especially if former incidents have been managed by applying a coating to seal in the residual radioactivity that was not removed at the time.

Consideration should be given to the benefits that can be gained from providing training to existing staff so that they can effectively carry out the decontamination stage of the decommissioning project. For any given technology, the less confidence and experience the worker has in utilizing the technique, the more likely the results will be ineffective, his radiation exposures will be higher and the probability of injury will be increased. If the technologies to be utilized for decontamination are unfamiliar to the workers required to perform the task, it is essential to provide adequate training and an opportunity to work with any tools and equipment to be used during mock-up trials, so they become familiar with the tools and techniques. The benefits gained from a trial use scenario before proceeding to the full-scale decontamination task, which facilitated workers being comfortable in carrying out the work, cannot be overstated.

Decontamination sometimes involves elaborate equipment and operator action, while segregation might require expensive measurement equipment, such as a Germanium co-axial detector system with associated software to facilitate identification and activity quantification of the radionuclide inventory. Table 14 summarizes typical inadequacies in decontamination and associated impacts.

4.5. DISMANTLING

Dismantling is the one aspect of decommissioning where a small nuclear facility may benefit from employing external experienced contractors, especially for larger projects such as decommissioning of a medical cyclotron. The contractors need to be managed by someone familiar with dismantling and cutting techniques to ensure that satisfactory progress is made, ensuring safety and cost effectiveness. The appointment of a decommissioning consultant to oversee the project is beneficial for larger decommissioning projects where existing staff have no previous experience in project management, especially where extensive dismantling is required. The decommissioning manager should oversee the cutting and dismantling work, to ensure optimized recycling and clearance of wastes is achieved.

For small facilities, existing maintenance staff can participate in dismantling of the structures that they usually maintain. Specialized services; e.g. advice of a structural engineer, will be required for heavy dismantling where the impact on the structure must be considered as part of building stability before any walls are demolished. Where large concrete blocks are to be moved, specialist contractors equipped with the correct equipment will complete the task more quickly, effectively and safely.

Early categorization of dismantled materials should be carried out. An initial assessment and categorization, with appropriate segregation relevant to further management needs to be implemented at an early stage. Adequate

TABLE 13. RECOMMENDATIONS FOR GETTING STARTED ON DECONTAMINATION

What requires decontamination?	Suggested method
Floor surface of sealed welded linoleum with a wax polish finish.	Use a conventional wax polish remover for floors and in most cases, this will also remove the surface contamination that did not penetrate beyond the wax finish. If residual contamination remains, use conventional methods of wet cleaning using an anionic surfactant cleaner, with the waste water volumes being minimized Abrasive steel wool can be used to remove areas of persistent contamination. If contamination has penetrated the concrete floor below in damaged areas of the floor covering, scrabbling is likely to be required to an appropriate depth. For isolated hot spots of contamination, it may be more cost effective to cut out these areas and remove them. For extended fixed contamination on floors that is difficult to remove, it is more cost effective to cut and remove the flooring material. When decontaminating floors, cover the cleaned areas with plastic after each working shift to prevent contamination settling onto the cleaned areas during the next working day.
Contamination on walls.	If the wall has an intact impervious paint finish such as acrylic emulsion or gloss paint, conventional wet cleaning methods with minimization of the water volume may be sufficient. If the paint finish is still contaminated, consider removal of the paint using either a chemical method, such as Nitromors (a mixture of methanol and dichloromethane) or paint stripper, or removal using a blow torch and paint scraper, taking due account of the suitability of the method for the area and compliance with all necessary safety measures. If contamination has penetrated the plaster beneath the paint removal by surface scraping or use of steel wool or sand paper or other mechanical techniques may be sufficient, depending on the depth of penetration. Always remove ‘hot’ spots of activity prior to decontamination of the extended area, to facilitate ease of activity measurement and to avoid spread of contamination from a high activity area to areas of lower activity. When decontaminating a wall, always start at the top of the wall and work downwards to avoid recontamination of an area that has already been cleaned. Never use acetone to remove contamination due to its explosive properties. To avoid cross-contamination of already cleaned areas of a wall, a fixing agent can be applied to the clean wall surface, so that any further dust settlement can be readily removed by using a vacuum cleaner.
Wooden bench surface.	If the bench has an intact varnish finish, initially use conventional wet cleaning methods with water volume minimization. If residual contamination remains, remove the varnished surface using a commercial varnish remover, such as Nitromors (a mixture of methanol and dichloromethane) paying due account to the safety precautions for its use. Alternatively an electrically operated wood plane, preferably with an attached dust collection bag, should be used to remove the surface of the wood to an appropriate depth if remaining contamination is extensive. If only small areas of contamination remain after wet or chemical cleaning, these can be removed with steel wool abrasive or sand paper.
Granite or laminate work benches.	The sealed surface of granite and laminate work benches usually requires simple washing techniques with detergent solution to remove surface contamination. Where the surface has become damaged and contamination has penetrated, mechanical removal techniques may be required.
Contaminated porcelain or enamelled sinks or sluices.	The first consideration is whether the surface of the basin is in good condition. If there are cracks or defects in the finish, complete decontamination may not be possible. For intact surfaces, decontamination with conventional detergents or CO_2 blasting may be suitable.
Stainless steel sinks or sluices.	Initially use conventional detergents. If this is insufficient to remove the contamination, a chemical method appropriate to the chemistry of the contaminant should be selected. A range of acids are suitable for chemical decontamination of stainless steel, such as nitric acid, sulphuric acid or citric acid. Where alkaline decontamination techniques may be more appropriate, consider use of alkaline permanganate, perhaps followed by ammonium citrate, or with addition of a chelating agent such as EDTA. A mechanical technique suitable for stainless steel is CO_2 blasting. Abrasives techniques using steel wool or sand paper may also prove effective.
Drainage pipes beneath sinks/sink traps.	Pressure washing or overnight treatment with a strong detergent or a surfactant anionic solution such as Decon 90, followed by continuous water flushing for 15 minutes is often sufficient to remove contamination bound to organic material, such as slime mould growing on the inside of pipes. Acid salts are useful for removal of contamination from the inside of metal pipes. Organic solvents may be useful to remove organic contamination from inside metal or plastic pipes. Oxalic acid solution is useful to flush out rust from the inside of metal pipes.

TABLE 13. RECOMMENDATIONS FOR GETTING STARTED ON DECONTAMINATION (cont.)

What requires decontamination?	Suggested method
Underground drainage pipes.	It is important to establish that such pipes are intact using telemetry or another suitable technique before carrying out decontamination that could result in further ground contamination if the pipe work is damaged or leaking. Many of the techniques mentioned above are equally suitable for underground drainage pipes. Where the pipe network is extensive, often pressure washing can be most effective, supported by flushing the pipe work with suitable detergents or chemical cleaning agents (Fig. 11).
Surplus laboratory equipment.	Consider at the outset whether there are any internal sealed radioactive source standards as part of the equipment, such as in liquid scintillation or gamma counters. These should be removed and appropriately managed. Consider first the possibility of biological contamination, especially when decommissioning equipment from a medical environment. Gamma sterilization may be a necessary precursor to decontamination. Small components can often be effectively decontaminated in an ultrasonic cleaning bath. A range of techniques involving use of detergents, acids or alkalis may subsequently be necessary. In complex designed equipment, it may not be possible to decontaminate it to free release.
Cupboards and other furniture/fittings.	Depends on the composition. For sealed non-porous surfaces, washing with conventional detergents may be sufficient to remove surface contamination. For wood, superficial contamination can be removed by use of fine sand paper or steel wool or removal of the varnish finish with a chemical varnish stripper. Greater penetration can be removed by mechanical sanding with dust collection or use of an electrically operated wood plane. Consider cracks and crevices not normally accessible while the furniture was installed, as past spills may have resulted in contamination behind parts that are usually accessible.
Glove boxes [33–35]	Prior to decontamination, all free standing objects must be removed. Must also consider possibility of non-radiological contaminants such as chemicals or biological hazards when selecting the decontamination technique for radioactive decontamination. Where non-porous surfaces exist, conventional cleaning methods with detergents, progressing as necessary to acid or alkali cleaners as required (dependent on the chemistry of the contaminant). Often the use of a hand spray containing detergent is sufficient to decontaminate glove boxes. In some cases, use of foam decontamination or a water jet may be appropriate. Although Freon jetting may be used for discrete parts inside glove boxes, its use is not recommended for environmental reasons. It is important to have a local ventilation extraction system in place such as a cyclone industrial vacuum unit, whilst carrying out decontamination. NOTE: When using a vacuum cleaner for decontamination of glove boxes and hot cells, radiation shielding of the filter in the vacuum system will be required due to the high radionuclide activity that will be collected on the filter, which if unshielded, would cause an unacceptable radiation exposure of the worker. When dealing with high radiotoxicity nuclides, such as plutonium, metal surfaces can be sprayed with a rubber peel fixative, which can then be peeled off to remove the contamination.
Hot cells.	Prior to decontamination, all free standing objects must be removed. Where high levels of contamination exist, the possible dose to the workers may necessitate minimum contact times. In such circumstances, an ALARA assessment may rule out decontamination and identify only cutting and removal of the hot cell as the optimized option. Hot cells generally have a stainless steel interior, making the surface suitable for decontamination by a whole range of detergent and chemical agents. Before using wet methods, an attempt to decontaminate using a damp cloth held in the manipulators can often prove successful. A range of special tools are commercially available for use with the hot cell manipulators, including a vacuum cleaner. High pressure or ultra-high pressure jet washing, or foam decontamination may be useful where doses do not permit more ‘hands on’ decontamination. Where alpha contamination is present, it is not recommended to use high pressure jet washing as this produces a large volume of liquid waste which is both difficult and costly to manage. Where lower contamination levels exist, use of organic, acid or alkali cleaners appropriate to the chemical nature of the contaminant should be selected. It is important to establish a local ventilation extraction system before decontamination of hot cells commences. For metal surfaces, where high radiotoxicity nuclides are present, such as plutonium, the surface can be sprayed with a rubber peel fixative to immobilize the contamination. The contamination is then removed by peeling off the rubber strip which has been fixed onto it.

TABLE 13. RECOMMENDATIONS FOR GETTING STARTED ON DECONTAMINATION (cont.)

What requires decontamination?	Suggested method
Ventilation ducting systems.	Prior to decontaminating a ventilation ducting system, it should be switched off and made safe to work on. A local ventilation extraction system, such as a cyclone industrial vacuum extraction unit should be in operation before decontamination work commences. An initial consideration is the accessibility of the ducting system. Only the base and the final exhaust part of the duct may be readily accessible for cleaning and characterization, hence necessitating a contingency aspect to the decommissioning budget (Fig. 4). The ventilation system should be decontaminated towards the end of the project task as the system is often needed to be operational during decommissioning. Hand saws or electrically operated cutting equipment may be required to remove and cut the ventilation ducting into manageable size sections to carry out decontamination procedures. A large tank containing a suitable chemical cleaner relevant to the chemistry of the contaminant in which cut sections of the ducting are immersed may be the easiest way to achieve decontamination. Other methods may include pressure washing, steam cleaning or foam decontamination. Keep ventilation systems operating until the end of the decontamination process if possible!
Medical devices.	Consider the possibility of biological contamination before proceeding with radiological decontamination. May require gamma sterilization before radiological decontamination can proceed. A surfactant detergent may be suitable for washing impermeable surfaces. For electrical equipment to be decontaminated for future use, take care in selection of wet decontamination methods. Match any detergents or chemical agents used both to the nature of the chemistry of the contaminant and the chemical composition of the material requiring decontamination.
Areas of wall or corridor tiling.	Consider the possibility that the tiles may contain NORM within the glaze finish; e.g. uranium, mineral sand, thorium or other pigmented glaze products. If so, discuss with the regulator the disposal options for NORM material. The tiles will require controlled removal rather than any attempt to remove the glaze finish, with careful attention to worker protection from sharp pieces of glaze that will break off during removal using a hammer and chisel or other suitable mechanical tools. A tented facility will be required to control airborne releases of NORM-containing dust. Where tiles require decontamination in situ, there is often a need to remove and replace the grout as any contaminants will penetrate porous grouting. Tiles can be washed with a range of detergents to remove surface contamination. Often use of a de-greasing agent will successfully remove most of the contamination. Where persistent fixed contamination is present, it is better to totally remove the tiles as this will be more cost effective. A wipe test will confirm surface contamination in the presence of NORM containing tiles.
Refrigerators or freezers.	Defrost the fridge/freezer and collect the water for laboratory assay. This provides information on decontamination requirements. Initial washing with a strong detergent or a surfactant cleaner such as Decon-90 may be sufficient.
Copper pipes.	Due to the commercial value of recycled copper, decontamination to clearance should always be the gaol. For short lived radionuclides, this may be achieved by natural decay but longer lived radionuclides will require cleaning. Hydraulic scissors or a hand saw can be used to cut the pipe into suitable lengths to facilitate decontamination. Note that hydraulic scissors close off the end of the pipe, so this is useful during removal, but the pipe will need to be opened up under controlled conditions to facilitate decontamination. In hard water areas, a 5–10% solution of citric acid can be used to remove lime scale deposits from the interior of copper pipe, followed by flushing with water, as the lime scale may have retained contamination activity. Organic cleaning agents, acids or alkalis or detergents may be useful, having been selected relevant to the chemistry of the contamination to be removed. For small diameter pipes, demonstration of suitability for release at clearance level is best achieved through random batch sampling for measurement.

TABLE 14. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES IN DECONTAMINATION

Failure to recognize the full extent of the contaminated area and related decontamination requirements due to an inadequate characterization.	Ensure sufficient radiological characterization planning is performed to avoid later problems. Due to inadequately scoping the project, there may be a need to backtrack and extend the boundaries of the area and revise the decommissioning plan. May need to review health and safety assessment. May need to do further characterization and likely to incur additional costs for sample measurements and work activities. Consider the need for new areas that will require decontamination.
Failure to adequately characterize the identified contamination.	Inappropriate selection of the preferred decontamination method may result in safety issues from release of vapours or undesirable chemical interactions. The complexity of the technique should be justified relative to the radiotoxicity and extent of the contamination.
Failure to use the simplest decontamination method before proceeding to more complex methods.	Workers may be subject to unnecessary hazards in completing the task. Task likely to cost more in terms of money and effort. May result in additional secondary waste production.
Failure to adequately remove residues of one decontamination chemical when switching to another one.	Could result in undesirable chemical reactions and unforeseen risks. Might produce a secondary waste that is difficult to dispose.
Failure to adequately research and test the technique prior to carrying out mock-up trials where uncertainties exist in decontamination techniques.	Unable to adequately refine safety assessment. Staff may not be as confident when carrying out the task, leading to additional risks and possible injuries. Decontamination may not be as effective. Application of inefficient techniques.
Failure to fully consider all of the characterization survey data when deciding on the decontamination strategy.	Inappropriate use of decontamination methods, leading to possible additional risks to workers, less effective decontamination, need for additional effort and incurring additional costs.
Failure to identify and provide the necessary training to the workers who will carry out the decontamination tasks.	Workers may incur injury, especially where mechanical techniques are used to remove depth penetrated contamination. Unacceptable risks to worker and unlikely decontamination will be as effective.
Failure to adequately consider in advance the production of secondary wastes from decontamination.	Waste volumes will not be minimized leading to additional disposal costs. Secondary wastes for which no regulatory authorized disposal route is authorized may be generated. There may be inadequate storage arrangements or safe further management options for the wastes generated.
Failure to decontaminate hot spots of activity first before starting decontamination of the extended area.	Difficult to accurately measure the true level of contamination on the extended area when hot spots of activity are present. Failure to decontaminate the hot spot first may result in spread of the higher level of contamination to less contaminated areas.
Failure to set-up suitable control barriers at the entrance/exit to the contaminated area with an area for changing into and out of protective clothing. Failure to recognize that decontamination activities can be associated with an increase in hazard impact.	Can lead to spread of contamination requiring an extended area to be decontaminated with production of additional waste and staff labour costs. If not considered could lead to spread of contamination and elevated exposure of workers and environment.
Failure to carry out decontamination before starting cutting procedures.	Spread of contamination and exposure of personnel. Operations will not be ALARA. Could lead to spread of contamination and elevated exposure of workers and the environment.
Surface decontamination of the wall started at the bottom instead of at the top of the wall.	As decontamination of the higher portion of the wall progresses, the lower part of the wall which has already been cleaned becomes recontaminated from aerosols of liquid or loose contamination debris falling onto it, causing the process to be less effective.

preparation for dismantling is essential and includes electrical and service isolation, emptying of tanks and associated facilities. Suitable arrangements need to be put in place for contractors to sign off that the preparatory work has been satisfactorily completed before the dismantling work commences — this might be managed through a ‘permit to work’ arrangement.

Prior to commencing dismantling operations, the aim should be to achieve regulatory clearance for as much of the constructed parts of the facility as possible. This has the advantage that non-radiological workers can demolish the walls under controlled conditions and the rubble will already be cleared for disposal. Consistent with other sections, Table 15 provides some hints for dismantling and Table 16 highlights poor practices in dismantling and their possible consequences. The suggestions provided in Table 15 are not intended to be prescriptive or to identify the best possible option in all circumstances. The more experienced worker may select options other than those suggested, whereas the suggestions provided are aimed at assisting the novice to dismantling during decommissioning.

4.6. WASTE AND MATERIAL MANAGEMENT

In preparation for decommissioning, all operational wastes will need to be removed and properly managed. If this cannot be achieved, the operational waste needs to be included in the decommissioning project.

The main objectives of waste management within the context of decommissioning are to:

- Minimize the quantities of radioactive waste at all stages of decommissioning;
- Prevent the mixing of waste of different categories;
- Comply with all applicable regulations in the handling, storage, processing and disposal of the waste.

The IAEA has published numerous publications that provide guidance on the conditioning and packaging of waste for storage and disposal that is generated from non-nuclear power operations [14, 24, 38–44]. A number of publications are also available to assist those wishing to quantify the level of activation products present in concrete and to assist them in understanding the limits of detection of various instruments [13, 45–49]. Record keeping is required for each step in the waste management chain [8]. Relevant safety aspects are also dealt with in another IAEA publication [3, 9, 24]. Guidance on internationally agreed criteria for clearance of solid materials was promulgated by the IAEA recently [17].

There may be additional risks associated with the management of decommissioning waste. This may have many of the characteristics common to operational wastes, but may have additional properties or features that necessitate different handling, processing and disposal techniques. The logistics related to the management of decommissioning material and wastes may overwhelm the newcomer to decommissioning, who may not have foreseen the large volumes of material and waste that might be generated in such a short period of time, once dismantling is underway. It is essential at an early stage to approach the operators of the facilities that will be receiving each type of waste from the decommissioning project (including any opportunities that exist for recycling or return to a manufacturer of sealed sources) and ascertain details of their waste acceptance criteria and any specific packaging requirements. It is especially important to understand any items that would be unacceptable for inclusion in the waste, as these can be segregated at source rather than having to rework waste packages at a later date. The waste and material need to be segregated at source by the producer in accordance with identified waste and material categories. Multiple handling of waste packages increases the doses to staff, increases the possibility of worker exposure to non-radiological hazards and adds to overall costs. Failure to correctly plan for the range and volumes of waste that might be produced might result in problems in safe storage pending measurement for release from site. Decommissioning activities should not be initiated until well defined waste management arrangements are in place, to include any new or revised regulatory permission, and the workers are fully trained in the implementation of the new procedures and any associated risks. In case of chemical waste, it needs to be properly identified and cleared for disposal to the appropriate route.

Once the waste is generated, the overall waste management plan generally includes most if not all of the following stages:

- Pre-treatment that includes segregation, collection and chemical adjustment;
- Treatment; e.g. volume reduction (compaction, combustion), decontamination;

TABLE 15. RECOMMENDATIONS FOR DISMANTLING

What requires dismantling	Suggested method
Laboratory bench.	Isolate any water, gas, electricity or vacuum air supply prior to dismantling. Decontaminate prior to dismantling. Dismantle using conventional cutting tools, such as a handsaw or powered cutting equipment. Hand tools such as a screwdriver will be needed to remove any securing screws/bolts to facilitate removal. Cut into manageable size pieces for packaging and disposal. For tiled benches, need to remove the tiles prior to dismantling. Consider removal of any inset sinks that will require disconnection and removal.
Ventilation ducts.	Ventilation ducts may be required until the end of operations. Dismantling should be made using normal assembly and maintenance arrangements. Start dismantling the ventilation system from the furthest point of containment measures. The ventilation system should remain operational during the early dismantling phase when it may be required to control significant contamination. The contamination of the ventilation system is a good indicator to past work that has been carried out. Consider the possibility of asbestos or other non-biological insulation; e.g. fibreglass or mineral wool that might be present when deciding on the appropriate dismantling technique. It will be necessary to switch off the section of the ventilation duct to be dismantled and seal off the ends with plastic bags or thin metal plate. Vacuum the duct to remove debris before cutting it into sections. The geometry of the duct (round or square) influences the ease of further decontamination; i.e. round is easier to decontaminate as there are no corners/crevices. Round shaped ducting is also easier to cut into sections than square section. Ducts may be at ceiling level, on or buried in a wall, or in the roof space, so the dismantling technique must reflect the ease of access. When buried in a wall in a corner, consider whether the duct is composed of steel or aluminium for cutting purposes. Need something to secure the ducting in place during cutting; e.g. electrical platform or scaffolding. If the duct is fitted with filters, these need to be removed and securely packaged at an early stage as part of contamination control measures. Where the ducts are located on the roof, scaffolding will be required as well as lifting equipment to lower any heavy sections to ground level. If the duct is plastic or textile, this will be light enough for manual handling. As soon as a section of ducting is removed, both ends should be sealed off with a plastic bag to contain any contamination inside the duct. Every ventilation system relies upon an electric motor which must be dismounting (very heavy) to check the cooling vent of the motor. Hand tools are suitable for dismantling, although lifting gear will be needed to set the motor down on a pallet at ground level, with plastic sheeting placed beneath it for contamination control. Where the ventilation duct to a single room is to be removed but the overall system is shared with other rooms, isolate the sections to be decommissioned to avoid contamination spread to the other rooms. Special gloves and eye protection is required when cutting aluminium or other metals due to the sharp edges and metal splinters.
Exhaust stacks from ventilation systems.	The issues to consider when dismantling stacks are similar to those for a ventilation system. Stacks may typically be concrete or metal so the dismantling technique must be appropriate to the building material. Check the stack with a suitable monitoring instrument to establish whether the filtration system was operational for the entire life of the building. If the stack can be cleared as free from contamination, the dismantling job can be given to a demolition contractor.
Laboratory fume hoods.	Prepare for dismantling by removing filters, isolating sinks; consider air, water, gas or electricity supplies to be disconnected and made safe. Often in old teaching facilities, the fume hood has a tiled work surface and a wood/glass front aperture. Remove all loose items, front cover, tiles, etc. Decontaminate remaining surfaces. The fume hood may be standing on a metal frame that will need disassembly or cutting. Sometimes a lead shielded storage area is built-in beneath the fume hood, used as a source safe. The lead bricks will be suitable for recycling once free of contamination.

TABLE 15. RECOMMENDATIONS FOR DISMANTLING (cont.)

What requires dismantling	Suggested method
Concrete walls.	If you have to remove concrete walls, you can clear the wall prior to dismantling. The wall can then be dismantled as cleared rubble providing criteria are controlled to prevent cross-contamination. Depends on the wall construction. If the wall is concrete panels, ideally these should be decontaminated for reuse. The securing bolts should be removed and individual panels should be lifted with suitable lifting gear, stacked onto a fork-lift truck with wedges placed between them, transferred to pallets in an area where they can be cleared for future reuse. Several techniques can be used to remove a contaminated concrete wall. Need to consider the presence of iron reinforcement in the concrete — if present, need to expose the metal and cut it out to break up the concrete. Several techniques and tools are suitable for breaking up concrete — diamond saw, drilling, diamond wire cutting, water jet cutting, or for large areas use a commercial digger. A series of wide holes can be drilled into the wall to weaken its structure, with a crow bar inserted into the holes to facilitate dismantling. A series of holes at 45^o angle downwards can be drilled into the wall and filled with expansive grout (drilled so liquid does not run out) to weaken the structure to facilitate dismantling.
Concrete floors.	Remove any floor coverings such as tiles or linoleum. If soil is directly beneath (instead of the expected concrete floor) collect soil samples and measure the activity to decide on further management. If a concrete floor beneath, scrabble off the first 5cm layer to see if this is sufficient to remove any contamination. Tools suitable for removal of concrete floors include circular saws, manual or electric pneumatic hammer drills. The concrete floor can also be broken up by drilling holes and filling them with liquid expansive grout (non-explosive), wait 12 hours, and expands to 8000 t/m^2 (max. pressure) and breaks up the concrete floor.
Pipes.	Isolate and check they are free of liquid or other residues. Often pipes contain historical sediments or fixed deposits (scale). Access to pipes may require excavation, or there may be the need to consider ground contamination from leaking pipes. If the pipe work system is pressurized, dismantle to release the pressure using a hand wrench. If the pipes are up in the air, find the lowest point of the pipe and carefully drill into it using a hand drill (non-electric) to check if anything drains out. Pipes at ground level should be similarly checked for any content prior to dismantling, although such checks are not possible where the pipes are entirely located beneath the floor. For small diameter highly contaminated pipes, drill a small hole and inject the pipe with plastic grout or expanded polyurethane foam and leave to harden, so that the pipe can then be cut and removed whilst keeping control of contamination. Specific tools required for cutting pipes include electrical shears for cutting small copper pipes or a range of saws, either manual or electric. Cold cutting techniques should be given priority over other alternative options; e.g. plasma cutting. Underground pipes can be cut with automated guillotine cutters (band saws). These automated systems can be programmed to cut automatically at fixed intervals without the operator being present and are useful where high dose rates are present. Cut lengths of stainless steel pipes can be further decontaminated using chemicals in an ultrasonic or chemical bath. Consider the cost–benefit before spending a lot of effort on pipe decontamination as disposing as waste might be the best option. Where pipes have electric cables running through them, manually remove the pipe and segregate the electrical waste. Hydraulic shears can be used to cut the pipe and close off the ends. A range of different tools can be used to seal off the ends of cut sections of pipes; e.g. nibblers or crimpers. Prior categorization for material processing requirements should be established at an early stage so that pipes are appropriately managed.
Roofing material (roofs and ceilings).	Roofs and ceilings are usually dismantled at a later stage in the dismantling phase of the project, along with ventilation systems. Before taking down a ceiling, vacuum to remove dust and contamination from its surface before taking the ceiling down. In old buildings, the ventilation duct often runs in the ceiling — this should be identified as part of the characterization. Where possible, aim to clear a roof or ceiling for disposal prior to dismantling. If the roof has concrete panels, lower by crane to ground level, fork-lift truck to transfer for further measurement and management. Large concrete roof sections can be cut using a diamond wire to make into more manageable sections. If hot spots of radioactivity are present on the roof, these can be manually removed using the most appropriate technique. The roof is always one of the last areas to be dismantled when fully decommissioning a building. The roof may be composed of bitumen asphalt felt and pebbles or a concrete roof with a bitumen sealant. Be aware that it can be problematic to dispose of concrete waste contaminated with bitumen due to the polyaromatics of the bitumen.

TABLE 15. RECOMMENDATIONS FOR DISMANTLING (cont.)

What requires dismantling	Suggested method
Hot cells.	Hot cells are usually associated with high risks, both radiological and non-radiological and should only be dismantled by experienced professionals. Specific precautions in the dismantling of hot cells are required. This necessitates some preliminary engineering work in respect of containment. It is generally necessary to wear a pressurized suit to dismantle a hot cell, and skilled professionals with the knowledge of how to safely work in this time and movement restricted protective clothing is necessary. In old hot cells, the lead windows may be so loaded with static electricity that you get an electrical shock, sufficient to prevent an individual working for several weeks. Initial decontamination should be carried out prior to dismantling. Often there are liners on hot cells which need to be removed prior to further dismantling. Often hot cells are made of stainless steel, which can be cut using angle grinders, plasma torch, nibblers and grinders, hydraulic or electrical shears. Thermal cutting tools should not be used where alpha contamination is present, and cold tools such as nibblers and grinders should be used as the method of choice, but it may be necessary to use an angle grinder. The vacuum system used when dismantling hot cells must be fitted with an HEPA filter. Beware that broken lead glass has very sharp edges. Where a hot cell is not scheduled for prompt dismantling, a permanent coating can be put on the walls to fix contamination.
Glove boxes.	The advantage is that these units are often free standing and are easy to remove intact to another area for controlled dismantling to be completed. The contamination risk is often high, so dismantling is best carried out in a controlled environment. The front face of the glove box is easy to break when using glove ports as it is often made of acrylic sheet. A sheet of heavy duty adhesive film should be placed over the acrylic so that if it breaks, it will be held in situ to avoid spread of contamination. The acrylic sheet is usually mounted in a metal frame, which is usually contaminated at the time when selected for decommissioning. This metal frame needs cleaning/decontamination prior to removal of the acrylic sheet to avoid spread of contamination. The gloves should be replaced with new ones to carry out the dismantling operation. Loose contaminated items or component parts of the glove box for disposal as radioactive waste can be painted or varnished to fix contamination to prevent spread of contamination when dismantling. The most contaminated part of the glove box will be the shielding. The dismantling technique depends on the size of the glove box. For small glove boxes, where the contamination risk is high, a ventilated tent and HEPA filter system should be erected around the glove box. The acrylic plate at the front is removed first prior to cutting up the frame. Frequent changes of gloves on glove boxes should be made during dismantling operations as often they become damaged.
Tanks.	A tank requires draining and drying prior to dismantling or removing intact. For large tanks, it is essential to ensure that there is not a toxic atmosphere before entering the tank. Full information on dose rates and any levels of contamination must be available for assessment before entering a tank. Prior to tank entry, it will be necessary to set-up a 24 V safety lighting system alternatively transformers, select appropriate protective clothing/equipment, set-up a ventilation system to supply fresh air and extract expired air (with an oxygen monitoring system). For small tanks, isolate the tank, drain and clean, cut up any pipes, decide whether tank is suitable for decontamination for clearance or disposal as waste. Consider metals recycling if suitable for clearance. For large tanks, consider the shape. Tank may have a V shaped bottom which is difficult to walk inside so need to erect a level working platform inside the tank. Clean inside the tank; any residual sludge needs to be removed and placed in drums. Require a suitable lifting system to hoist items into/out of the tank. Once the tank is clean and decontaminated (if this was achievable), cut into sections either from inside or outside the tank (as appropriate) using thermal cutting equipment. A problem exists where a tank is beneath or embedded in the floor. Such tanks require cleaning, decontaminating and then use of a large digger to get the tank out. It is worth checking whether the regulator will permit for the tank to be cleaned and decontaminated as far as possible, then filled with concrete slurry and left in situ. A transformer and 24 V lighting system should be used in tanks as the workers are not electrically shielded in this confined system and electric shocks must be avoided. There is also a need to consider and plan for emergency evacuation of employees before commencing work inside tanks, so that any necessary arrangements are in place should an incident occur.

TABLE 16. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES IN DISMANTLING

Failure to employ specialist contractors where heavy or specialized demolition work is required.	Use of existing workers for heavy demolition work may result in injury or unacceptable hazards. Work likely to take longer to complete. Need to carefully balance cost effectiveness before going down this route.
Failure to identify sufficient storage space to accumulate dismantled materials and wastes — initial, interim and final storage once segregated for specific disposal or recycling routes.	Project delays whilst materials and waste are managed for removal to free up space to proceed with further dismantling operations. Need to be able to sort and segregate radiological from non-radiological materials; e.g. electrical waste. Need space for package measurement and areas to hold different material categories pending disposal or recycling. Obstruction of buffer storage areas that inhibits work progress.
Failure to maintain equipment and fixtures pending dismantling.	Dismantling will be more difficult when bolted sections cannot be separated, hence require cutting to dismantle. Additional hazards to the workers and extra time required to complete the task. Need for revision of the safety assessment and consideration of requirement for a shielded enclosure whilst using cutting tools.
Failure to carry out mock-up trials where new tools or techniques are to be used.	Unable to finalize safe work procedures for the task and adequately refine the risk assessment. Inability to identify whether further staff training will be required to safely complete the task.
Failure to consider all of the environmental conditions that exist at the time of dismantling.	Could lead to undue stress of workers; i.e. thermal stress, leading to loss of concentration and possible accidents. Need to fully consider the physical parameters of the dismantling task and how these may interact with the environment and ensure all variables are considered as part of the risk assessment.
Failure to verify in advance by inspection, the published specifications of any tools or machinery to be hired to facilitate dismantling.	Hired equipment may not be fit for purpose or require modification for use, leading to delays and possible safety issues.
Failure to correctly identify and install adequate lifting equipment for the dismantling tasks to be completed, or failure to adequately check the current status of existing lifting equipment available at the operators site, which may be poorly functional, obsolete or does not meet current regulatory standards. Failure to check all support equipment needed for dismantling.	Delays in proceeding with decommissioning. Possibility of accidents from items being lifted falling due to equipment failure. Project delays and additional costs incurred. Safety issues need reconsidering and there will be a need to review and revise the safety documentation.
Failure to ensure any tanks are emptied, pre-cleaned and properly prepared prior to dismantling.	Increased possibility of accidents and injury of the worker, especially chemical or radiological contamination. Potential biological health hazard if liquids have been stagnant in tanks for many years. Needs to be stated clearly as a requirement in health and safety documentation and in the work procedures, with a work authorization sheet (permit to work) provided to the worker by the site manager verifying that the tanks have been emptied and prepared prior to commencement of dismantling operations.
Failure to ensure any electrical power and pressure systems are disconnected prior to starting dismantling operations.	Increased possibility of accidents and injury of the worker. Needs to be stated clearly as a requirement in safety documentation and in the work procedures, with a work authorization sheet provided to the worker by the site manager verifying that the power and pressure systems have been disconnected.

FIG. 11. Trade waste drain cleaned using water jetting system.

— Conditioning; e.g. immobilization, waste package preparation;
— Characterization needs to be performed at all relevant stages of waste management;
— Storage;
— Transport and disposal.

Details of the IAEA waste classification scheme can be found in Ref. [50]. Often radioactive wastes are classified using a system that is based on half-life and activity (or activity concentration), although other options may be selected if more appropriate to the circumstances.

Waste management procedures for the decommissioning project need to be established and documented, if not already available. Existing documented waste management procedures may require review and/or revision to take account of any new waste streams or increased volumes of waste arising from decommissioning, legislative changes that have occurred since they were originally drafted, or to take account of any amendments identified through consultation with the regulatory body. Consideration might usefully be given to the possibility of any biological hazards, including disease-causing organisms, which may be present especially when decommissioning of medical premises is required. The possibility of biological hazards might need to be considered in all facilities (wet areas, sewage systems, sludge in storage tanks, etc.).

The waste management procedures should identify any personal protective equipment that may be necessary and should be supported by a safety assessment. Where increased quantities of disposable protective clothing is to be used for the decommissioning work, their purchase and disposal needs to be considered, as well as management of the increased waste volumes pending disposal. Where a project is going to run over an extended period, it is prudent to evaluate whether the installation of a laundry facility to wash coveralls is more practical and cost effective when compared to using disposable coveralls and adding to the waste disposal inventory. As part of the overall budget for protective clothing, it is also important to include the cost of rental of isolated air suits where aerosols or airborne particulates that could result in respiratory inhalation are a problem.

Every decontamination technology will generate waste that will need to be managed, although careful planning and use of the most appropriate decontamination technique will minimize the production of secondary waste, often releasing much larger quantities of previously contaminated material as suitable for clearance [14, 17]. Minimization of the volume of waste generated is a standard consideration in any use of radioactive materials and is not restricted to decommissioning. The lower the volume of radioactive waste for disposal, the lower the disposal costs of the project will be. It is important to balance savings in the waste disposal aspect of the project budget with radiation exposures of the workers and cost of employment, as sometimes additional handling to reduce active waste volumes results in an unacceptable exposure or increased costs for waste disposal.

Appropriate use of decontamination technology might lead to reduced waste disposal costs. If further decontamination makes the waste suitable for recycling, this can have a positive impact on the decommissioning project. Lead and copper have a ready resale value from recycling. Even for steel and high grade steel, decontamination costs are more expensive than recycling the material. It is therefore essential to evaluate a cost–benefit analysis, comparing the costs of further decontamination vs. the benefits of clearance to recycling This exercise should be carried out at an early stage of planning for waste and material management.

Some decisions regarding the method of waste disposal will require prior agreement with the regulator. For wastes that either have no detectible radioactivity or contain only very nominal levels of radioactivity, disposal as cleared waste along with normal refuse might be permissible. However, using this disposal technique requires approval from both the regulator and the waste disposal facility that is intended to receive the waste. It is important to be able to demonstrate to the regulator both the levels of accuracy of the instrumentation used to make measurements at clearance levels and any error margins in the measurements that might result in the use of clearance being equivocal. Where the predicted waste volumes from a project are very small, the cost and effort input to demonstrate regulatory clearance levels have been met might exceed those for disposing of the waste as very low level waste (VLLW). This should be considered as part of the decision making process when identifying the segregation and waste management options for the project. Without a doubt, where larger volumes of waste for disposal are predicted, and the level of contamination is low and can be easily decontaminated to make the waste suitable for clearance, this should be the selected option both for financial reasons and best environmental option.

Early consideration should be given to all the categories of materials and waste likely to arise and their individual characteristics [51]. Materials and waste need to be appropriately segregated at the point of generation to avoid the need for further duplication of sorting and handling. The IAEA has a number of publications describing the different characteristics of the waste classes, but a particularly useful reference is Ref. [50] in which the IAEA has tried to promulgate a standard categorization for use across the Member States to avoid the confusion that exists when States define their own waste activity levels for the waste categories. Waste disposal routes often impose limitations on the properties of the waste that they will accept. These limitations often include the physical waste form, activity level and the presence and concentration of other non-radiological constituents. The low level waste repository in the UK has an extensive list of waste properties that are unacceptable, such as wet waste, biological materials, waste with corrosive or explosive properties etc. These factors must be explored in full before any license application is made to the regulator to accommodate the disposal of the waste streams arising from decommissioning.

It is important to carefully select any chemicals proposed for use in decontamination procedures. This is because some decontamination chemicals may generate a mixed waste; i.e. one that contains both radioactivity and hazardous chemicals or some chemicals can cause the mobilization of radioisotopes in the disposal site (complexing agents). Time could be spent investigating the opportunities that exist for disposal of mixed waste and the relative cost before any such wastes are generated. It could be that the disposal cost of this specialist waste makes it uneconomic to decontaminate the item, and instead it may be the preferred option to dispose of it directly.

Suitable instrumentation with a traceable calibration must be available for measurement of waste and materials. In some cases, existing monitors available in the laboratory will be suitable, but for more complex decommissioning projects, it may be necessary to purchase specific equipment, such as a Germanium detector. Where identified single radionuclide activity is present in soil; e.g. ^{137}Cs, a dose rate instrument suitable for measurement of ^{137}Cs, can be used and a formula used to equate the measurement made to a dose rate equivalent, subject to agreement with the regulator (as seen in the example given in Annex I.5. It is possible to derive a dose rate equivalent for the instrument that relates to the regulatory end point for ^{137}Cs in Bq/g. The expense of purchasing a Germanium detector is rarely justified when decommissioning a simple facility, but the costs are worthwhile when considering decommissioning of a larger research laboratory or more complex facilities such as a particle accelerator. For a simple facility, often a sodium iodide detector is sufficient.

An agreed method of compiling the records of the wastes generated from decommissioning should be included in the decommissioning plan, as approved by the regulator. Again consideration should be given to license termination, when the regulator will be seeking evidence in the final report that all of the wastes generated have been disposed of to the legally appropriate routes and that materials intended for re-cycling were managed by this methods. Table 17 provides a large, if not exhaustive, list of examples of poor waste management practices.

TABLE 17. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES IN WASTE MANAGEMENT

Failure to adequately categorize and segregate materials and wastes.	Additional resources will be needed to retrospectively solve the problem. Increased worker exposures due to additional handling requirements and waste disposal costs likely to be increased.
Failure to identify and apply for any additional authorizations or permissions to manage or dispose of decommissioning wastes.	Lengthy project delays whilst applications are made. Additional costs to obtain the permissions. May require services of an external consultant where a new disposal route requires quality documentation to be drafted that existing staff believe exceeds their capabilities.
Failure to provide sufficient storage arrangements for decommissioning materials and wastes.	Project delays and possible safety and security issues. Additional resource requirements that could exceed the decommissioning budget. Possibility for errors to occur in segregation of waste packages due to inadequate space to separate the different waste categories.
Failure to avoid the generation of problem wastes.	Loss of confidence by regulator. Possible safety and security issues. Additional resource requirements. May be left with a waste for which there is no existing disposal route, causing delays to license termination. Long term RAW storage may be required.
Failure to have available suitable instrumentation and formulae to identify, measure and quantify wastes.	Shortfall in project budget when additional equipment has to be purchased or need to employ an external approved contractor to complete the task.
Failure to achieve timely processing of decommissioning waste.	Delays in waste processing (accidentally or intentionally) can cause loss of information, deterioration of storage facilities for radioactive wastes, etc. As the cost of waste disposal increases constantly, disposal cost will be higher. The acceptance conditions for disposal could change and the waste characteristics may not meet the new conditions and its processing could be more expensive. The appropriate disposal space might not be available in the future and long term storage would need to be secured.
Underestimation of waste volumes due to insufficient characterization.	Lack of budget. Possible storage issue.
Failure to agree with the regulator waste storage arrangements as decommissioning progresses.	Work may be delayed as regulator may require removal of waste as it is produced, hence delays to the overall project.

4.7. HEALTH AND SAFETY

Health and safety must be an intrinsic part of any work carried out and is equally applicable to decommissioning as it is to routine work activities. There are a number of publications in this field [52–55]. Routine operations need to be covered in a comprehensive safety assessment, but it is unwise to assume that this operational safety assessment will be sufficient to cover all of the situations that might arise during decommissioning. Activities undertaken during delivery of the decommissioning plan might create a number of previously unforeseen hazards for the operators carrying out the work, for members of the general public, or even visitors to the site. These hazards might be the direct result of the physical state of the building, or due to circumstances in a particular room or arising from a piece of equipment subject to decommissioning. Additional hazards might arise from the technologies in use or changing environmental conditions; e.g. airborne contamination that might arise as decommissioning gets underway. The performance of a comprehensive hazard evaluation is essential prior to commencement of work. The hazard evaluation is likely to be more comprehensive if the operators and any external contractors who will participate in the project are invited to contribute to its development.

During dismantling of small facilities various hazards may appear either in isolation or jointly:

— Hazard of radiation;
— Hazard of work place contamination;

— Hazard of environmental contamination;
— Conventional hazards (biological, physical, chemical).

An integrated approach to management of hazards is essential to work safely. This is especially relevant when decommissioning small radiation facilities where the hazard from radiation may be less than conventional hazards.

Radiological hazards can stem from a few diverse causes such as:

— Radioactive sources not included in the inventory;
— Leaking radioactive sources or loss of shielding;
— Leaks of liquids produced during the operation of the plant;
— Piping systems containing radioactive liquids or sediments;
— Buried pipes with highly contaminated liquids which might be broken;
— Tanks with liquids or contaminated sludge;
— Accumulation of radioactive dust present in ventilation and filtration systems;
— Accumulation of a significant radioactive inventory typically in the form of contaminated and activated tools and materials/waste;
— Clean areas can be contaminated due to loss of containment; e.g. opening of closed systems, such as ventilation ducts, glove boxes, tanks, etc.;
— Decontaminated zones can be recontaminated due to personnel movement and material handling.

Not all of the hazards during decommissioning will be radiological. There will likely be construction hazards, engineering hazards, chemical hazards, biological hazards, thermal considerations, hearing and eye protection issues, and an increased potential for slips, trips and falls. Therefore the health and safety plan and the risk assessments and contingency plans must be adequate to deal with all such circumstances as are relevant.

When a site has both radiological and non-radiological hazards it may be a requirement of the Member State that each of the hazards is assessed separately. In some Member States, there is a requirement for a consolidated hazards assessment. Be sure to check which option is relevant for your project. Also be aware that the regulation of each of the above may be handled by a different regulatory organization, so it will be essential to consult with each of them in advance to ascertain their preferred method of calculating and combining hazards. Where explicit standards do not exist in a Member State, the regulator may operate to constraints, so be sure that you have a clear understanding of how to comply with them.

Hazards of environmental contamination are generally minimal for small facilities but should however be assessed on a case by case basis. In assessing an environmental impact, defining the affected environmental boundaries, which could be in close proximity, will be essential.

Once all the hazards have been identified, comprehensive safety assessment documentation appropriate to the project needs to be drafted, along with supporting contingency plans and the purchase of any identified protective clothing and equipment; all of which should be supported by relevant staff training and rehearsals of contingency plans. The preparation and communication of a relevant and appropriate health and safety plan is an essential part of any decommissioning project. It is essential that workers are trained in the potential hazards they might encounter, the procedures that have been established for protecting them from those hazards, their role and responsibility for implementing the procedures and the mechanisms that exist for them to raise health and safety concerns with their supervisor. Hazards are assessed so that they can be eliminated if possible. If hazard elimination is not possible, administrative controls need to be put in place to control and minimize their impact.

General measures of worker protection from hazards are:

— Appropriate use of engineering control; e.g. shielding, ventilation systems etc.;
— Planning of the work in detail to reduce the exposure levels and time (ALARA review/dose budgeting);
— Training and information of the personnel about working procedures and specific hazards;
— Surveys and sampling for individuals and defined working areas (note: the quality requirements for sample retention);
— Compliance with all relevant health and safety standards and written procedures;
— Appropriate use of personal protective equipment — PPE;

— Work practices aimed at minimizing exposure levels in the work place; e.g. storage of waste in isolated areas and frequent removal;
— Avoidance of contamination in the workplace also requires appropriate signage, zoning and access/egress control.

Where various options exist to perform a particular aspect of the decommissioning plan, an evaluation of the benefits of the methodologies should ideally be made (an ALARA assessment) and the most appropriate technique adopted for use. It is important to bear in mind that the final choice of methodology may not be the one that delivers the lowest radiation exposure. It could be that in trying to reduce radiation exposure, other hazards increase disproportionately; hence the optimized approach necessitates a slightly increased radiation exposure. Not only should non-radiological hazards that exist while the facility is operational be considered, because it is likely that the activities arising from delivery of the decommissioning plan will create new non-radiological hazards. Completing a comprehensive characterization survey may require investigating areas that operators do not usually access. This might involve removal of ceiling tiles in a laboratory which might expose the operator to asbestos in the tiles themselves or in the lagging applied to pipe work in the ceiling space between floors. Decontamination can involve use of chemicals or equipment that may never have been used on-site. Demolition may introduce a whole host of physical hazards, not least of which might include slips, trips and falls. Working in a confined space, from an elevated position or below ground surfaces that were never designed for personnel access can introduce a host of potential accident scenarios that will need to be considered. Issues such as extending utilities to the new work areas, erection of platforms, scaffolding or other structural supports, provision of adequate lighting (which might mean an enhanced level of lighting above that in existence or a new lighting supply where none exists), provision of simple communication equipment such as a two way radio, supply of breathable air in a restricted space, supported by heating/cooling methods will all be important. Some examples of poor management in this field and possible consequences are given in Table 18.

5. TERMINATION OF THE DECOMMISSIONING PROJECT

After the final objectives of the project have been achieved, specific activities are required to achieve closure. The main activities are the following:

— Final survey;
— Review financial management;
— Preparation of a project final report/records;
— Termination of licence/ licence revision.

5.1. FINAL SURVEY

The final survey is the last ‘hands on’ task in decommissioning, but the job is not completed until the final survey report has been written and presented/accepted by the regulator. The final survey needs to achieve two objectives. Firstly, it must demonstrate that the decontamination work and remedial action was effective, and secondly, that all of the actions in the decommissioning plan have been satisfactorily completed to achieve the end points for license termination or revision. The data collected during the characterization survey and implementation phase of the project should be used to scope the final survey. Where the data collected during the characterization survey identified areas that already met the standards for license termination, the final report should include the evidence to prove this. It will be necessary to demonstrate that the obtained data is valid. The IAEA guidance on closing a decommissioning project until and including site release and termination of nuclear licence is given in [56].

TABLE 18. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES IN HEALTH AND SAFETY

Failure to adequately integrate health and safety planning within the decommissioning plan.	Health and safety could be compromised leading to events or radiation exposures not being ALARA.
Failure to keep the safety assessments under review as the project progresses, especially following any agreed changes to work procedures etc.	Safety assessments may not be all inclusive, resulting in possible accident or incident scenarios previously not envisaged.
Failure to draft a comprehensive safety assessment that integrates both radiological and non-radiological safety.	The relevant importance of safety is not appropriately considered, resulting in safety issues not being properly weighted and managed. Unnecessary risk to workers.
Failure to coordinate health and safety for all workers, especially where both external contractors and in-house workers are involved in the project.	Misunderstanding of roles and responsibilities for delivery of health and safety, leading to unacceptable risks or adequate control consistent with ALARA. There may be additional RP requirements such as radiation passbooks for contractors working in the operators controlled areas.
Failure to adequately communicate revisions to risk assessments or health and safety procedures as the project progresses.	Workers unaware of the additional safety risks associated with the work, leading to possible events. Possibility of loss of confidence with the regulator or regulatory enforcement action.
Failure to correctly identify and specify protective equipment and staff training required for each stage of the decommissioning project.	Inappropriate checking and use of protective clothing. Incorrect use of protective equipment due to lack of training.
Overlooking the presence of chemical, biological or asbestos hazards.	Inappropriate management controls leading to disproportionate health and safety management.
Failure to comply with recommended inspection and testing periods for protective equipment.	Protective equipment may no longer be safe for use leading to staff exposure to unnecessary risks.
Failure to establish and provide appropriate protective clothing relevant to the selected work procedures.	Staff may be subject to unnecessary additional risks or doses may not be ALARA. For long term decommissioning projects, consider use of establishing a laundry service on-site for coveralls instead of using single use disposable coveralls in order to reduce waste volumes and disposal costs. Pay particular attention to ensure that where airborne contamination, especially alpha radionuclides, is present that operators are provided with isolated air supply suits rather than full face respirators which provide a lower level of operator protection.
Failure to adequately appraise the physical parameters of the chosen work procedures on staff well-being; e.g. temperature, dehydration when wearing a respiratory suit.	Insufficient rest periods may be provided, or staff wearing protective clothing may become dehydrated and lose concentration, leading to increased risks of accident/incidents.

The scope of the final survey may need to be discussed and agreed in advance with the regulator. In some Member States, the regulator may only require advance warning of when to expect receipt of the final survey report, so he can plan its evaluation and any site inspection into his own work schedule. Many regulatory agencies have issued screening values for assessing the maximum value of residual radiological contamination that can remain in situ at a decommissioning site — in some cases, these are radionuclide specific. In countries where radionuclide specific values exist for defining a decommissioning end point for unrestricted use, it may be difficult for the decommissioning laboratory to measure individual radioisotopes accurately where they are known to have overlapping energy profiles. In these circumstances, it is important to discuss the problem with the regulator at an early stage and arrive at a solution/formulae that can be used to satisfy end point criteria by measurement of the combined radionuclide activity. Much of the data required for the final survey report will have been identified from the decommissioning operation, although do not forget that the regulator will require evidence of removal and compliant clearance and disposal of the entire inventory, which may include toxic chemicals and sealed sources that have been recycled or returned to the manufacturer. The final survey report needs to convince the regulator(s) that all of the activities described in the decommissioning plan have been completed to the agreed end points. Evidence must also be provided of compliant disposal or release to authorized routes of the entire radiological and non-radiological inventory. Finally, it will be necessary to demonstrate that if any residual radioactivity remains at the facility, it meets the agreed end point criteria and appropriate records of the residual activity and any future financial liability for decommissioning to unrestricted release have been considered.

The regulator will evaluate the final survey report, and the licensee should ensure that he is available to answer any questions that the regulator may raise during his review of the final survey report. It would be sensible to have all of the supporting documentation generated during the decommissioning project filed in a logical way to facilitate ready retrieval and for access to this information to be readily available should the regulator wish to visit the site and inspect the supporting paperwork. In some cases, the regulator may perform (or contract a third party to perform) an independent verification survey to confirm the data recorded in the final survey report. Should the regulator find an area where additional decontamination is required, even though it is borderline for having met the end point criteria, it is often more cost effective to perform further minor decontamination work than try to argue the case with the regulator.

Where the decommissioning end point is for future restricted use of the facility, consider benchmarking the remaining contamination at the point of license revision/termination for inclusion in the final report, especially where there is a change of ownership, as this will aid in establishing future liabilities when the new use is scheduled for decommissioning.

Environmental regulation for the country in question may set either grouped generic limits or element specific limits for identified toxic chemicals, and these must be achieved to comply with the end point for decommissioning of the facility, as well as demonstrating compliance with any radiological standards. Table 19 identifies possible poor practices associated with the termination of decommissioning and possible outcomes.

5.2. FINANCIAL REVIEW

Throughout the project, and in closing out the project, it is helpful in terms of financial management to carry out reviews to check on the status of the budget. Where overspends have occurred, there may be an option to make savings elsewhere so the project can be delivered within the allocated budget. This financial close out is important

TABLE 19. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE WHEN CARRYING OUT THE FINAL SURVEY

Final survey does not include all of the areas included as part of decommissioning plan.	Incomplete report will be rejected. Need to complete all aspects of the decommissioning plan and make the data available to the regulator.
Final survey has inconsistent use of units when compared to previous measurements.	Difficult for regulator to reconcile data and have confidence that agreed end points have been met. Need to repeat work so that the final survey report will be approved.
Scope of final survey not agreed in advance with regulator.	May not include all of the required information for license termination so will be rejected as incomplete.
Measurements in final survey are not supported with appropriate background measurements.	Regulator will require additional work to be satisfied that clearance levels have been met.
All of the data and evidence to support license termination is not readily available on-site for inspection by the regulator as part of review of the final report.	The regulator will be concerned that all of the requirements for license termination may not have been completed, hence will require the evidence to be produced by carrying out further work as necessary.
Failure to clearly agree the clearance criteria in the presence of NORM.	Likely that the final survey results will lead to a requirement for further work before license surrender will be granted. Essential to clearly document any NORM activity and agree end point status acceptable to the regulator with this having been considered.

to ensure all of the creditors are paid using the residual funds. A final check of anticipated costs versus amounts paid is necessary to account for how the money was spent. This is not a statutory requirement as part of termination of the project, and will be of no interest to the regulator, but will be required by the management of the facility.

During preparation for decommissioning it may be necessary to create a financial reserve to complete the task; i.e. a ring-fenced funding arrangement. Where decommissioning is not to unrestricted use, the regulator may require some funds to be held in reserve into the future to meet the residual financial liability for the facility. Table 20 shows how poor management of financial reviews may lead to undesirable consequences.

5.3. FINAL REPORT

The final report of decommissioning is the documented evidence that the regulator will require when making the decision that all of the activities described in the decommissioning plan have been completed and the end points for license termination or revision have been met. The document needs to include evidence that the entire radiological and non-radiological inventory identified in the output from the characterization survey has been dealt with appropriately in full compliance with agreed waste management procedures and license terms. The final survey must clearly demonstrate that any residual radioactivity remaining at the facility or external to the building meets the limits agreed as the end point for the decommissioning project [56].

The close out requirements to be included in the final report may have been agreed in advance with the regulator and should all be covered in the final report. The final report forms the basis to initiate the process of license termination or revision. This may require the transfer of key-records to the regulator for archive storage. Be aware that the regulator is only likely to require receipt of a small sub-set of the overall documentation that will exist and a system must be set-up to archive and retain the remaining records for whatever period the regulatory agency or national legislation may require.

Typical contents of a final report include:

- End state;
- Record of events;
- Dose records for the project;
- Accounting for the full inventory;
  - Sealed sources;
  - Waste;
  - Recycled materials;
  - Other materials — non-radiological;
- Benchmarking remaining contamination where the facility is for restricted reuse;
- Lessons learned.

The licensee should anticipate that the final report will be subject to detailed evaluation by the regulator, who may choose to attend the site and independently verify specific measurements included as part of the final survey. The licensee will be required to keep all supporting documentation relating to the final report readily available should the regulator wish to review it. The regulator is more likely to agree to a prompt termination or revision of the license if any requests to attend site or review documentation are met with a timely response, with the licensee being readily available to answer any queries that the regulator may pose with a technically sound response.

TABLE 20. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE FOR THE FINANCIAL REVIEW

Failure to review the overall financial commitments of the project at project termination.	Not all of the creditors may have been paid. Remaining funds may be inadequate and an application for additional money may be needed.
Failure to agree a requirement with the regulator for a financial reserve for future decommissioning liabilities where the project termination involves restricted use of some or all of the facilities.	Problems when future decommissioning of the facility occurs. Funds may not be available to meet financial liability.

Effective planning for license termination is impossible without a thorough understanding of what standards and their basis the regulatory agency is seeking in respect of impacts on the workers, on the general public and possibly also the environment. In some cases, such as where protracted delays may occur in return of packaged spent sealed sources to the vendor, the regulator may agree to license termination subject to a conditional clause relating to the shipment of the sealed source. The final license termination will not be provided until evidence is provided to the regulator to prove that the source was shipped back to the vendor and was safely received. Where only partial decommissioning of a facility is to occur, the license termination documentation will only apply to the area included in the decommissioning plan, and a new or revised license will be issued detailing the more restricted area where radionuclide activities will continue into the future. Examples of the consequences associated with poor practices when terminating a project have largely been addressed in Table 19, which relates to the issues surrounding the final survey. Table 21 complements the information given in Table 19 by providing details on issues regarding the final report.

5.4. TERMINATION OF LICENSE/LICENSE REVISION

Termination or revision of the license is the last step once the final report has been accepted by the regulator. Termination and/or revision of the license is formalizing the process in order to implement a change of use of the facility and to apply new regulatory controls. The proposed new use of the facility after decommissioning defines the content and extent of the documentation/application for the licence or its revision once the final report has been accepted by the regulator [56].

License termination is likely to require the handover of some of the documents produced during decommissioning to the safe keeping of the regulator for his records. This will still leave an extensive range of records in the custody of the former licensee, which will require safe long term management. Adequate provision for the safe archiving of these records must be considered as the final stage of license termination or revision. It is important to check with the regulator how many years these records must be retained.

The regulatory aspects of de-licensing/licence revision are likely to vary in different countries. Sometimes it is necessary to terminate the operational licence and apply for a decommissioning licence before decommissioning can be carried out, and then to apply for a new license for continued use of the site after the decommissioning project has been completed. The licensing arrangements are likely to be more complicated where there is multi-facility/multi-ownership of a site. Where shared facilities such as ventilation and drainage arrangements remain operational after completion of the decommissioning project because they are required by the other user, any future liabilities when the remaining operations are decommissioned must be considered.

Where the regulator requires the facility to consider future liabilities for decommissioning as part of the license revision where decommissioning is not to unrestricted use, adequate arrangements in terms of both infrastructure and financial resources need to be put in place. Table 22 deals with operator-to-regulator interactions in terminating a nuclear licence.

TABLE 21. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES IN PROVISION OF A SUITABLE FINAL REPORT

Inadequate or incomplete final report.	Regulator will refer the report back to the operator to correct the deficiencies.
Inadequate records to support statements in the final report.	Regulator is likely to require additional work to be carried out and included in a revised report before the final report will be accepted.
Final report does not include information on how the entire inventory has been managed.	Final report will be rejected as incomplete. Further evidence of how the entire project inventory has been managed must be provided in the final report before it is resubmitted to the regulator.

TABLE 22. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE WHEN SEEKING LICENCE TERMINATION OR REVISION

Failure to obtain regulatory approval for any models or estimation methods to be used during the project.	Likely to face difficulties in satisfying the regulator that the end point has been achieved. Likely to require further work before license surrender or revision will be granted. If contingency provision in budget is already spent, likely to exceed project budget.
Failure to provide for future decommissioning liabilities as part of license termination/revision where the end point was not unrestricted use.	Funds will not be available when required. Regulator may require resolution of future arrangements before agreeing licence termination.

6. SPECIFICS OF INDIVIDUAL TYPES OF SMALL MEDICAL, INDUSTRIAL OR RESEARCH FACILITIES FROM THE VIEWPOINT OF DECOMMISSIONING PLANNING AND IMPLEMENTATION

Irrespective of the type of the facility, the following steps for establishing a decommissioning strategy are common:

- — Appointing or identifying a responsible person as the project lead;
- — Communicating with the regulatory authorities;
- — Establishing timing and schedules;
- — Gathering radiological data on the facility to be decommissioned;
- — Identifying the alternatives for decontamination and dismantling;
- — Identifying the alternatives for waste management;
- — Establishing the staffing and financial resources necessary;
- — Collating the records and archives.

For the simpler facilities, it is quite reasonable to anticipate that existing staff will be able to complete the decommissioning task in full compliance with all regulatory requirements. In some cases, this will require existing staff learning some new skills and attending further training. As facilities become more complex, it is often more cost effective to employ an experienced project consultant to oversee the delivery of the decommissioning task to both timescales and budget. Where heavy demolition or dismantling work is required, it is generally better to employ the services of workers experienced in these tasks as this option tends to be more cost effective both in terms of time and money, not to mention the safety aspects. The following sections provide more detail on the decommissioning of individual types of facilities addressed by this report.

6.1. A SMALL SCALE MEDICAL OR INDUSTRIAL RADIOTRACER LABORATORY

It would be unusual for such a facility to already have in place a decommissioning strategy or a cost projection for the costs of decommissioning. Nonetheless, this should not be seen as an obstacle to taking forward decommissioning of the facility for future unrestricted use. Often the skills and knowledge of the existing workforce can be redirected to take the task forward with the minimum of external intervention. It is important to understand the decommissioning requirement of the facility — is it cessation of radiotracer work altogether or relocation to another site, which necessitates planning simultaneously for decommissioning and the setting up of the start of the work at a new location.

Characterization of the facility becomes much easier when comprehensive records exist identifying that throughout the lifetime of the facility, only MBq quantities of two or three radioisotopes have been in use. Staff members are likely to be familiar with decontamination procedures for these radioisotopes as part of routine safe operation of the laboratory, hence will be able to carry out any further decontamination that might be required when the laboratory is decommissioned. Furthermore, the laboratory is likely to already have the necessary equipment to assay any samples that may be collected during characterization of the laboratory, given that the routine work of the laboratory is sample assay. The key issue is to speak to the facility manager to understand his expectations before speaking to the regulator to ascertain all that will be required in terms of regulatory compliance for the decommissioning plan.

At an early stage, some money will be required to apply for any regulatory permission required to take the project forward. The key problem in small laboratory decommissioning is often one of storage space for the dismantled laboratory fixtures and fittings pending their measurement and further decontamination (if required), before being disposed of as free release waste. The decommissioning plan is likely to be a relatively short document that will reference existing supporting documents from routine laboratory operations. The existing waste management plan will almost certainly require updating to take full account of all the waste streams and increased waste volumes that will result from decommissioning activities. The laboratory risk assessments will require a full review, as there will be a range of new activities occurring due to decommissioning. Further information on small laboratory decommissioning can be found in Refs [3, 4]. Some common issues that are often overlooked in laboratory decommissioning are:

— Failure to deal with contamination in fridges/freezers, with staff being of the belief that since radionuclide sources were always in boxes or packages when stored in the fridge or freezer, there will not be any contamination. It is wise to always defrost the fridge or freezer and assay the thawed liquid. This may reveal the presence of radionuclide contamination that must be further managed; e.g. tritium, which is highly mobile.
— Failure to consider the removal of the internal radionuclide standard from a gamma counter or liquid scintillation counter prior to disposal as scrap.

A case history for decommissioning of chemical laboratories is given in Annex I–1.

6.2. NUCLEAR MEDICINE DEPARTMENT

Nuclear medicine departments are engaged in in vitro and in vivo techniques for diagnosis and treatment of patients and utilize sealed and unsealed radioactive sources. A whole host of typically short lived radioisotopes are used for patient diagnosis and therapy, using in vivo techniques; i.e. the radionuclide is administered to the patient. These types of sources may also be used in medical laboratory diagnosis using in vitro techniques, such as radioimmunoassay. Nuclear medicine departments also use a range of sealed radioactive sources, typically for calibration of equipment such as gamma cameras, positron emission tomography (PET) scanners and radionuclide dose calibrators. Depleted uranium shielding may be used on the two ^{137}Cs sealed sources used for attenuation correction mapping with PET coincidence scanning using F-18. Across the range of medical facilities, nuclear medicine departments generate the largest quantity and widest variety of radioactive waste. A nuclear medicine department will typically receive a weekly delivery of one or more radionuclide generators, which may be subject to a return to manufacturer agreement after retention for a suitable period of radioactive decay once the period of medical use has elapsed. In countries where the radioactive generator is not returned to the manufacturer after a suitable decay period, the generator can be dismantled and useful components recycled; e.g. the shielding. Nuclear medicine departments also have liquid wastes, which might include surplus radiopharmaceuticals from in vivo diagnostic techniques or unused radionuclide therapy doses; e.g. where the patient administration is cancelled after the patient dose has been purchased. As many of these radionuclides are of short half-life, typically these liquid wastes will be held to decay prior to disposal, but must be accounted for in the total inventory as part of routine practice. The IAEA has produced a number of guidance publications on medical radioactive waste; e.g. [44, 57]. Most of this waste will soon decay to below clearance levels [14, 17] making it suitable for disposal as biological waste, which is usually pre-treated by incineration to destroy the biological hazards and reduce the waste volume, prior to disposal of the ash residue in a landfill site.

A number of high activity unsealed radioisotopes are used in radionuclide therapy, such as ^{131}I, ^{32}P or ^{90}Y. These radioisotopes are administered to the patient in activity levels ranging from MBq to GBq. Many of these patients are not required to remain in hospital but return home after administration of the radionuclide. Where it would be unsafe on radiation protection grounds to allow the patient to return home soon after the radionuclide is administered, these patients will remain in hospital, usually in suitably shielded rooms designated for radiation patients. Great care is taken to avoid contamination at the time of administration, although subsequent contamination of the patient’s bedroom or bathroom on the hospital ward may occur due to contaminated body fluids. Decontamination of the in-patient shielded en suite room at the time of patient discharge from hospital is generally undertaken such that if later decommissioning of the ward is required, contamination does not present a problem, although a comprehensive characterization survey will be required to confirm this situation.

Space for storage of decommissioning wastes is usually at a premium in medical facilities, so it may be necessary to secure additional storage before decommissioning activities can commence. In many cases, any radionuclide contamination will have been satisfactorily dealt with at the time that the incident occurred (to minimize exposure of the staff and the public in the nuclear medicine department), making extensive decontamination unnecessary at the time of decommissioning. It is not unknown for problems to arise in respect of locating the full inventory of small sealed sources that may have been purchased, such as ^{57}Co anatomical marker pens or ^{137}Cs resin sources used for radionuclide calibrator performance checking. Often such small sources that were previously lost are found behind installed furniture, such as drawer units, when they are removed as part of decommissioning. It is important not to overlook the small sealed calibration sources that may be in-built into some laboratory equipment such as liquid scintillation counters or gamma sample counters. The counterweights in some nuclear medicine equipment, such as in gamma cameras, may be of depleted uranium, so appropriate recycling arrangements for the depleted uranium need to be put in place.

It is not unreasonable for existing staff to plan for the decommissioning of a nuclear medicine department. Often decommissioning of such a facility must be planned to coincide with relocation of the services to a new hospital building, so it is likely to be easier if a single project manager with experience in provision of the patient service oversees the coordination of the timely completion of both projects. The key issue is to ensure planning for both decommissioning and commissioning of a new facility to coincide, ensuring all the necessary regulatory permissions and critical safety inspections are carried out. It is not unreasonable for closure of one facility for decommissioning (with transfer of equipment as appropriate) and commissioning of the new facility (ready to resume patient services) to be scheduled to occur within a 14–28 day period. Whereas the actual decommissioning and commissioning tasks will be completed within this short timeframe, this can only be achieved as the culmination of many months of careful planning and communication, with every participant clearly knowing and understanding their role and responsibilities and the timeframe in which they must be completed.

When decommissioning a nuclear medicine department, it is important not to overlook the need for decontamination of the pipes and traps on sinks and sluices that have been used for radioactive liquid waste disposal, including contaminated body fluids from patients. Furthermore, older hospital premises may still have historical sealed source lightning conductors on their roof, intended to discharge the effects of a lightning strike on the building. Appropriate decommissioning of such items from the roof, with disposal of the sealed source in compliance with regulatory guidelines, is essential. The regulator is likely to require sight of a certificate of disposal for the source at the time that the final report is submitted, prior to license termination. An example of a decommissioning project for a nuclear medicine department in Slovenia is given in Annex I–11.

6.3. A RADIOTHERAPY FACILITY

Radiotherapy is a multidisciplinary speciality which uses complex electrical equipment, such as medical accelerators or X ray machines, as well as radiation sealed sources, for the delivery of patient treatments. Radiotherapy plays a major role in cancer treatment and is given with either curative or palliative intent; i.e. to relieve the symptoms. The largest number of radiation treatments are delivered by external beam radiation sources. High energy X ray beams in the range 4–25 MeV from linear accelerators and to a lesser extent, ^{60}Co gamma rays from teletherapy units are the most common therapy treatments, although the use of particle therapy is also discussed later in this section. A lesser used (in terms of the overall number of patient treatments worldwide), but still very important aspect of radiotherapy treatments is brachytherapy involving the use of small sealed sources.

Low dose brachytherapy employs either manual or remote afterloading equipment, except for some situations; e.g. permanent implants such as ^{125}iodine seeds, or eye implants [58]. A large number of sealed sources may be used in a hospital for teletherapy and brachytherapy. The use of ^{60}Co teletherapy units as an alternative source of high energy photons for external beam radiotherapy has diminished in popularity and has largely been superseded by use of linear accelerators (linacs). As of 2008, it was estimated that approximately 3 300 teletherapy machines were installed in developing countries [58] and approximately 12 000 teletherapy machines remain in operation worldwide (data from the IAEA database, Directory of Radiotherapy Centres (DIRAC)).

There are thought to be in excess of 10 000 medical linear accelerators in operation in radiotherapy departments worldwide, which will require future decommissioning. For relatively modern linacs subject to early replacement, the manufacturers may accept the unit back as suitable for refurbishment prior to sale to another facility, although the sale value will be minimal due to the expense of refurbishment. Alternatively, some of the linac components may be usefully recycled as spare components for similar units in use elsewhere. A linac unit is suitable for extensive dismantling once the machine has been certified to be free of radioactivity. A dismantled linac will yield a substantial quantity of scrap metals which will be suitable for recycling; e.g. scrap copper, lead, steel, aluminium etc., although once again, the financial benefit will be relatively small compared to the time required to complete dismantling of the linac. Medical linear accelerators for patient treatments are usually mounted isocentrically on a C–shaped gantry. The significance of this mounting arrangement is that there will be a strictly limited solid angle of possible direct beam incidence on the walls, floor and ceiling of the treatment room, which will have been designed as primary shielding barriers. When decommissioning a linac, there will be a considerable amount of radiation shielding present in the target area of the radiation head. The possibility that depleted uranium may have been used as part of the shielding should be considered. In linacs used for treatments above 10 MeV, the potential exists for neutron production as a result of photonuclear reactions. Neutrons may also be emitted from elements heavier than bismuth by photon or electron induced fission, an interaction process which has no lower energy threshold but which is usually negligible, even in uranium [59]. Although use of megavoltage linacs may result in induced neutron activation in the walls of the treatment room and the radiation head of the linac when operating at energies above 10 MeV, such activation is rarely found to be a problem at the time of decommissioning, although might be more relevant on radiation protection grounds during maintenance of the linac head soon after it has been used for patient treatment. Nonetheless, the potential for contamination due to neutron induced activity should always be considered when planning for decommissioning. Further information on decommissioning of linear accelerators and the potential for neutron activation in concrete is given in Section 6.9.

Although external beam treatments contribute the greatest number of all radiation therapy treatments for cancer, the importance of brachytherapy treatments should not be overlooked. Brachytherapy sources are small sources in the form of needles, wires and seeds, that are placed either temporarily or permanently inside the patient, and may involve the use of a source applicator (when sources are to be placed in situ in the patient for a defined period and then removed). A large hospital may have an inventory of many hundreds of such sources and often a source custodian is appointed to ensure day to day accountability for the location of the sources. Two practical examples of decommissioning of a brachytherapy facility are given in Annexes 1.B and 1.D. of the IAEA Technical Reports Series No. 414 [4]. A particular problem remains in respect of old radium needles, which have not been used in medical treatments for several decades. Historically, radiotherapy departments used radium sealed sources for patient treatments but this practice was discontinued many years ago. Many of these old sources are now leaking and it is difficult to accurately quantify the radium activity. Even in developed countries, there is a paucity of facilities able to encapsulate radium sources to make them suitable for interim safe storage pending a repository being available for final disposal. The IAEA has published recommendations for the safe management of radium sources [60, 61]. See also Ref. [62].

Teletherapy machines typically contain high activity sealed sources of ^{60}Co, with an activity range of 100–500TBq. Historically, ^{137}Cs sealed sources were more commonly used in teletherapy, but its use has now greatly diminished and almost all of the ^{137}Cs teletherapy units worldwide have already been decommissioned. At present, there are only about 30 old ^{137}Cs teletherapy machines in use, principally in the Czech Republic, and these are being gradually decommissioned. The teletherapy sealed source is housed in a shielded head, which may contain depleted uranium. Removal and transport of such sources in their shielded housings requires extensive planning, often involving road traffic police and other transport regulatory authorities and may require specialist security arrangements. Contingency planning in the event that the vehicle might be involved in a road traffic accident is essential and must be considered within the overall decommissioning plan. Removal of the source out of the building might require the construction of specialist lifting equipment, which may necessitate closure of a road for a number of days both prior to and post source removal, whilst a crane is assembled and removed. Although the example given in Annex I–3 is from Turkey, similar theratron units have also been decommissioned elsewhere; e.g. in the United Republic of Tanzania and India.

In some countries, the larger activity sealed sources are subject to a leasing arrangement with the vendor, with periodic replacement of the sources timed to coincide with removal of the spent sources from site. For the larger sources used in teletherapy treatment machines, the replacement source is usually delivered to site complete with its shielded housing, making source changeover a slick operation that can be completed in a single day, hence necessitating the equipment to be non-operational for a minimum period. A specialist contractor is required for removal of teletherapy sources at the time of decommissioning of a facility. Although past incidents of loss of control of a teletherapy source have occurred, the likelihood of further incidents has been reduced by the more stringent regulatory regime and IAEA recommendations that have been made following such incidents. Methods to locate lost radiation sources are described in Ref. [60].

A less frequently used external beam therapy treatment modality is particle therapy, also termed hadron therapy or proton therapy. To date, only 34 particle therapy units are in existence worldwide although a further 24 facilities are either in the planning stage or under construction as of July 2010 (data obtained from the Particle Therapy Co-Operative Group, available on their web site at http://ptcog.web.psi.ch/ptcentres.html). Proton therapy is considered beneficial as an advanced cancer treatment because protons do not scatter much in human tissue and release most of their energy when they hit the tumour and deliver much less exit dose beyond the tumour boundary, hence minimizing damage to healthy tissue surrounding the target tissue. Proton therapy facilities typically have one or more treatment rooms located adjacent to a room containing the medical accelerator (typically a cyclotron or synchrotron). The cyclotron accelerates protons to 60% of the speed of light, facilitating the penetrating powers of the beam to reach deeply-seated tumours. A beam transportation line or other similar assembly will be used to deflect the proton beam from the cyclotron into the patient treatment room. The maximum clinical energy output of currently manufactured particle therapy equipment is in the range 230–250 MeV. Practical information on decommissioning of proton therapy facilities was unavailable at the time of drafting of this document, although the generic principles for decommissioning of megavoltage external beam therapy units and medical accelerators will be relevant.

Guidance on decommissioning a radiotherapy department can be found in Refs [3, 4]. As with any decommissioning project involving radiation, the appointment of a suitably qualified and experienced radiation protection officer as part of the decommissioning team is essential for the safe execution of the project. Examples of problems that have occurred in decommissioning a radiotherapy department include:

— Failure to check that the type tested packaging, intended for use to return the sealed source to the vendor or to send to recycling, meets current transport regulations;
— Failure to read the terms and conditions of a return to manufacturer agreement for the sealed source at the time of decommissioning (terms are often different during operational lifetime when routine source exchanges are made). Often the cost to remove the source as part of decommissioning of the facility and to load it onto a vehicle outside of the building must be met by the licensee. It is therefore essential to make adequate financial provision for this liability;
— Failure to check for neutron activated items in the radiotherapy treatment room;
— Failure to identify the presence of depleted uranium in shielding in the radiotherapy equipment or in counterweights, necessitating that part of the contingency fund is required to arrange for recycling or disposal if a recycling option cannot be secured.

Examples of decommissioning of radiotherapy facilities are given in Annex I–2, I–5 and I–11.

6.4. GENERAL RESEARCH LABORATORY

The term general research laboratory encompasses a wide range of laboratories that use small quantities of radioactive tracers or sources, including for the following applications:

- Medical and pharmaceutical research applications. These may be used in the study of metabolic and toxicological pathways leading to the development of new medicines;
- Veterinary research applications;
- Environmental pathway studies that involve the dispersion of pesticides, fertilizers and other chemicals;
- Basic and applied research in the fields of physics, chemistry, engineering and biology at universities and research institutions;
- Agricultural research in which sealed sources using isotopes such as ^{241}Am/Be and ^{137}Cs are used.

In all of the above applications, the monitoring and control of the radioactive material and radiation sources is difficult, owing to the changing nature of research projects and their applications. The problem of maintaining comprehensive records of all of the radionuclide uses within a facility becomes difficult when many of the staff may be employed on short term research grants and there is a regular turnover of staff. Possibly there is not a permanent staff member in post, who has the role of ensuring records are retained and archived for retrieval, to facilitate future decommissioning. These problems will impact upon the radiological characterization in decommissioning and waste characterization of the facility. In addition to general IAEA guidance [3, 4], useful information on decommissioning of a pharmaceutical research and development laboratory can be found in Refs [63, 64]. Lessons learned when decommissioning a medical research building were usefully applied when deciding the most appropriate strategy for decommissioning of a similar facility at a later date [6].

Where a lot of uncertainties exist from the laboratory characterization due to lack of past records, it is prudent to increase the size of the contingency fund, so that the decommissioning budget will be sufficient to provide for radiological or non-radiological hazards discovered once the project has commenced. The regulator may stipulate key holding points when either further dialogue or a site inspection will be required once uncertainties in the project are clearly identified and a way forward needs resolution, as part of agreeing any major revision of the approved decommissioning plan.

A problem common to decommissioning a general research laboratory is finding unlabelled sealed and unsealed radioactive sources/solutions in cupboards, fridges and freezers, for which no records are available. These items will require careful identification and characterization before they can be added to the inventory for further management. Where agricultural research has involved field trials with low levels of radioactivity, or accidents such as a fire involving dispersal of a radionuclide source has occurred, the remediation of soil or other ground contamination may be required. IAEA has published several guidance reports in this area [65–69].

Examples of decommissioning of general research laboratories are given in Annex I–1, I–8 and I–12.

6.5. SMALL RESEARCH REACTORS AND CRITICAL ASSEMBLIES

Critical assemblies usually consist of an array or pile in which the neutron multiplication associated with nuclear fuels can be investigated. As the fission product yields of such facilities are low, their radiological inventories are also low. Critical assemblies are generally classified as having power levels of less than 5 kW, and therefore their radiological inventories are low, with a resultant straightforward decommissioning strategy. Following the removal of the fuel, dismantling and waste management can be carried out under the radiological control procedures that would have been in place for normal operation. The removal of the fuel will require careful planning and will be the largest cost in decommissioning.

Small research reactors; e.g. having thermal powers less than 100 kW, will have relatively low radiological inventories after the spent fuel is removed prior to the start of their decommissioning and are therefore included within the scope of this report. Typical of these types of reactor are Argonauts, Slowpokes and TRIGAs. The radiological inventories of research reactors are usually not insignificant and the selection of the most appropriate strategy is a challenging process. Once the fuel has been removed, most of the remaining activity is associated with highly irradiated parts and components; e.g. reactor internals and vessels, or with components contaminated by strong gamma and/or alpha emitters, which require additional shielding. The necessary tools and equipment for remote handling and for shielding must be available and the requirement for their use needs to be identified within the decommissioning strategy. Careful consideration needs to be given to access routes during decommissioning of reactors, such that people and materials, including waste have the required controlled level of access into and out of the area. The radioactive waste management policy and the waste acceptance criteria need to be established before decommissioning of the reactor commences, as waste accumulation on-site can delay progress once active dismantling is underway and contractors are being paid a daily fee for the work that they do. The dismantling and size reduction processes often require significant investment costs, and sometimes infrastructure changes or modifications.

The dismantling and decontamination of research reactors will produce large amounts of waste of various categories. Most material released from dismantling will be either non-radioactive waste or potentially contaminated material that requires measurement prior to release at clearance levels [14, 17]. Often some decontamination will be required to meet clearance levels. A good example of decommissioning of the Jason Argonaut reactor (10 kW) is provided in Annex II–4.2 of Ref. [4]. See also Annex I–3 of this report.

For critical assemblies and small research reactors, the decommissioning strategy can be significantly simplified if the final removal of the nuclear fuel from the facility is planned and carried out under the provisions in force during normal operations. The decommissioning safety case will then need to focus on the decontamination and dismantling of the facility, in which most of the waste can be classified as short lived low and intermediate level waste, cleared waste or material for reuse or recycling with no radiological restrictions. The volume of low long lived intermediate level waste generated during decommissioning of small reactors and critical assemblies is likely to be very small, unless the fuel assemblies have been damaged.

The decommissioning strategies for critical assemblies and small research reactors may draw upon the experiences and lessons learned from the decommissioning of many similar reactors in recent years; e.g. [3, 4, 20, 70]. A useful checklist for decommissioning of small facilities is given in Appendix III of Ref. [4].

Examples of decommissioning of small research reactors and critical assemblies are given in Annex I–3 and I–8 of this report.

6.6. NUCLEAR RESEARCH LABORATORIES AND HOT CELLS

Research laboratories are usually associated with research reactors, universities and industrial facilities. Research facilities are typically equipped with fume hoods, glove boxes and/or hot cells. A wide range of radioisotopes and activities may be handled. Fume hoods are mainly used for low activity radioactive materials that present a low risk to workers and the environment. Fume hoods are associated with active ventilation systems which can become contaminated.

Material presenting a risk of inhalation for workers or a significant contamination problem for the environment is usually handled inside a glove box. Typical applications occurring inside glove boxes are the mechanical and chemical preparation of fissile material for fabrication of fuel or the handling of very low level activity radioactive material for radiological characterization. Fume hoods may be used for biological work involving use of radioisotopes, and in such circumstances, the biological risk at decommissioning may be greater than the radiological risk.

Materials that present a higher risk of both external and internal radiation exposure, due to the possibility of inhalation, ingestion or skin contamination, is usually handled in a hot cell. A hot cell usually consists of a stainless steel chamber surrounded by a radiation shield, which may be lead or concrete. It usually has a lead glass window for operator protection and radioactive sources are handled using tongs or manipulators. The hot cell is often operated at sub-atmospheric pressure. Typical work carried out in a hot cell includes characterization of higher activity waste and the packaging and sealing of radioactive sources recently produced in a high energy neutron flux reactor.

Fume hoods, glove boxes and hot cells have connections to an active ventilation system and may also have a connection to an active drainage system. It is essential when planning for decommissioning that these aspects are fully investigated and characterized. A ventilation system may contain asbestos products, or may have resulted in roof contamination at its exhaust point. Removal of the ventilation system for further management may require expert cutting into manageable sizes in a controlled environment. The drainage system may not be intact and identification of any leakage to ground must be identified before decontamination of the pipes releases current fixed contamination and adds to the ground remediation at a later stage. The spread of airborne contamination in the ventilation ducts associated with hot cells and glove boxes is also a potential issue for decommissioning.

Often decommissioning of hot cells requires employment of an experienced decommissioning project consultant and his team of workers. The existing workforce may have a role to play in laboratory measurements, collation of records, contributing to the characterization and further management of wastes for disposal

For decommissioning purposes it is important to record not only the type of contamination (beta, gamma and/or alpha) but also whether the facility was used for mechanical; e.g. cutting or chemical activities. If chemical activities are carried out inside a hot cell or a glove box, the residual material and equipment may be more difficult to decontaminate, especially if a buildup of radioactive substances occurs over many years of operation. Consider also that where cutting into manageable sizes is required prior to decontamination, the presence of chemicals might add to the possibility of fire or explosion or release of toxic fumes, so a comprehensive risk assessment is essential.

These facilities have common features when considered for decommissioning. They are likely to be contaminated with a wide range of radioactive material, which may have a variety of chemical forms that can influence their solubility and their ability to become airborne. Some materials can also have bacterial or infectious properties. Activation of enclosure walls or containment is not likely to be a problem. The facilities are likely to be extensive, covering large areas and numerous buildings. Soil contamination is also a possibility, especially at old facilities.

These facilities should be considered for decommissioning on a more urgent basis, ideally with a strategy of immediate decommissioning after shutdown or as soon as possible thereafter. Increased effort in care and maintenance of the facility will be required where immediate decommissioning is not the selected strategy, usually for technical reasons, such as the benefits derived from decay of short lived radionuclide activity that may be present. If necessary, some wastes may have to be safely stored until a disposal route becomes available, but this should not be viewed as an obstacle to making progress with decommissioning.

Reference [71] details the decommissioning of a radiochemistry laboratory in AECL, Chalk River Laboratories. The laboratory was constructed in 1945 and consisted of a 37 000 sq ft (3 300 m^2) building. The north portion of the building was constructed of 12” (30 cm) thick concrete walls on an elevated concrete pad with a wood truss roof while the rest of the building was constructed primarily out of wood framing perched on concrete piers. In 1947, two active exhaust fan rooms were added, in 1948 addition of concrete wells for fuel storage, a 1951 addition of a basement and office section which joined two buildings together, 1952 addition of a lab and a 1983 addition that expanded a laboratory within the building.

The radiochemistry laboratory was used for numerous experiments throughout its life cycle. These experiments included alpha and plutonium materials, mass spectrometer, active liquid waste experiments, accelerators and other fission product research. A safe shutdown plan document was prepared that detailed the requirements of the shutdown of the facility prior to turnover to decommissioning with both operations and decommissioning signing off acceptance of the plan. This project started in 2003 when transfer to decommissioning commenced. In 2005, funding was approved to proceed with the decommissioning of the radiochemistry laboratory. The first phase of decommissioning included removal of 37 vintage fume hoods, removal of laboratory benches, furniture and other debris left behind by the former building occupants. The work plan included the complete shutdown of building exhaust systems, air conditioning, mechanical and electrical services and isolation of any possible systems including telephone, fire safety systems and security systems, to minimize the potential of unplanned service interruptions.

Decommissioning of a laboratory in Germany is reported in Ref. [35]. Examples of decommissioning of nuclear research laboratories and hot cells are given in Annex I–4, I–8 and I–9 of this report.

6.7. FACILITY WITH SMALL PORTABLE OR MOBILE RADIATION SOURCES

These facilities include sealed radiation sources for medical, research and industrial uses, for example:

- Radiotherapy facilities, specifically for brachytherapy;
- For gamma radiography;

— For measurements of, for example, thickness, density, fluid level and humidity;
— Universities with small portable sources (calibration sources).

These sources can give rise to immediate hazards because of their small size, apparently benign appearance and sometimes high scrap value. Establishing the total inventory of these sources is often a problem and may be impossible to quantify accurately; e.g. for old radium sources [38, 39]. Spent sealed sources often pose significant hazards that must be addressed. When a radiation source is no longer to be used for its original purpose, a hierarchy of management options should be considered, with disposal as radioactive waste being the final option:

— Transfer to another user for application elsewhere;
— Return to the manufacturer or supplier;
— Storage for decay of sources containing radioisotopes with a short half-life, followed by disposal as non-radioactive material;
— Transport to a centralized interim storage facility, followed by interim storage;
— On-site conditioning of the source followed by interim storage until a centralized storage or disposal facility is available;
— Transport of the conditioned source to a disposal facility, if available;
— Final disposal in a licensed repository.

The preferable strategy for spent sealed sources is to send them back to the manufacturer although often this option is fraught with difficulties. It is not unknown for spent sources to be packaged ready for shipment out of the country for a number of years prior to the relevant regulatory and governmental bodies agreeing for the shipment to take place. Wherever possible, advice and assistance should be sought from the manufacturer in respect of the paperwork that needs to be completed to achieve the shipment of the source. It is essential that interim safe storage arrangements are made for the packaged sealed source until it can be shipped back to the manufacturer. Examples of current initiatives for the management of spent and disused sources are given in Refs [24, 61, 72]. Detailed recommendations for the steps to follow when adopting a shutdown and decommissioning strategy for a facility using sealed sources is given in Section 3.4.1 of Ref. [4].

Examples of decommissioning of facilities with small portable or mobile radiation sources are given in Annex I–8 and I–11 of this report.

6.8. FACILITY WITH HIGH ACTIVITY SOURCES INCLUDING IRRADIATORS

High activity sources are beta/gamma emitting radioisotopes with inventories of up to 100 PBq and are enclosed in thick metal or concrete shielding. Some are kept in pools to provide protective shielding when not in use. Their handling, transport and disposal are particularly difficult without proper equipment and training. A typical large irradiator would be housed in a building of possibly 30 000 m^2although the irradiated cell may only be 10–15% of this [54].

The most appropriate and usual strategy is to remove the whole source in a special package that is suitable and approved for transport to a major nuclear research centre or to a centralized facility that has the appropriate equipment [61]. The possibility of the reuse of the source at another facility may be considered but will be subject to regulatory agreement and the necessary licenses being in place before the transfer of ownership is made. The loss or theft of these types of sources is unlikely due to the engineering work and lifting equipment that is usually required to safely remove and handle these sources for transfer from site. Be aware that often the engineering work to remove the source and get it outside of the building ready for transport by road can be the most costly aspect of this type of decommissioning project. Where sources are located in basement facilities, it may be necessary to remove the lift from its shaft and assemble a crane to lift the source out of the building. It has even in some cases been necessary to remove part of the roof of a facility to assemble a crane to hoist the source complete with its shielded housing (weighing many tonnes) out of a building for scheduled for decommissioning.

Although not a common occurrence, the possibility of internal leakage of the source inside its housing should be considered prior to removal, as this can add substantially to the overall work and costs when decommissioning the source. Some facilities may become contaminated owing to an internal leakage of the source and consequently may require an alternative decommissioning strategy.

If the source itself is to be replaced with a new one for the continued operation of the irradiator, a strategy for its return to the vendor to coincide with installation of the new source is preferable. If this is likely to prove impractical, an advance plan should be available for safe interim storage until the source can be removed by the vendor. Absence of a viable alternative strategy could result in serious problems, both in terms of safety of the source and potential exposures of the workers. Details of the decommissioning of the Brookhaven National Laboratory Building 830 gamma irradiation facility are given in Ref. [7].

Examples of decommissioning of facilities with high activity sources including irradiators are given in Annex I–2 and I–8 of this report.

6.9. PARTICLE ACCELERATORS

Accelerator types include:

- Van de Graff accelerators;
- Linear accelerators;
- Cyclotrons;
- Synchrotrons.

All these accelerators have similar features and physical characteristics important for decommissioning. For decommissioning purposes it is important to stress that only charged particle accelerators delivering beams with energies higher than a few MeV per nucleon and a beam power of at least 100 W are able to induce significant activation in building structure materials. There are a number of useful publications that provide information on the estimation of activation products in concrete [45, 47–49].

In contrast to the generally well characterized waste generated in nuclear reactors, the characterization of contaminated or activated material in accelerator facilities may suffer from poor records of the experiments performed as well as of beam times, beam currents, the materials used and suppliers. The large volume of the materials used and a complicated nuclide inventory increases the problem of inadequate information.

For radiation shielding, accelerators are sometimes housed in large thick walled concrete structures and activation of trace elements in the construction materials gives rise to large quantities (possibly thousands of cubic metres) of low active waste. Decay periods to achieve conditions that will allow for removal from regulatory control can be several decades. Large accelerator facilities can become activated by neutrons to levels many times higher than the permitted release criteria (levels of up to 300 Bq/g have been reported). Masumoto et al reported that the maximum induced neutron activity in their accelerator building was 10 cm in the concrete and the radionuclides present were ^{60}Co in the range 0.02–0.04 Bq/g, ^{152}Eu at levels < 0.01Bq/g, ^{134}Cs, ^{22}Na at levels not exceeding 0.2Bq/g and ^{54}Mn at levels not exceeding 0.2Bq/g. The activity level of tritium was 1.3Bq/g. This report also contains some information on the surface dose to activity linear relationship and specific activity levels compared to regulatory clearance levels [47].

Activation levels in concrete and metal can be derived from separate alpha, beta and gamma counting of samples and control samples compared to the gamma spectroscopy values obtained. A state of the art detector can be quite good at detecting elevated background levels, particularly where there is a bulk concentration of activated solids, such as concrete and metals.

The selected option for decommissioning may be one of immediate or deferred dismantling to permit decay of radioactivity. Numerous IAEA publications discuss optimum or preferred decommissioning strategies [1–4, 20, 73] and there is an NRC publication on decommissioning non-fuel cycle facilities that discusses decommissioning alternatives [55].

Examples of decommissioning of particle accelerators are given in Annex I–7 and I–10 of this report.

6.10. A LARGE SITE INCORPORATING MANY DIVERSE FACILITIES

There are a number of large sites with diverse nuclear facilities in most of the industrialized countries that participated in the development of nuclear technologies. Many of these organizations are under State control and rely on a substantial commitment of government funding to be made available to progress a decommissioning strategy. Some of these facilities are old and have been waiting for decommissioning activities to get underway for many years, but often no clear strategy has been formulated. Furthermore the total resources required to fully decommission the site will be vast and are not readily available. Often the simplest way to make progress with such a complex decommissioning programme is to consider the task as numerous smaller projects, many of which will be relatively small uncomplicated facilities within a confined area. Such smaller individual projects could be satisfactorily progressed and completed to the satisfaction of the regulator whilst awaiting the results of mock-up trials to decide the way forward on some of the more complex areas to be decommissioned. Furthermore, utilizing the existing workforce to carry out the less complicated decommissioning roles whilst further planning proceeds for more complex and costly decommissioning activities that are likely to be completed by an external contractor workforce ensures maintenance of staff knowledge to adequately scope some of the further characterization of the facility.

The overall strategy being adopted for large sites is one of defining the problems and priorities, aiming for hazards reduction as soon as feasible. This is likely to necessitate extensive planning, with the work being progressed relatively slowly as funds and resources become available. The strategy adopted for each small decommissioning project can be taken from the various strategies outlined in earlier parts of this section, relevant to the type of work activity that was undertaken in that area. The role of coordination of individual projects taking place on-site to make best use of common services and facilities, such as waste treatment and interim storage, is essential and should be assigned at the outset. Large sites may take 20–30 years or even longer before they are released from regulatory control, making it essential that there is both adequate knowledge retention and transfer between key members of the workforce and effective communication. Such action will ensure optimized use of resources and will avoid duplication of effort.

There are many published documents on decommissioning proposals for large sites with diverse facilities, which identify the progress of the partial works during decommissioning that have been carried out [4, 37, 74–79]. For large diverse sites, the possibility of land contamination from past activities (including also the possibility of on-site disposal to land of radioactive materials) must also be considered. The IAEA has published a number of publications that provide useful guidance on this aspect of site remediation [65–69]. In 2005, the US Nuclear Regulatory Commission reported on the established fundamentals for decommissioning large diverse sites or portions of them [80]. It requires that a facility, or separate buildings or areas, be decommissioned if no principle activities are conducted for a period of 24 months. Experience has shown that the decommissioning of a large, complex facility can take greater than five to ten, or more, years to accomplish. The possible synergies and complications in decommissioning a multi-facility site are highlighted in [81].

An example of a large site including many diverse facilities is given in Annex I–8 of this report.

6.11. SMALL NORM FACILITIES

Only small NORM facilities are included in the scope of this report, such as:

— Facilities for thorium gas mantle production;
— Small scale fertiliser production;
— The mineral sands industry; e.g. titanium dioxide used in paints for the motor industry.

In these industries, the primary work does not involve use of radioactive materials, but the presence of NORM is coincident to the manufacturing process. Such facilities are likely to be registered as chemical manufacturing facilities rather than be subject to the radioactive regulatory regime of the Member State. In many Member States, facilities of this type will not require a regulatory license/authorization to operate their business, but once the facility is considered for a future reuse or demolition, decommissioning of NORM will be required and may require a license/authorization to be obtained as part of decommissioning.

Larger industrial processes, such as uranium milling and mining or NORM associated with oil and gas industry production, are outside the scope of this report which deals exclusively with decommissioning of small facilities.

An example of decommissioning of a facility that produced incandescent gas mantles is given in Annex I.6. Details of the problem and lessons learned from decommissioning a thorium gas mantle production facility are given in Ref. [82]. This reference relates to a company that since 1900 had produced gas lantern mantles with thorium, and other related equipment for camping/outdoor pursuits. Production was stopped because there was no longer a market for incandescent mantles as their use had been superseded by electrical street lighting and torches. Thorium was not used for its radioactive properties in the production of incandescent mantles. The production of gas mantles included their impregnation with naturally occurring thorium, which contains ^{232}Th as the radioactive isotope of interest. The thorium (a solution as $Th\ (NO_3)_4$) impregnation was essential to prevent the gas mantles from burning out too soon and to increase their light efficiency.

Early decommissioning efforts were made in the 1990s, but only existing production areas were considered. There was no historical review of the site undertaken as part of the characterization and no surveys were made of what were considered to be 'unaffected' areas. The decommissioning plan established DCGL's (derived concentration guideline levels) and a release level of 0.25 mSv (25 mrem) per year.

Early decommissioning was unsuccessful and so an external contractor was appointed who placed a part-time inspector on-site to oversee the project. Due to the absence of historical data, health protection techniques were used to characterize the facility and many previously unrecognized problems were identified. The surveys uncovered other earlier production areas. Hidden rooms under floors and alleys were found once demolition began as well as buried tanks (fuel oil and others). A further surprise was that mantle materials had been used as insulation and filler around windows and penetrations. There were undocumented sewers, a contaminated fire ring, a sump under solid floors and a disposal site was found under a building. It was identified that thorium travels through sand but not clay soil. Profile mapping of ^{232}Th activity in the five-storey building was made. Other problems also arose due to contamination from hazardous chemicals. Originally the plan was to recover the building for changed use, but the scope had to change from reclamation to demolition once all these extra problems were identified.

7. KEY CONCLUSIONS AND RECOMMENDATIONS

Taking forward any decontamination and decommissioning project is always so much easier if the planning process has been started well in advance of cessation of operation and adequate financial provision has been made. In many cases, no prior planning and budget provision had been made, or at best, only an outline strategy with proposals on how to secure funding existed. This should not act as a deterrent to making progress as costs are certain to rise and additional difficulties will occur when there is a protracted delay in taking forward decommissioning. Where an outline strategy and budget costing exists for decommissioning, this needs to be reviewed periodically and the cost projection increased relevant with market forces.

If time is of the essence, and there is a paucity of decommissioning experience within the existing workforce, the project will be progressed more quickly if the services of a suitably qualified and experienced project manager are secured. It is essential to fully research the market to ensure the most appropriately experienced consultant is appointed. Do not overlook the benefits and financial savings that can be achieved through getting the existing workforce fully involved in decommissioning, even when this necessitates provision of additional training. Do not be unrealistic in respect of the role of the existing workers when heavy demolition work is required. It is more cost effective to employ experienced demolition experts to remove concrete or large metal structures, than to train the existing workers for heavy manual labour that they are unfamiliar with. The following recommendations are not intended to be prescriptive. Their consideration may be of benefit when a newcomer to decommissioning is faced at the outset with what appears to be a daunting task, but with time, becomes an achievable objective.

Do not allow the absence of early planning for decommissioning to become an excuse for not making progress with the task.

Ensure timely communication with all relevant regulators, including making any necessary applications for licenses or regulatory permissions.

Do not overlook any requirements that exist to consult and apply for local authority planning permissions/licenses where relevant, in addition to nuclear regulatory license requirements.

Homework should be done before appointing a project management consultant to oversee the delivery of the project within agreed timescales and budget. Ensure his suitability as it can be costly and result in delays if a change of appointment becomes necessary once the project is underway.

Ensure timely identification and delivery of training. Ensure records are maintained of training provided.

Take time to thoroughly scope the project and complete a comprehensive characterization survey of radiological and non-radiological hazards. The benefits from adopting this approach cannot be overstated.

Where staff does not have the knowledge and experience to draft the tender document for appointment of an external contactor to carry out decommissioning, an external project manager should be appointed at an early stage, so that accurate information, especially in relation to waste estimates, appears in the tender document. This will avoid the contract being underpriced so that not all of the necessary work and waste disposal will be budgeted for.

Write the decommissioning plan to match the task — do not make it unnecessarily complex and only include actions in the plan that you intend to do. Make as much use as possible of suitably reviewed/revised existing supporting documents; i.e. waste disposal arrangements, laboratory decontamination methods.

At the outset, if required, ensure agreement of units of measurement and methodology to be used to derive; e.g. activity concentrations, as well as suitability of instrumentation and its calibration with the regulator(s). Ensure consistency of use of agreed units and methodology throughout the project.

Ensure a clear understanding and ability to accurately measure down to clearance levels. Clearance of material is essential to optimize waste and materials management throughout the project.

Set-up a decommissioning organization, which may consist of only a few individuals, with clearly assigned roles and responsibilities to avoid confusion or tasks being overlooked.

Establish clear lines of communication and maintain them throughout the project, especially when safety assessments or work tasks are reviewed and changed. Maintain appropriate dialogue with the regulators, but do not cause nuisance to the regulator by contacting him unnecessarily. The operator needs to demonstrate an appropriate level of self-sufficiency in delivering the approved decommissioning plan without further reference to the regulator.

When carrying out decontamination, fully utilize all of the characterization data to select the simplest, most appropriate method, moving on to other methods as required, having due consideration to minimization of secondary wastes.

For heavy dismantling, such as demolition of concrete walls or decontamination and cutting up of hot cells and alpha contaminated glove boxes, engage specialist contractors with proven experience in the field. This is a better use of resources compared to attempting to train the existing inexperienced workforce.

Mock-up trials and simulations should be used to establish optimized working practices for decontamination or dismantling when appropriate.

The simplest proven technology/tools for decontamination or dismantling should always be selected.

All stakeholders should be identified and appropriately engaged with throughout the project.

During the operational lifetime of a facility, safe retention and archiving of records should be ensured to facilitate easy retrieval. Scoping and characterizing a facility is easier if good records are available to support the task. The record system should also be sufficiently robust to permit archiving for retention of all the decommissioning documents that must be retained once decommissioning is completed.

A comprehensive options appraisal should be completed, supported by cost projections, ALARA assessment and safety assessment, where more than one option exists to complete the decommissioning project. Failure to do this could result in the regulator requiring more costly techniques that he/she is more familiar with to be used.

Nothing should be written in the decommissioning plan and all the supporting documentation unless it is intended to be done. The regulator will look for evidence of completion of all key stages of the decommissioning project before he/she will agree to license termination or revision.

View the decommissioning plan as a living document supported by cost projections and safety assessments. If a major change is agreed to with the regulator, as the work progresses ensure it is fully documented and the supporting documents are reviewed and revised as necessary, and properly communicated to all involved.

In the decommissioning plan, early removal of any sealed sources or high activity radioisotopes should be arranged to reduce the overall radiation burden on the workers.

Ensure the quantities and types of waste and materials to be generated during decommissioning are adequately scoped and that suitable arrangements for their segregation and storage pending further management are put in place. Failure to make such plans can result in delays in progressing the work and increased costs.

Decommissioning to unrestricted use should be the preferred option for facilities that cannot be reused, or where no future reuse can be identified. A phased approach to decommissioning may be the optimized strategy to achieve unrestricted use for larger more complex facilities.

For diverse facilities, in order to make progress, it is often better to consider the overall site as a number of much smaller individual decommissioning projects and progress each of these in turn, rather than focus on achieving decommissioning globally as a single project.

The extensive range of published material that is available as guidance for decommissioning should be fully utilized, taking special note of the lessons learned so as to avoid the same mistakes.

Specialized contractors should be used for tasks which require specialized equipment and/or skills.

Ensure adequacy of any lifting equipment to be used for dismantling operations. Beware of obsolete lifting equipment on an operator’s site that may be badly maintained and does not meet present day safety standards.

Ensure adequacy of any utilities required for decommissioning; e.g. electrical safety, sufficient lighting, supplied air etc.

Ensure adequacy of the structure of the building and the routes of access into and out of the facility for movement of waste, material and equipment; e.g. floor loading capacity.

As decommissioning progresses, it is often necessary to move the boundaries of controlled areas. Always ensure that these boundary changes are clearly demarcated with appropriate signage, and that relevant staff is personally informed of the change (and not by an email which might not be received or read!).

Always ensure adequacy of protective clothing provided to the workers and keep the appropriateness of the protective equipment provided under review throughout decommissioning.

Appropriate quality assurance standards must be consistently applied and audited throughout the decommissioning project. This relates to standards for radiation protection and contamination, waste management and instrumentation.

Ongoing surveillance of the impact of decommissioning on surrounding areas must be maintained throughout the decommissioning project. This may, for example, necessitate environmental monitoring or sampling.

Appendix I

EXAMPLE OF COMPLETED PRO-FORMAS FROM A SMALL LABORATORY CHARACTERIZATION SURVEY

TABLE 23. CONTAMINATION MONITOR MEASUREMENTS AND WIPE TESTS IN LABORATORY X

Floor plan Ref. No. for sampling and measurement	Description of location of measurement/sampling (Figs 12, 13)	Bq/^{3}H wipe test	Bq/^{14}C wipe test	Mini monitor serial No. D0000534 (CPS)
1	32 cm out from corner of alkali cupboard	58.0	53.6	200
2	275 cm from entrance door. 120 cm from wall	80.5	386	200
3	307 cm from door, 94 cm from wall	977	687	500+ OFF SCALE
4	Reswab of above	317	220	
5	Halfway between centre pillar of right hand *f/c* and centre island bench	292	28.7	3–5
6	2 feet from centre of link door	197	61.4	10–20
7	Older tile under 2nd pillar of left hand *F/C*	60.3	108	100
8	*F/C R316/1a/19* left pillar between water and gas labels	1543	6122	500+
9	*F/C R316/3a/11* right pillar top right of on/off switch	4.44×10^{4}	7.89×10^{4}	500+
10	*F/C R316/2a/20* right pillar 1" left of bottom socket	782	868	500+
11	Window ledge 10" in from door middle of radiator top	41.0	15.3	150
12	Lintel Of *F/C R316/4a/22* 20" in from window end	477	2588	500
12a	Reswab of above	98.2	36.7	
13	Drawers under drying oven bench left hand set, handles of bottom drawer	991	1942	200
14	Right hand set of drawers under drying oven bench top drawer 22.5 cm from left	477	197	500+
15	Drying oven bench 60 cm in from right already marked	77.5	364	500
16	Next to telephone	591	144	100
17	In front of end sink around red tape	935	75.3	500+
18	2nd cupboard right hand side centre benching left hand door 11.25 cm in 21.2 cm up	428	1003	500
19	1st cupboard left hand side centre benching left door, top right corner	6576	2484	500+
20	3rd cupboard under left hand centre benching left door 17.5 cm from bottom	682	898	500
21	Lab side of entrance door top of door handle	137	432	100
22	Source store floor 10 cm from left rear post	4241	3960	500+
23	Shoe rack in clean room front top	206	331	100
24	Clean room side of corridor mortise catch	114	52.1	100
25	Door to 2nd Lab (right) clean room side, edge and push plate	310	94.5	100

Legend: ‘f/c’ is an abbreviation for fume cupboard used in describing the location of sampling or monitoring points.

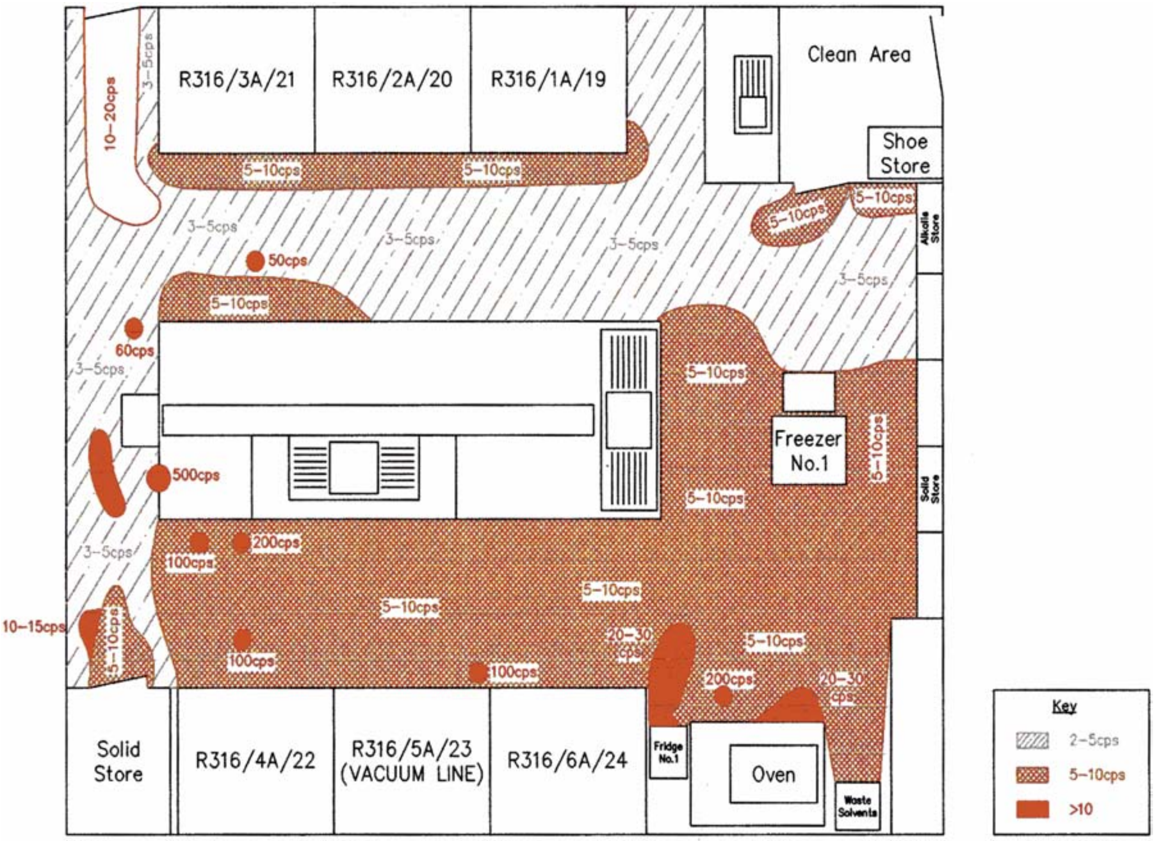

FIG. 12. Floor contamination monitoring survey for laboratory X (see Table 23).

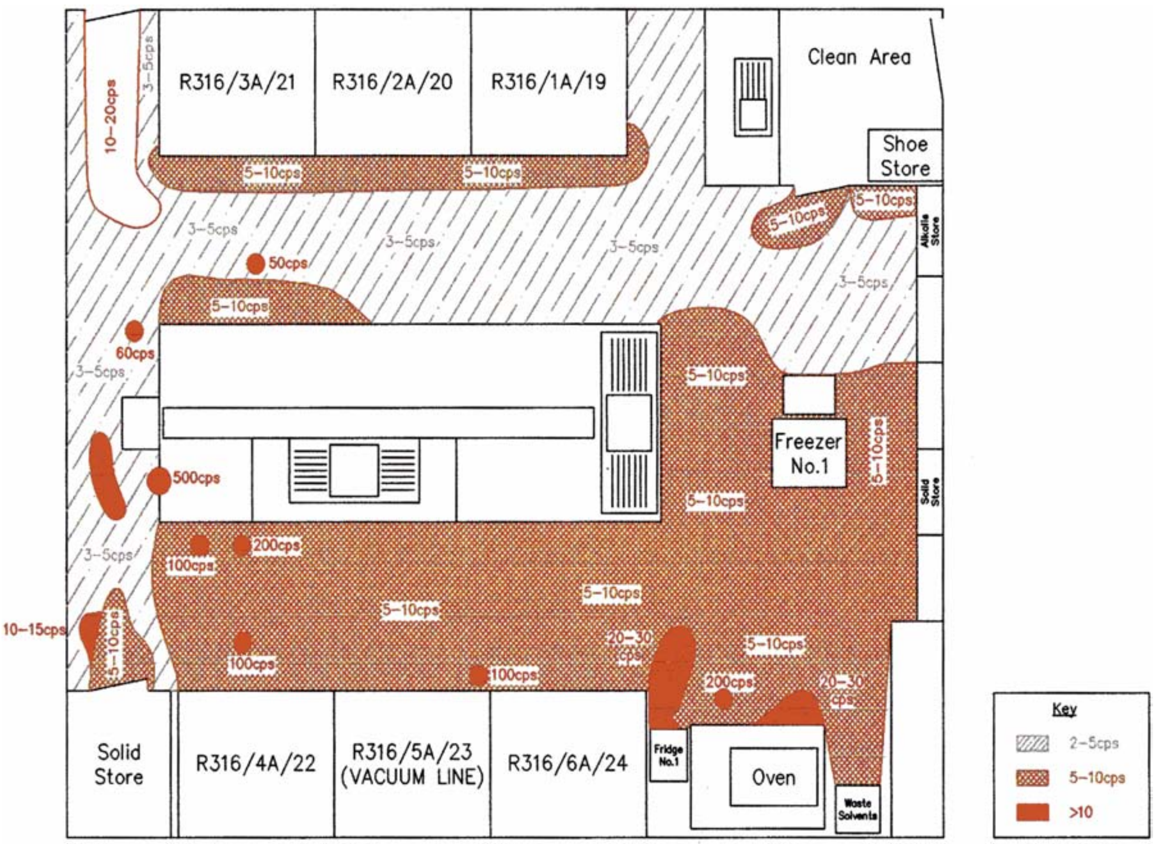

FIG. 13. Wipe test sampling points in laboratory X (see Table 24).

TABLE 24. PRO-FORMA FOR WIPE TESTS AND SURVEY MEASUREMENTS IN LABORATORY Y

Floor plan Ref. No.	Description of location of measurement/sampling *(see Figs 14, 15)*	Bq *I* ^{3}H wipe test	Bq/^{14}C wipe test	Mini monitor serial No. D0000534 (CPS)
1	Floor 20 cm from 318 entrance door pillar 3 cm out from s/board	11.2	318	100
2	Floor top corner of left hand bench (25 cm down)	1634	3500	300
3	Floor 20 cm out from top corner of left hand bench	490	1002	500
4	Floor 1 metre down from top corner of right hand bench	430	374	200
5	Floor 0.9 metre down from top corner of right hand centre bench 25 cm out from skirting board	83	400	200
6	Left hand glass fronted cupboard (end wall) middle shelf front, 15 cm in from left	592	1629	200
7	End cupboard (under glass fronted cupboard) right hand door top 3 cm in from opening	942	2052	300
8	Inside entrance door 5 cm above push-plate	322	170	200
8a	Reswab of above	190	102	—
9	316–318 link door just above lock	638	265	500+
9a	Reswab of above	358	198	—
10	Radiator 2nd in from right under air flow control	104	54	200
11	318–320 link door 5 cm from centre edge of push-plate	164	240	500+
12	Under right hand bench 2nd set of drawers from window top drawer	126	92	200
13	Under right hand bench cupboard nearest window right hand door top	559	554	500
14	Right hand bench top next to nitrogen outlet nearest window	437	1032	200
15	Right hand corner at front edge of sink basin	3.25 ×	9.55×10^{4}	500+
16	Floor under sink where leaking drain has dripped	2.74×10^{4}	1.59×10^{4}	500+
17	Skirting board top under left hand draining board	2461	1448	100
17a	Reswab of above	303	500	—

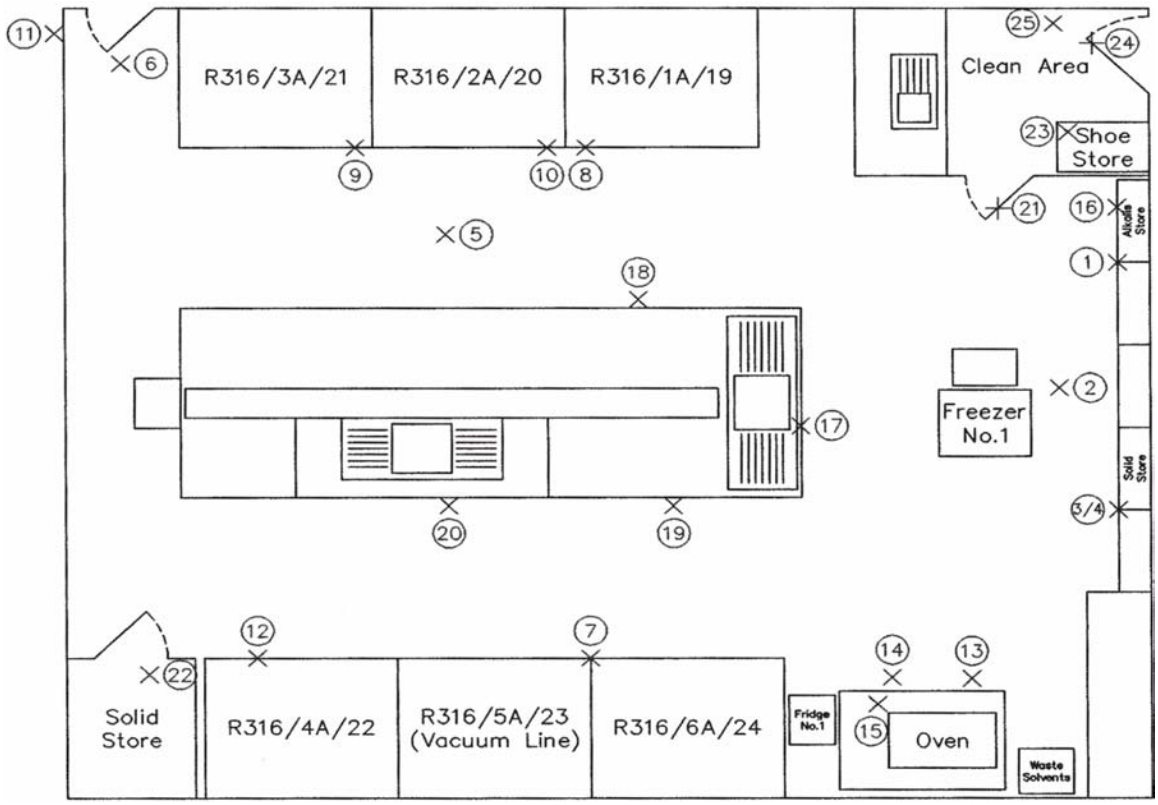

FIG. 14. Floor monitoring characterization survey results in laboratory Y (see Table 24).

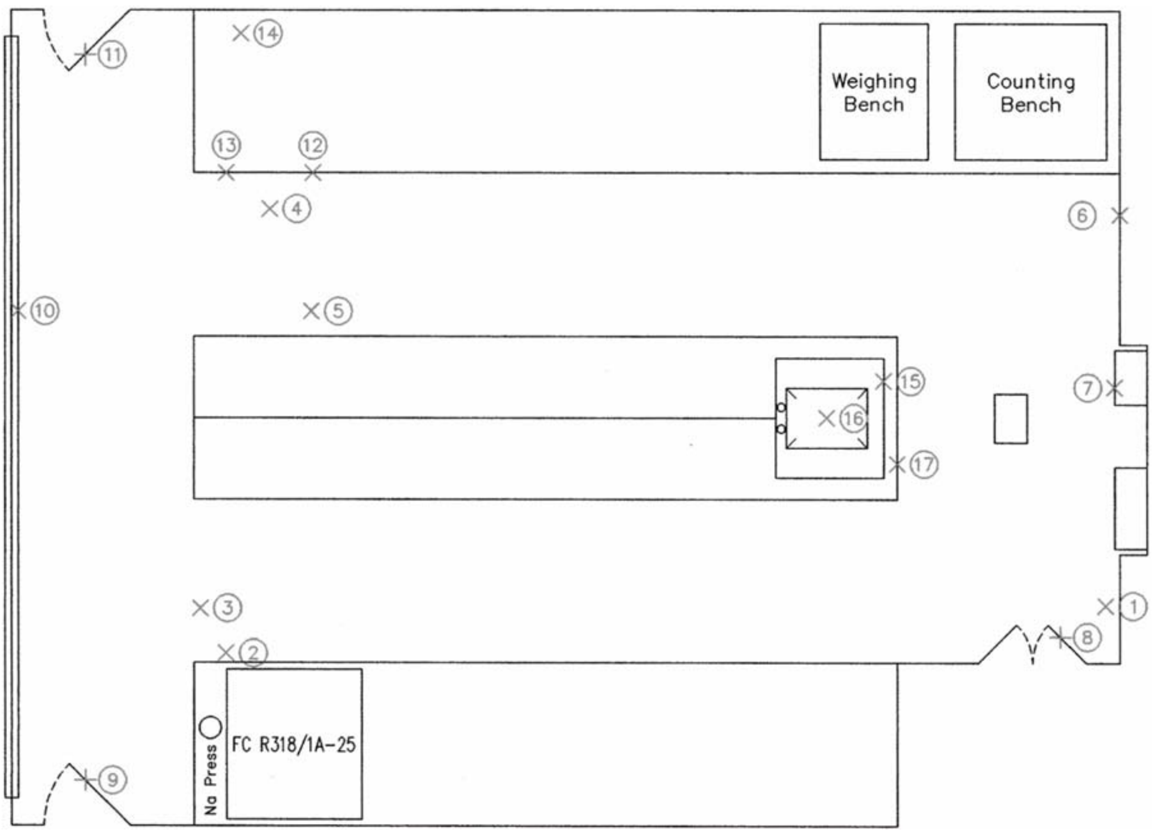

FIG. 15. Wipe test sampling points in laboratory Y (see Table 24).

Appendix II

EXAMPLE OF THE CONTENTS OF A DECOMMISSIONING PLAN

Section	Contents
Introduction.	Objectives, scope and goals to be achieved.
Description of the facility	Physical description of the site and the facility and its operational history. Inventory of the radioactive and toxic material.
Decommissioning strategy.	Objectives and decommissioning alternatives. Selection and justification of the preferred option.
Project management and planning.	Resources. Organization and responsibilities. Review and monitoring arrangements. Detailed estimates of waste quantities. Training and qualifications. Reporting and records. Risk and hazard management. Scheduling.
Decommissioning activities.	Decontamination and dismantling activities. Waste management. Maintenance programmes.
Safety assessment.	Dose prediction for tasks and demonstration of ALARA for tasks. Non-radiological hazards. Risk, hazard and uncertainty analyses. Operating rules and instructions.
Environmental impact assessment.	Demonstration of compliance with environmental standards and criteria.
Quality assurance programme.	Setting up a quality assurance and/or quality control programme. Verification of compliance with established quality assurance requirements.
Radiation protection and safety programme.	Radiation monitoring and protection systems. Physical security and material control. Emergency arrangements. Management of safety. Justification of safety for workers, the general public and the environment (use of ALARA).
Continued surveillance and maintenance.	Development of surveillance and maintenance programmes.
Final radiation survey.	Demonstration of compliance with the clearance criteria.
Costs.	Cost estimate. Provision of funds.

Appendix III

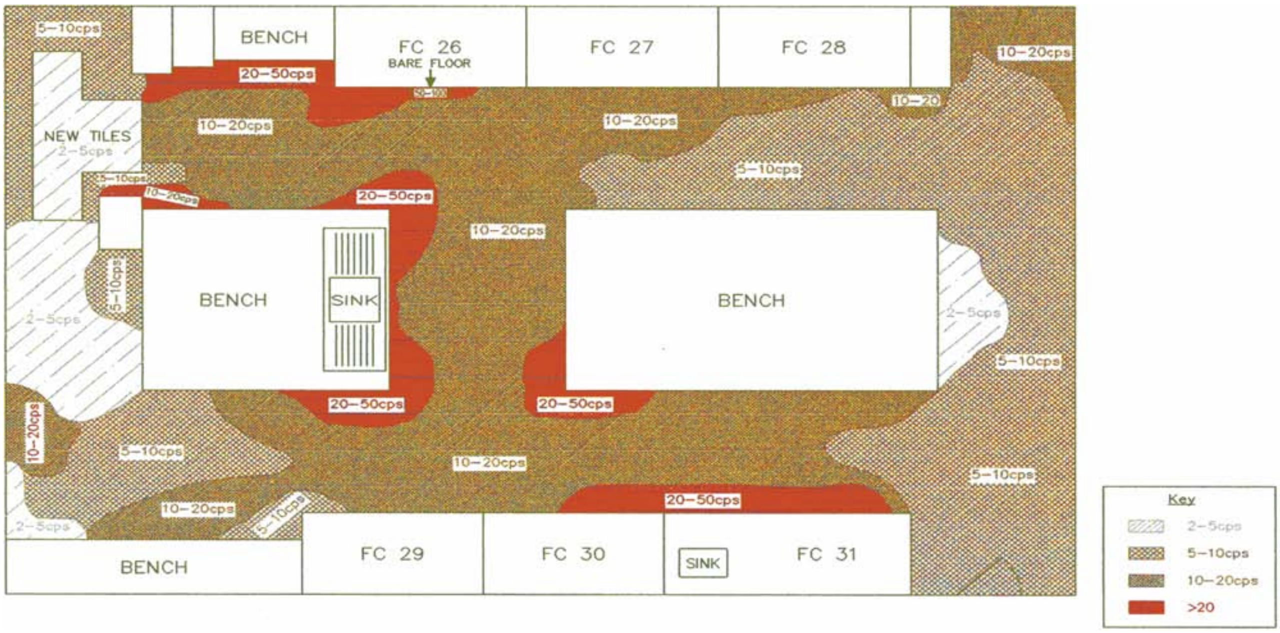

FIG. 16. Example of a laboratory floor plan from a characterization survey showing the areas that require decontamination.

Appendix IV

DECOMMISSIONING COST ESTIMATION COMPONENTS
Modified from the system used in Washington, USA

I. Decommissioning development

Labour fees for…

Historical facility assessment
and records review

Regulatory body interactions
(clearance criteria determination)

Required regulatory paperwork preparation
e.g. application for license or authorization as required

Specialized staff/contractor procurement

Specialized staff training

Decommissioning plan development including:
- Work plans and procedures
- Health and safety plan
- Quality assurance project plan

II. Decommissioning implementation

Scoping radiation survey and sampling and analysis
- Labour
- Expenses
  - Equipment purchase/rental costs
  - Consumables; e.g. gloves, containers, wipes
  - Analytical costs

Characterization radiation survey and sampling and analysis
- Labour
- Expenses
  - Equipment purchase/rental costs
  - Consumables; e.g. gloves, containers, wipes
  - Analytical costs

Decontamination and dismantling efforts
- Labour
- Expenses
  - Equipment rental
  - Consumables; e.g. PPE

Final radiation survey and sampling and analysis
- Labour
- Expenses
  - Equipment purchase/rental costs
  - Consumables; e.g. sample bottles etc.
  - Analytical costs

Waste management including sealed source disposition
- Labour
- Expenses
  - Supplies
  - (Waste containers)
  - Transportation costs
  - Treatment costs
  - Facility access charges
  - Disposal/storage costs

Miscellaneous
- Personnel protective equipment
- Insurance
- Taxes
- Miscellaneous fees
- Contingency fund

III. Decommissioning termination
- Labour for…
  - Analytical data reduction and validation
  - Final decommissioning report preparation

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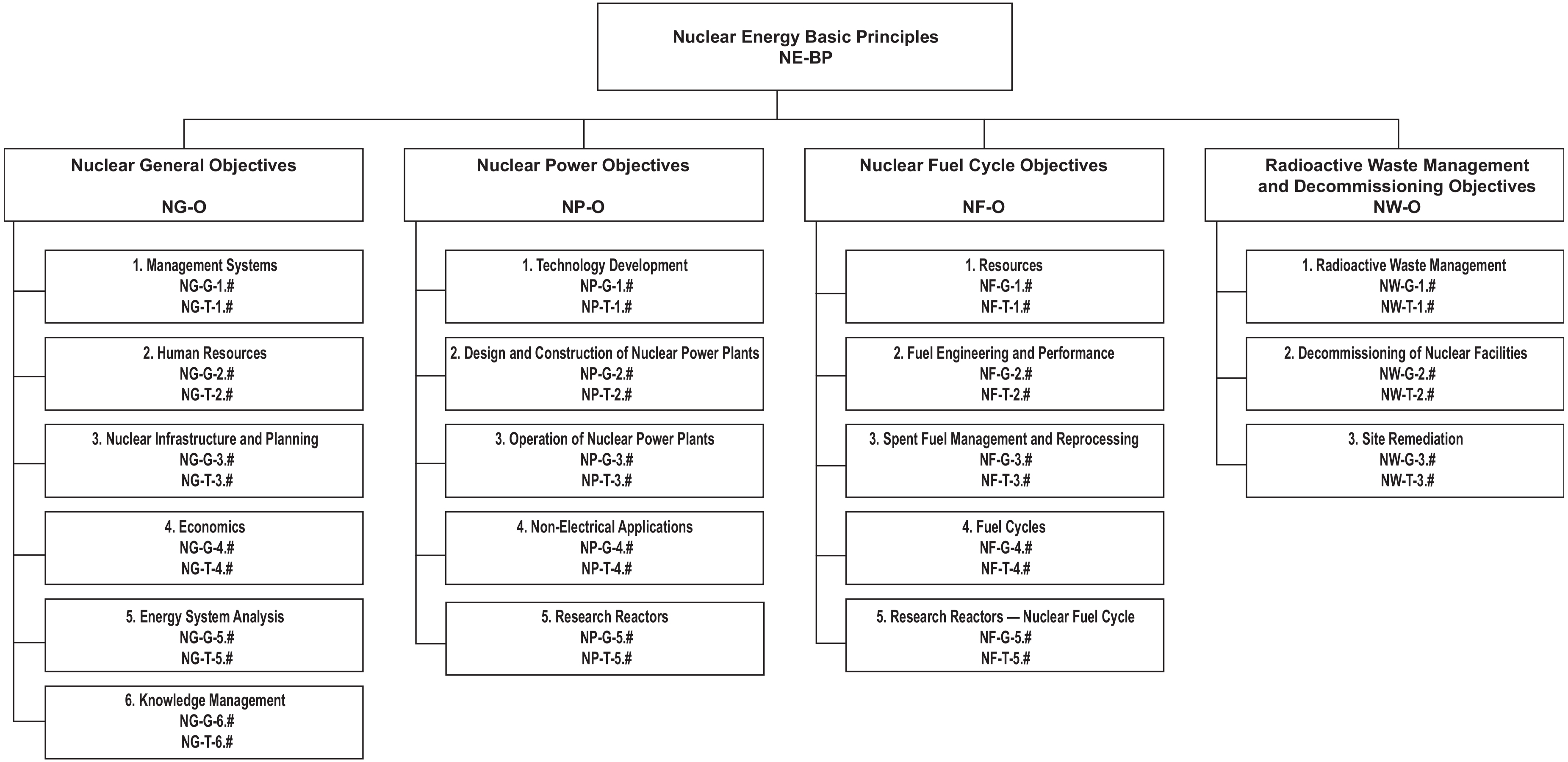

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