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DECOMMISSIONING OF PARTICLE ACCELERATORS

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DECOMMISSIONING OF PARTICLE ACCELERATORS

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

The advent of the first particle accelerators was prompted by efforts to study the structure of the atomic nucleus. Development and improvement of this new invention quickly leaped from 'smashing atoms' to a multitude of other practical applications. Although the largest and most powerful accelerators are used for high energy particle research, medical and industrial applications have been responsible for most of the accelerator proliferation in the 20th century and in the present. The most prevalent machines are electron linear particle accelerators used for radiotherapy; the use of proton and ion therapy accelerators continues to grow rapidly. Increasing demand for accelerator produced radionuclides in medicine, industry and research ensures expansion in this field. In research, the use of synchrotron and free electron laser light sources facilitates accelerator applications in a much wider array of scientific disciplines, from solid state physics to biology to archaeology, leading again to a steady growth of such facilities.

As for all nuclear facilities, decommissioning is the inevitable end of an accelerator's life cycle. The evaluation of potential challenges (including the radiological exposure of workers and the public), characterization, dismantling techniques, generation and management of radioactive waste, costs, and site reuse are all important aspects of the decommissioning process of any nuclear facility, including those housing accelerators.

In many countries, accelerators are not regulated in the same way as nuclear installations such as nuclear reactors or nuclear fuel cycle facilities, yet staff at accelerators may have less knowledge of waste management and decommissioning than staff at other nuclear installations. In some cases, accelerators have been semi-abandoned owing to lack of interest or an incorrect perception that their decommissioning is a low priority activity. Under these circumstances, even the minimum requirements and strategies might have been disregarded in decommissioning, resulting in unnecessary costs, delays and, possibly, safety issues.

This report provides practical information on the selection and implementation of decontamination and dismantling strategies and techniques for accelerators. It is written for those carrying out decommissioning with little or no experience in this discipline.

Owing to the number of accelerators and their ubiquitous distribution in IAEA Member States, the need to address the decommissioning of accelerators has been recognized by the IAEA. Although several guideline publications addressing radiological protection requirements during the operation of accelerators have been published, the decommissioning of these facilities has not been fully addressed.

This report is intended to contribute to the systematic coverage of the entire range of decommissioning activities within the IAEA's decommissioning programme. Following the initial draft prepared by the late E. Fourie (South Africa), a series of consultants meetings with international experts was held to review, amend and finalize this report. Special thanks are due to C. Griffiths (United Kingdom), who chaired two consultants meetings and reviewed the draft for publication. The IAEA officers responsible for this publication were M. Laraia and V. Michal of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Since the early 1930s, it has been recognized that accelerators are important research tools that provide great potential for development in industrial and medical applications. Accelerators range from thousands of smaller versions to the unique and gargantuan Large Hadron Collider (LHC). In 1994, the total number of accelerators was about 10 000; the progression rate is about 15% per year [1].

Today, nearly all IAEA Member States use particle accelerators, and tens of thousands of units are in use around the world making an essential contribution to human well-being and to many services and products used in daily life [2–4]. Over 97% of these accelerators are used for dedicated medical or commercial applications. Only a few hundred, mainly at universities, research institutes and international organizations, are used for scientific research. The most common accelerator applications include:

(a) Radioisotope production;
(b) Medical applications, such as the diagnosis and treatment of cancer;
(c) Sterilization of medical devices and food products;
(d) Mineral and oil prospecting using neutrons produced with small accelerators;
(e) Materials sciences and applications, such as modification of material properties, neutron activation analysis, fusion material testing and processing semiconductor chips;
(f) Fundamental and applied physics research;
(g) Archaeological dating, cargo inspection and research.

Manufacturing of user friendly compact medical cyclotrons has increased in the past ten years owing to advances in medical imaging instrumentation (positron emission tomography (PET), and more recently PET combined with computed tomography (PET–CT)). The additional supporting factor has been the recent decision in the developed countries that some of the PET radiopharmaceuticals are eligible for reimbursement either by the insurance companies or by their respective government.

PET plays a fundamental role in medical imaging, with a wide range of applications covering, among others, oncology, neurology and cardiology [5]. It is expected that this rapid growth will continue and that the demand for new radionuclides that can be applied in industry, as well as in medicine, will continue to expand. With this expansion, there will be a greater need for cyclotrons and the radionuclides they can produce [6]. Another growing area is related to light sources (synchrotron light facilities and free electron lasers) that span a wide range of research and industrial applications.

In accelerators, the typical charged particle reactions utilize electrons and protons, although deuterons, helium nuclei ($^{3}He^{2+}$ and alpha particles) and other heavier ions play a role. Radioactivity can be induced either by direct interactions of the primary beam or by indirect interactions of secondary particles in the surrounding structural materials, resulting in the production of a range of radionuclides. The specific activity of the radioactive materials produced in accelerator installations varies considerably, depending on the type of accelerator, the location of the material in relation to beam losses and the cooling time following activation; in most cases, it is rather low. Radiological characterization is an essential component of decommissioning planning. Computer codes have been developed to estimate accelerator activation; typical applications are illustrated in this publication.

The radiation emitted during the operation of high energy accelerators can interact with the surrounding region and may cause activation of the components and infrastructure. As a result, during the decommissioning of the installations, considerable amounts of radioactive waste need to be evacuated. In many cases, the decommissioning of accelerators is not emphasized and pursued with the same motivation as the installation and operation of the devices. In the early years of construction and operation of accelerators, the radiological hazards were not even recognized and did not receive the appropriate level of attention. However, when the hazards associated with the daily operation and maintenance of these facilities were identified, relevant radiation protection measures were implemented. A number of international reports [6–9] and documents have been compiled to address the radiological hazard and the management of the risks of operating and maintaining accelerators.[1] Activation results in residual ambient dose rates inside accelerator tunnels and target areas, which present a radiation protection challenge for decommissioning that is dealt with extensively in this publication.

It was not until the late 1970s that attention started to be focused on the generation of radioactive waste and the radiological hazards associated with decommissioning. By that time, thousands of accelerators around the world were already in operation. A wide variety of examples of national experience is given in Annex I. Annex II presents a brief history of accelerators up to the development of present day accelerators. One of the first comprehensive studies on accelerator decommissioning was presented to the international community at a 1979 conference in Sun Valley, Idaho, United States of America (USA) [10]. Since then, accelerators of all types have been decommissioned. Some of the earliest betatrons and cyclotrons to have been decommissioned were just disassembled using simple techniques, and their components were either reused for other purposes or sold as scrap metal. The energy and intensity of the beam in the early machines were generally very low, so any induced radioactivity would have been virtually undetectable except by very sensitive measurement techniques. Virtually no records exist for the decommissioning of early betatrons and cyclotrons, although accelerator components of some of the early machines can be found in the exhibition 'Atom Smashers: Fifty Years' at university museums and at the Smithsonian Institute [11].

As cases of early accelerator decommissioning projects are only periodically described in the technical literature, only a few detailed decommissioning reports from the 1970s and 1980s are publicly available.

In 1979, it was already estimated that there were more than 1200 particle accelerators in the USA, ranging in size from the very small Cockcroft–Walton and electron linear accelerators (linacs) to the multigiga-electronvolt research synchrotrons [12]. At that stage, at least fifty accelerators were capable of producing significant induced activation, and several hundred more were able to produce significant activation of a range of components at the accelerator facility. It was recognized that during decommissioning, some accelerators could produce low level radioactive waste. Argonne National Laboratory, under the auspices of the US Department of Energy, carried out a study of the decommissioning of five accelerators in the USA. The information obtained from these five decommissioning projects was used to evaluate the potential for reuse of accelerator components as part of a decommissioning perspective. The five accelerators and their decommissioning information can be summarized as discussed in Ref. [12]:

(a) *The 250 MeV synchrocyclotron operated by the University of Rochester.* Operation of the accelerator ceased in 1968, and it was dismantled in 1971. The steel mainframe was reused as shielding material, and the radioactive waste was buried, but very little information on the type of nuclides present in the waste is available. The facility building was left intact for further use by the university; thus, no analysis of the possible concrete activation was made. The highest dose rate encountered during dismantling was 1.4 mSv/h. The cost of decommissioning was US $104 500.
(b) *The Cambridge Electron Accelerator, a 6 GeV electron synchrotron at Harvard University.* Operation of this accelerator ceased in May 1973, and most of the removed components were shipped to other laboratories for reuse. The facility building was not demolished, and the highest dose rate encountered during the decommissioning was 1 mSv/h. The cost of decommissioning was US $735 200.
(c) *The 440 MeV synchrocyclotron at the Nuclear Research Center at Carnegie Mellon University.* The accelerator was shut down in 1969 and decommissioned in 1974 and 1975. The radioactive waste was disposed of, and the maximum dose rate was 1.75 mSv/h. The cost of decommissioning was US $504 000.
(d) *The heavy ion linac at Yale University.* The accelerator was shut down, and dismantling commenced in January 1975, almost immediately after the cessation of operations. Most of the major equipment was sent to other laboratories for reuse. The building was found to be radiologically clean. The cost of decommissioning was US $105 000.
(e) *The 3 GeV proton synchrotron at Brookhaven Cosmotron.* The accelerator was shut down in December 1966 and left in a standby condition for a year. It is claimed that this delay in the commencement of decommissioning activities resulted in a significant reduction of induced activity levels. The majority of the equipment was reused, and other material was released to scrap dealers.

[1] A list of relevant IAEA publications can be found at www.iaea.org/publications/.

A common feature of these five decommissioning projects was that the major components were identified either as suitable for reuse at other facilities or were shipped for storage at other accelerator laboratories [13].

A wave of decommissioning projects followed those previously mentioned. Over time, documentation on decommissioning planning, costs and lessons learned became available to the international community. As one example among many, in 1999 the European Commission issued the report Evaluation of the Radiological and Economic Consequences of Decommissioning Particle Accelerators [14], but that study was limited to accelerators located in the European Union. This is the first publication that systematically provides information and guidance on accelerator decommissioning that can be usefully applied worldwide. The decommissioning of accelerators is becoming quite common in developing countries, not just in developed countries.

1.2. OBJECTIVE

This publication is intended to provide information on experience and lessons learned from decommissioning projects for particle accelerators for all those having a role in this process and to highlight typical issues and concerns. It is intended for use by operators of accelerator facilities, particularly those approaching the decommissioning stage or maintaining a facility in a deferred dismantling state; regulators; waste managers; decision makers at government level; local authorities; decommissioning contractors; and designers of accelerators.

This publication also provides information on overcoming the typical decommissioning constraints arising from accelerator induced radioactivity in facilities and the associated waste management strategies and plans. It is anticipated that the lessons identified here will contribute to future consideration of decommissioning planning during the design stage of new facilities and therefore minimize the generation of activated materials and radioactive waste without compromising structural characteristics and the effectiveness of the construction. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.3. SCOPE

This publication provides information on the decommissioning of particle accelerators, with a special focus on those that are significantly activated or contaminated. The various types of accelerator in use at nuclear and industrial facilities, hospitals or research centres are identified, and how their design, construction and operational features affect decommissioning is described. Practical information is given on decommissioning strategies, organization and technologies.

The publication covers the decommissioning of particle accelerators, including all their systems and subsystems, but does not cover the associated facilities (e.g. research experimental halls, radiopharmaceutical and radiochemical laboratories). Although fusion machines are not accelerators, their decommissioning has a number of similarities to that of particle accelerators, and therefore Annex III includes a description of and decommissioning experience relating to such machines.

1.4. STRUCTURE

This publication has been structured so as to assist the inexperienced worker in following a logical stepwise approach to the decommissioning of a particle accelerator.

After this introduction, Section 2 expands on the world's inventory of accelerators, including the number, types and geographical distribution. Section 3 presents, for convenience, the classification of accelerators into four groups, largely on the basis of the energy range of operation of the machine and the accelerated particle type. Details of this classification are also presented. Section 4 covers the radiological characterization of accelerators for decommissioning purposes, using the categories defined previously in Section 3. Section 5 details the entire decommissioning process for accelerators, moving from the need for and definition of a strategy, to drafting a decommissioning plan, executing activities and conducting site release. Section 6 addresses the post-decommissioning reuse and redevelopment of accelerator facilities. Section 7 elaborates on the costs of and funding for accelerator decommissioning, including regulatory requirements in some countries. Section 8 provides information on decommissioning waste management, including treatment, packaging, transport, storage, and disposal options. Section 9 highlights health and safety (including the identification of both radiological and industrial hazards) and radiation protection aspects of accelerator decommissioning. Section 10 provides conclusions arising from practical experience. The publication is complemented by two appendices discussing examples of accelerators and decommissiong, a list of references as well as a bibliography, a glossary, a list of abbreviations, and three annexes providing detailed information and lessons learned from specific accelerator decommissioning projects, a brief history of accelerators and information on the decommissioning of fusion machines.

2. INTERNATIONAL DISTRIBUTION OF ACCELERATORS

At present, most small accelerators are used for medical or industrial applications, although the number of all particle accelerators worldwide exceeds 30 000 [15]. This is consistent with the number of particle accelerators published in 2012 [16] (data collection in 2010), when 24 000 industrial particle accelerators were reported to have been built worldwide over the previous 60 years. The breakdown of the cumulative number of industrial particle accelerators shows their applications in diverse fields: 45% ion implantation, 30% material processing, 10% electron beam irradiation, 5% radioisotope production and 5% neutron generation.

Accelerators are also used for environmental protection purposes, such as purifying drinking water, treating wastewater, disinfecting sewage sludge and removing pollutants from flue gases [3]. Industrial accelerators continuously offer new applications and improved qualities and enhanced capabilities, thereby making them cost effective. Their impact continues to grow as they have the potential to address key economic or social issues.

It is very difficult to obtain inventory information about accelerators worldwide, because in most countries accelerators are not licensed and regulated in the same manner as nuclear installations, such as power reactors, nuclear fuel cycle facilities and research reactors. Usually, if accelerator facilities are regulated, it is not by the same regulator as for the other nuclear installations mentioned. There is also commercial competition among accelerator vendors, and they tend not to readily supply information about their customers to protect their own interest in future installations and ongoing contracts for maintenance and supply of replacement parts. In 1999, the European Commission sent out 266 questionnaires in an effort to compile a database and received only 91 responses, achieving only 40% of the data collection hoped for [14, 17].

In August 2003, the IAEA tried to compile an inventory of the status of particle accelerators that might require decommissioning in the near future [18]. The list was not comprehensive for the above mentioned reasons.

The lack of systematic information with regard to accelerator numbers, types and applications worldwide was recognized as a concern. The IAEA assembled a database [5] called the IAEA Database of Ion Beam, Spallation Neutron and Synchrotron Light Sources in the World. This database contains technical information on accelerator based facilities used for applied research and analytical services in IAEA Member States. It was compiled using information publicly available from other IAEA databases, research institutes in Member States and accelerator manufacturers. The wide variety of machine technologies in use today, both modern and earlier, is better categorized according to the accelerator manufacturers' terminology, which is widely used by the scientific community.

The database organizes the accelerator based radiation facilities into three categories: electrostatic accelerators, synchrotron light sources and spallation neutron sources. The database includes geographical maps of the global distribution of these facilities as well as individual entries by Member State. An example of such a map is shown in Fig. 1. An updated interactive map of particle accelerators around the world is available on the IAEA Accelerator Knowledge Portal [19]. This site provides information on different types of accelerator facility, along with accelerator type, location and parameter details, in various Member States.

The application of radioisotopes has shown significant growth in the past decade, and one of the major factors contributing towards this increased growth has been the availability of a large number of cyclotrons exclusively dedicated to the production of radioisotopes for medical applications. An IAEA survey conducted in the early 2000s [20] estimated that there were more than 350 cyclotrons available in Member States. Many of these cyclotrons are dedicated to the production of isotopes for PET, more specifically ^{18}F for the production of fluorodeoxyglucose. Although production of isotopes other than ^{18}F using these cyclotrons is limited, their use could be augmented for the production of the large number of isotopes useful in medicine and industry [8]. A separate source (Ref. [21]) estimated in 2003 that the total number of cyclotrons was 242.

More numerical details are given in Ref. [20]. According to this source, the total number of particle accelerators worldwide went up from some 10 000 to 17 370 over the period 1996–2002. The trend is roughly consistent with the recent estimate of 30 000 accelerators quoted above (Ref. [15]). Figure 2 shows the significant growth of PET cyclotrons over the period 2009–2016.

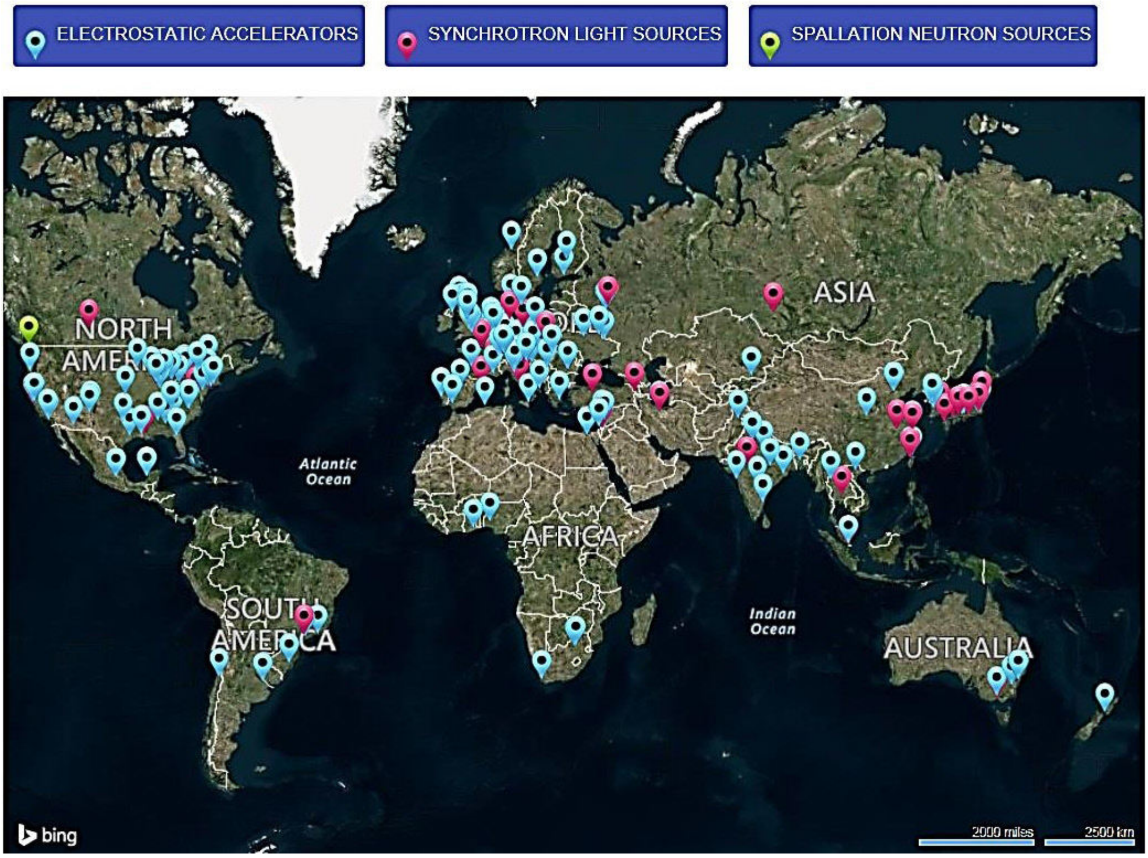

FIG. 1. Map of particle accelerators around the world (reproduced from the IAEA Accelerator Knowledge Portal [19]).

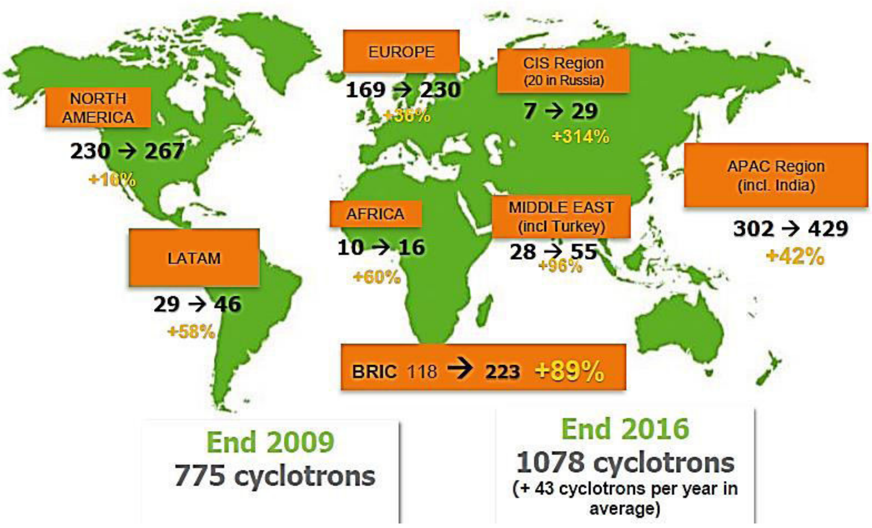

FIG. 2. Number of PET cyclotrons worldwide, 2009–2016 (courtesy of Ion Beam Applications).

TABLE 1. HADRON THERAPY FACILITIES OPERATING IN EUROPE IN 2017

State	Location
Austria	Wiener Neustadt
Belgium	Louvain-la-Neuve
Czech Republic	Prague
France	Nice
France	Orsay
Germany	Berlin
Germany	Darmstadt
Germany	Dresden
Germany	Essen
Germany	Heidelberg
Germany	Munich
Italy	Catania
Italy	Pavia
Italy	Trento
Poland	Krakow
Russian Federation	Dubna
Russian Federation	Moscow
Russian Federation	St. Petersburg
Sweden	Uppsala
Switzerland	Villigen
United Kingdom	Clatterbridge

A different classification is given in Ref. [22]. In this source, accelerators are named; they are grouped by world region and by accelerator type (Appendix I). In Europe, there are 43 sites; in North America, there are 37; in South America, five; in Asia, 13; in Africa, one; and in Australia, four. Several sites house more than one accelerator.

As an example, Table 1 shows Hadron therapy facilities already in operation in Europe in 2017.

3. ACCELERATOR CHARACTERISTICS, CLASSIFICATION AND COMPONENTS SIGNIFICANT FOR DECOMMISSIONING

3.1. INTRODUCTION

Accelerators vary in size, from small enough to fit on a laboratory desk to units several kilometres in length. Particle accelerators are the largest human-made machines. The LHC at the European Organization for Nuclear Research (CERN) is the world's largest and most powerful particle accelerator and consists of a 27 km ring of superconducting magnets. At the other end of the scale, a medical linac is typically 1–2 m long. Accelerators can be linear or circular, can operate in continuous or pulsed modes and can utilize many techniques to accelerate the charged particles. The energy of the utilized particles ranges from a few electronvolts to several tera-electronvolts in the case of colliders. A general introduction to particle accelerators is given in Ref. [23].

Accelerators accelerate ‘bunches’ containing a large number of particles. Several bunches can be present in the accelerator simultaneously. For example, the LHC can store up to 3000 bunches. Each bunch contains $\sim 10^{11}$ protons. The LHC can thus store up to 3×10^{14} protons.

The shielding selection and other radiological protection measures required to ensure the safe operation of accelerators contribute to a significant portion of the initial construction cost. The type of shielding and the construction material are typically lead, concrete or iron in different shapes and forms.

Over a service life that can reach decades, accelerators and their surroundings become activated through the impact of primary and secondary particles on the equipment and the structures housing the accelerators. Surface contamination may result from the deposition of radioactive substances (e.g. aerosols on accelerator components and nearby structures). However, contamination is a rare event during operation in most accelerators. In some facilities, tritium contamination can be an issue (e.g. as an impurity in the target material or detector gas or as a product of spallation reactions at high energies). In the longer term, the accumulation of contamination is a decommissioning issue. The radioactive inventory and the complexity of decommissioning challenges are strongly dependent on the type of accelerator, its operating history and the field of application; the complexity can range from almost nil to significant. Accelerators have a limited operational life expectancy and need to be designed, constructed and appropriately managed with a view to decommissioning.

There are no international standards or guidelines on the decommissioning of accelerators. Some documents include accelerators as a small part of a much broader scope (e.g. under decommissioning of small facilities [24]), but the guidance given in such documents is generic and not facility specific. There is guidance on decommissioning in the American National Standards Institute publication Radiation Safety for the Design and Operation of Particle Accelerators [25]. Although cases of accelerator decommissioning have been sporadically described in the technical literature, no systematic treatment of decontamination and no systematic dismantling technology and waste management for all types of accelerator have been established. These issues are quite common, as accelerator facilities are present in most countries.

The decommissioning of accelerators is a challenge for several reasons, including that:

(a) The range of residual activation is highly variable (residual activation is minor in some accelerators, and close to or below clearance criteria). In addition, the activation distribution varies considerably within a given facility, with the likely presence of hot spots.
(b) National or internationally recommended clearance criteria are very low, so measuring or evaluating residual activation can be a serious challenge.
(c) Clearance criteria vary from State to State, and the characterization procedures applied in one State may not be relevant in another in which there is no provision for generic clearance, such as in France (see Section I–5 on CERN decommissioning).
(d) End-of-life radiological characteristics vary substantially, depending on operational history, ad hoc specifications and modifications, and the presence of unusual radioisotopes. Such variability limits the application of generic decommissioning plans.

3.2. RADIATION ENVIRONMENT AT ACCELERATORS

Historical patterns of prompt radiation fields generated during accelerator operation are directly responsible for induced activity and radiation damage in materials handled during decommissioning. It is therefore useful to have a basic understanding of the nature and distribution of prompt radiation fields in electron and hadron (proton and ion) accelerators.

Prompt radiation results from planned and unplanned beam losses in beamline components. Planned and anticipated losses occur in beam stops, choppers, slits, narrow apertures, kicker magnets, magnet chicanes, septa, screens and other diagnostic devices. Beam losses may also occur almost anywhere if the beam is incorrectly steered during a malfunction of accelerator tuning hardware (e.g. steering magnet failure).

Activation results from nuclear interactions in materials of the beamline and its surroundings. In hadron machines, such nuclear reactions are possible in the mega-electronvolt range of the primary particles, which is well below 10 MeV for specific materials. Examples of (p, n) interactions for nuclei of low mass number with low threshold are given in Table 2. The effective threshold is higher for nuclei of higher mass owing to the effect of the Coulomb barrier.

As the energy of the primary protons increases, reactions producing evaporation neutrons, nuclear spallation and hadronic cascades progressively take place. In the latter process, the incoming proton collides with individual nucleons that may exit the nucleus with sufficient energy to cause a similar reaction further downstream. Up to proton energies of a few hundred mega-electronvolts, hadronic cascades are propagated mainly by neutrons owing to the short ionization range of lower energy secondary protons. Above ~450 MeV, the protons' ionization range exceeds their nuclear interaction range (i.e. most protons initiate a nuclear reaction before the end of their track). At this stage, protons contribute equally to neutrons in cascade development, and with increasing energies more exotic particles are generated.

At low energies, electrons also lose energy primarily through collisions, leading to ionization and excitation of atoms in the surrounding medium. With increasing energy, an increasingly larger fraction of energy loss is due to the emission of photons, called 'bremsstrahlung'. Radiative losses by bremsstrahlung emission reach the magnitude of collisional losses at the so-called critical energy E_c and dominate at energies beyond this value. For a given material with atomic number Z, critical energy can be estimated by the equation E_c [MeV] = $800/(Z + 1.2)$. It follows from this equation that radiative losses start to dominate at much lower energies for heavier materials than for lighter ones. For example, the critical energies predicted by this equation for aluminium, tungsten and lead are 56.2, 10.6 and 9.62 MeV, respectively. The angular pattern of bremsstrahlung emission has a sharp, forward-peaked component that further narrows with increasing energy.

At electron energies well above critical energy, where electrons lose their energy almost exclusively by the emission of bremsstrahlung, the phenomenon known as 'electromagnetic shower' or 'electromagnetic cascade' develops. An electron with energy much greater than E_c produces a bremsstrahlung photon after crossing, on average, a distance of X_0, called the 'radiation length'. As an example, radiation lengths for lead, iron and aluminium are 0.56, 1.76 and 8.9 cm, respectively. At these energies above E_c, the high energy bremsstrahlung photons interact primarily by pair production, after crossing an average distance of 9/7 X_0. The resulting electron and positron are still very energetic and are most likely to produce bremsstrahlung photons again. The cycle repeats, multiplying particles at every step, as long as the charged components of the cascade, electrons and positrons, have enough energy to mainly produce bremsstrahlung. It is clear from the above that an electromagnetic cascade can also be initiated by an energetic photon.

Unlike hadrons, electrons do not directly interact with nuclei, but bremsstrahlung photons of sufficient energy may interact by photonuclear reactions. At low energies, photons cause nuclear excitation followed by the

TABLE 2. ENERGY THRESHOLD FOR SEVERAL (p, n) REACTIONS
(reproduced from Ref. [26] with permission courtesy of National Council on Radiation Protection and Measurements)

Reaction	Threshold energy [MeV]
$^{3}H(p,n)^{3}He$	1.019
$^{7}Li(p,n)^{7}Be$	1.882
$^{45}Sc(p,n)^{45}Ti$	2.908
$^{51}V(p,n)^{51}Cr$	1.566
$^{63}Cu(p,n)^{63}Zn$	4.214
$^{65}Cu(p,n)^{65}Zn$	2.165

emission of ‘evaporation’ neutrons. The cross-section for this process has a maximum, called ‘giant resonance’, roughly from 13 MeV for heavy nuclei ($A > 40$) to 20–23 MeV for light nuclei. At higher energies, neutrons are also produced by pseudodeuteron breakup and photo-pion production. The latter happens beyond the threshold of ~140 MeV (i.e. the rest mass of a pion), where pion production becomes energetically possible. These pions then generate secondary neutrons as by-products of their interactions with nuclei.

In comparison with proton machines, in electron accelerators nuclear reactions (and activation) start at higher energies, and cross-sections for photonuclear processes are relatively small. As a result, for the same energy and integrated lost power over time, dose rates from long term activation in electron machines will be roughly between one and two orders of magnitude lower than at comparable proton accelerators. The longitudinal extent of an electromagnetic cascade is approximately 20 X_0, and the maximum is around 5–8 X_0, which translates to 35.2 cm and ~11.4 cm, respectively, in iron. In comparison, the extent of hadronic cascades is measured in metres.

Electromagnetic and hadronic cascades are both generated predominantly in the beamline components, and as a result, the highest residual activation levels will be encountered in beamlines and their immediate vicinity. Beam dumps, stoppers, narrow apertures and experimental targets are typically the most activated components. Neutrons and high energy photons escaping these cascades may also activate the surrounding structural and shielding materials, albeit at a much lower level by comparison.

Although generated by different processes, muons become important at both proton and electron accelerators at high energy (Class 4 accelerators, above 1 GeV). Because muons are mainly produced at narrow forward angles, they are of concern when they occur behind beam dumps. Muons do not initiate nuclear reactions and are slowed down by ionization losses. As a result, large amounts of forward shielding (typically iron) are used, which substantially adds to the bulk of materials to manage in the decommissioning phase.

Many aspects of radiation fields at proton accelerators described above also apply to ion accelerators. The rate of ionization losses of ions increases as z^2, where z is the ion charge. Even with a single charge, an ion heavier than a proton of the same kinetic energy will have a lower velocity and, therefore, a higher stopping power dE/dx in the non-relativistic regime. Ion ranges will therefore be shorter than those of protons, and substantially so as their mass or charge increases. Ions also initiate nuclear reactions, resulting in the production of secondary particles. The important differentiating aspect at ion accelerators will therefore be the first interaction step, when the first wave of secondary particles is generated. The subsequent steps are analogous to those discussed for proton accelerators above, including hadron cascades and neutron production at high energy machines.

Some light ion interactions are exothermic and have a particular importance in neutron production: $^2H(d, n)^3He$ (Q = 3.266 MeV), $^3H(d, n)^4He$ (Q = 17.586 MeV), and $^9Be(\alpha, n)^{12}C$ (Q = 5.708 MeV). The first two are widely used in so-called neutron generators (deuterium–deuterium and deuterium–tritium, respectively), using deuterons accelerated to only a few hundred kilo-electronvolts. These reactions, and the slightly endothermic $^{12}C(d, n)^{13}N$ (Q = 0.281 MeV), can be used for the production of monoenergetic neutron beams of variable energies, depending on the energy of the primary particles.

Induced activity may be generated in some accelerator equipment even without any beam operation. For example, radiofrequency accelerator cavities (in particular, superconducting radiofrequency cavities) are known to produce a ‘dark current’ of electrons emitted from the cavity surface. The high gradients in superconducting radiofrequency cavities may accelerate those electrons to several tens of mega-electronvolts, sufficient to produce electromagnetic cascades and subsequent material activation. This type of activation may therefore be encountered at ancillary facilities (e.g. test stands that are separate from the accelerator).

3.3. CLASSIFICATION OF PARTICLE ACCELERATORS

3.3.1. Classification criteria

The great diversity of particle accelerators does not facilitate the application of a single classification system or criteria for the location and layout of facilities. A number of criteria could be used to classify particle accelerators. They can be classified according to the technology by which acceleration is achieved (e.g. power source, acceleration path geometry), the application or use of the accelerators (e.g. industrial, medical), the maximum energy, the maximum beam current, and the time structure of the beam delivery [26]. Tables 3 and 4 demonstrate two different criteria used to classify particle accelerators.

TABLE 3. ACCELERATOR PRODUCED RADIATION CLASSIFIED BY ROUTINE APPLICATION
(reproduced from Ref. [26] with permission courtesy of National Council on Radiation Protection and Measurements)

Description	Electron	Proton	Ion	Photon	Neutron
Radiotherapy	*	*	*	*	*
Industrial radiography	n.a.	n.a.	n.a.	*	*
Analysis of materials	n.a.	n.a.	n.a.	n.a.	n.a.
Activation analysis	n.a.	*	*	n.a.	*
Microscopy, electron, ion or positron	*	*	*	*	n.a.
X ray fluorescence analysis	*	*	*	*	
Geological well-logging	*	n.a.	*	*	*
Neutron scattering	n.a.	*	n.a.	n.a.	*
Synchrotron light sources	*	n.a.	n.a.	*	n.a.
FEL	*	n.a.	n.a.	n.a.	n.a.
Ion separation	n.a.	n.a.	*	n.a.	n.a.
Archaeological investigations	*	n.a.	*	n.a.	n.a.
Ion implantation, wear assessment	n.a.	n.a.	*	n.a.	n.a.
Surface conditioning, roughening	*	n.a.	n.a.	*	n.a.
Radioisotope production	n.a.	*	*	n.a.	*
Radiation processing	*	n.a.	n.a.	*	n.a.
Radiation sterilization	*	n.a.	n.a.	*	n.a.
Research and training	n.a.	n.a.	n.a.	n.a.	n.a.
Nuclear structure physics	*	*	*	*	*
Neutron physics	*	*	*	*	*
Atomic and solid state physics	*	*	*	*	*
Biology, chemistry	*	*	*	*	*
Radiation effects on materials	*	*	*	*	*
Particle physics	*	*	*	n.a.	*

Note: * — existing or applicable; n.a. — not applicable.

TABLE 4. ACCELERATORS CLASSIFIED BY ENERGY RANGE
(reproduced from Ref. [14])

Class	Energy range[a]	Type of accelerator	Examples
Class 1	Low energy (2–30 MeV)	Electron linacs and electrostatic accelerators	• Radiotherapy linacs • Van de Graaff, tandem accelerators, Pelletron, with a potential lower than 10 MV
Class 2	Medium energy (10–100 MeV)	Proton, H^- or multiple particle cyclotrons and linacs	• Cyclotrons for PET/single photon emission computed tomography (SPECT) radionuclide production • Cyclotrons for neutron sources • Other accelerators (linacs and cyclotrons) in physics research (injectors) • Some cyclotrons or synchrotrons for radiotherapy
Class 3	High energy (100–several hundred MeV)	Proton cyclotrons and synchro-cyclotrons and linear high energy accelerators	• Proton therapy • Accelerators for physics research (injectors) • Neutron spallation sources
Class 4	Very high energy (range GeV–TeV)	High energy synchrotrons, storage rings, colliders	• Fundamental physics research • Wide range of interdisciplinary research with light sources

[a] For ions: kinetic energy per nucleon.

The energy ranges referenced in Classes 1–4 of the particle accelerators in Table 4 are provided solely for generic purposes. These energy ranges do not account for the differences that will be found between hadron and electron accelerators or between accelerators that have been used for different applications. In general, electron accelerators will exhibit much lower levels of activation than hadron accelerators. For this reason, the suggested threshold for Class 2 accelerators is 10 MeV for proton and 30 MeV for electron machines. No activation can be expected in electron machines up to roughly 8 MeV. The classification given in Table 4 will be used in the rest of this publication.

Another possible classification could make use of the expected amounts and extent of activated waste resulting from decommissioning. According to this criterion, the first category would be applied to accelerators for which activation is confined to the target. The second category would be applied when activation includes the target and its immediate surroundings (e.g. treatment head and collimator). The third category would refer to the activation of the entire accelerator machine. The fourth category would also include neighbouring infrastructure and services (e.g. shielding, building structure, soil). In complex facilities, categorization might vary between different areas of the facility.

3.3.2. Specifics of Class 1–4 particle accelerators

Many of the components of particle accelerators are common across all the categories of such accelerators. The components and their functions are listed in Table 5. The reader is advised to consult Ref. [27] for a full description of accelerator parts, operational techniques and so on.

Three potential categories of radioactivity can be encountered in particle accelerators:

(a) *Activation.* The principal components that become activated are those that can directly interact with the beam (i.e. targets, dumps, screens, collimators, jaws, kickers and septa, antiparticle and neutron sources). Other components likely to become activated are in positions where beam loss occurs (i.e. magnets and narrow apertures).
(b) *Contamination.* Contamination can arise from activated oil or cooling water leaks or from the spread of activated materials from damaged targets and the beamline windows. Contamination can also arise from

TABLE 5. TYPICAL COMPONENTS PRESENT IN ACCELERATOR ENCLOSURES AND THEIR FUNCTIONS

Component	Function	Main material (secondary material[a])
Source or gun	Producing charged particles	Steel, Cu (alumina, NEG[b])
Chopper	Imparting a pulsed beam structure	Fe, Cu, W, misc.
Vacuum chamber	Providing vacuum environment for the particle beam path	Steel, Al
Vacuum pumping system, vacuum valves	Generating and maintaining vacuum	Steel
Radiofrequency cavities	Accelerating beam	Cu, Nb
Radiofrequency wave guides	Conducting radiofrequency power to radiofrequency cavities	Cu, Al, Cu/Al
Magnetic systems	Bending, focusing or defocusing beam; limiting energy spread	Cu, Fe (steel, Al)
Electrostatic and magnetic kickers and septa	Switching beam direction	Cu, Fe (ferrites)
Cryogenic systems	Cooling superconducting magnets and accelerator cavities (for Class 3 and 4 accelerators)	Steel, Al (liquid N and He)
Cooling systems (pipes and ion exchange resin beds)	Cooling and maintaining de-ionized water	Steel, Cu, resin, water (steel, Al)
Collimators, jaws	Restricting aperture at beamline transitions	W/Cu alloy, Pb
Masks, heat shields	Absorbing the heat from synchrotron radiation	Cu (steel, Al)
Wigglers, undulators	Producing synchroton light	Cu, Fe (Co, Ni, Fe, rare earths)
Stoppers, beam dumps	Absorbing or terminating the beam	Steel, Cu, Al, water, graphite
Targets, beamline windows	Modifying beam composition by interaction with target material; used either for structural or experimental purposes; can be either internal or external to the vacuum system	Variety of materials; Be, Al alloys and C for windows
Screens, scanning wires, Faraday cups	Performing beam diagnostics	Cu, steel, misc.
Permanent magnets	Preventing accidental beam transport into optical lines at synchrotron facilities	Fe, Co, Ni, Al, Sm, rare earths
Dedicated antiparticle sources, neutron sources	Creating secondary beams, used in specific facilities; created by bombarding solid targets with the primary beam	W, Hg, misc.

Note: misc. — miscellaneous.

[a] Only typical materials are listed. A wide variety of materials may be used for specific applications (e.g. photocathode materials for electron guns, insulators, coatings).

[b] Non-evaporable getter of impurities in vacuum vessel.

accident scenarios, from sputtering or evaporation after beam interaction with materials, or from radioisotope production (including deposition from radioisotope beams or accelerator produced radionuclides).

(c) *Radioactive substances not generated by accelerator operation.* Such substances include calibration sources in experimental equipment and other components (e.g. depleted uranium shielding, detectors).

The presence and quantity of radioactivity that will require consideration as part of planning for decommissioning will be different for each of the four categories of particle accelerator and will typically be higher for hadron accelerators than for electron accelerators.

3.4. CLASS 1 PARTICLE ACCELERATORS

Electrostatic accelerators move charges mechanically carried by a conveyor belt (van de Graaff accelerator) or chains (Pelletron) from a low potential source to a higher potential collector. In a van de Graaff accelerator, a moving belt between two electrodes a few metres apart continuously transports electric charges. The discharge tube is encased in a large pressure vessel filled with several atmospheres of nitrogen or with a mixture of other gases, which inhibit breakdown. In the later models of van de Graaff machines, a cylindrical volume of nearly uniform field gradient is obtained by a large number of coaxial metal hoop electrodes maintained at successively graded potentials. Charged particles are injected and are accelerated up to approximately 10 MeV in the electric field created between the electrodes.

The Pelletron is another example of an electrostatic particle accelerator that is similar to a van de Graaff generator, except that it has a chain and not a rubber belt. The chain facilitates operation of the Pelletron at a higher velocity than a van de Graaff rubber belt; hence both the voltage and currents achievable by the Pelletron are far higher.

Tandem type accelerators are designed to produce high energy ion beams for accelerator driven mass spectrometry and ion beam analysis in a research environment. Tandems consist of coupled van de Graaff accelerators in which positive ions are first passed through a gas channel, where they pick up electrons and are accelerated to a positive high voltage terminal. The energetic negative particles then pass a stripper system, become positively charged and are once more accelerated through a second discharge tube to ground potential. The overall gain in energy can hence reach twice the potential difference applied. Three and four stage versions of these constructions exist. Tandems have the capability of producing a large variety of highly stable ion beams with energies of a hundred kilo-electronvolts up to several mega-electronvolts. The tandem accelerator has two stages (a van de Graaff accelerator can be used to generate energy in the first stage). In the first stage, negative ions (with extra electrons) are accelerated from ground to a positive high voltage, and then the ions are stripped of two to three electrons in a stripper and become positively charged. Positive (stripped) ions are then accelerated further by going from the positive high voltage to ground. The facility constructed at Daresbury, United Kingdom, had a vertical acceleration tube of 42 m in length. This was one of the largest tandem accelerators ever constructed and was in operation for many years. The centre terminal of this tandem accelerator could hold a potential of up to 20 MeV.

The Slovak University of Technology in Trnava has two accelerator facilities: a 6 MV Tandetron accelerator and a 500 kV open-air ion implanter. Figure 3 shows the 6 MV Tandetron accelerator system that has been in operation since 2016; details are discussed in Ref. [28].

The Pelletron has largely superseded many of the earlier van de Graaff and tandem accelerators. The vast majority of these machines operate below 5 MeV and therefore would not be associated with significant activation products during decommissioning. Devices with higher operating energies, such as the tandem van de Graaff accelerator (25 MV) at Oak Ridge National Laboratory, USA, may be associated with activation and need additional consideration when decommissioning.

A linac is an accelerator in which particles are propelled in straight lines by the use of alternating electric voltages. The alternating voltages are timed in such a way that they will provide increasing increments of energy to the particles. The velocity of charged particles is greatly increased in a part of the accelerator called the ‘wave guide’. The particles are subjected to a series of oscillating electric potentials along a linear beamline through the use of microwave technology (similar to that used for radar).

The vast majority of linacs are electron devices used for external beam radiotherapy. The electrons are accelerated and then allowed to collide with a heavy metal target, generating high energy X rays. Systems like these

FIG. 3. A 6 MV Tandetron accelerator at the Slovak University of Technology, Trnava, Bratislava (courtesy of the Slovak University of Technology).

are also used in industry and research when high dose rates are required for material modifications, sterilization, food treatment to extend shelf life, and so on [29].

A linac with a maximum energy of below 10 MeV will have very limited activation in the components, although the reuse of previously activated building blocks and activated spare parts will need to be considered. Linacs with energies of up to 30 MeV can show detectable activation, particularly in parts of the gantry and beam collimation system.

In addition to the issue of activation, when decommissioning linacs it should be noted that many of the early units used depleted uranium as part of the shielding (collimators, bars and jaws). In later models, the uranium has been replaced by tungsten or lead.

A betatron is a cyclic electron accelerator in a circular orbit. It has an approximately constant radius; electron acceleration is provided by means of magnetic induction. The betatron consists of a transformer with a torus shaped vacuum tube as its secondary coil. An alternating current in the primary coils accelerates electrons in the vacuum around a circular path. During one quarter of the alternating current cycle, the direction and strength of the magnetic field, as well as the rate of change of the field inside the orbit, have values appropriate for accelerating electrons in one direction.

Lower energy betatrons in the 7–20 MeV range, however, have been specially constructed to serve as sources of energetic ‘hard’ X rays for use in medical and industrial radiography. Portable betatrons operating at energy levels of approximately 7 MeV have been designed for specialized applications in industrial radiography, for example to examine concrete, steel and cast metal construction for structural integrity.

Activation is not an issue for consideration with low energy Class 1 betatrons. Betatron devices reaching higher energies exist and have been utilized for a range of purposes. These devices fall within Class 2.

An example of another type of accelerator that pertains to Class 1 is the Rhodotron used in sterilization and other industrial applications (Fig. 4). The Rhodotron is a high power electron accelerator specifically developed for the sterilization of medical products in an industrial setting. These accelerators, which are typically about 3 m wide, can produce up to 700 kW of beam power at electron energies of 7 MeV [16].

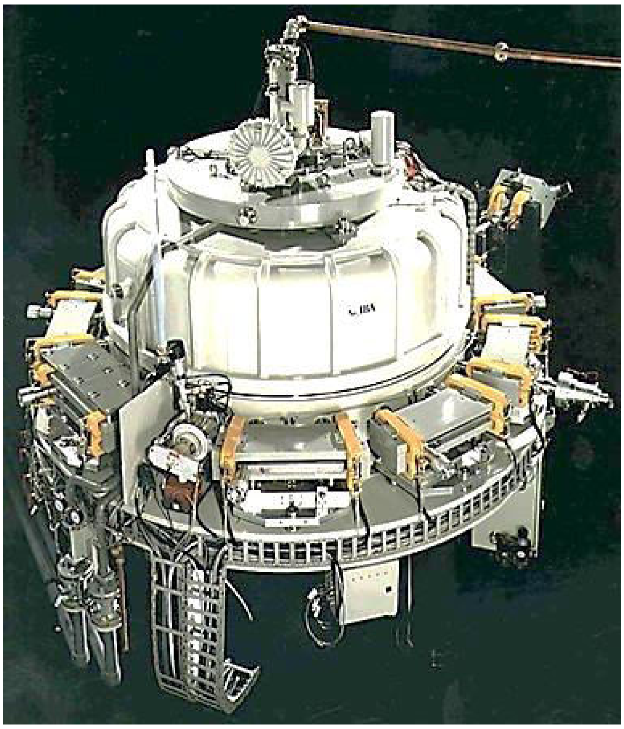

FIG. 4. Industrial application of particle accelerator, the Rhodotron (courtesy of Ion Beam Applications).

3.5. CLASS 2 PARTICLE ACCELERATORS

3.5.1. Medium energy accelerators

Class 2 accelerators include (a) electron accelerators operating in the energy range 30–100 MeV and (b) proton and other particle accelerators operating in the energy range 10–100 MeV. These medium energy devices are characterized by the production of activation from the primary beam as well as from secondary radiations (neutrons and high energy gammas).

3.5.2. Linear accelerators

Linacs are mainly used (a) as injectors, (b) in isotope production, (c) as neutron sources and (d) for materials science research. Figure 5 is an example of a linear proton accelerator. Most of the activated components will be located at the end of the acceleration pathway and in surrounding targets or beam stoppers.

3.5.3. Cyclotrons

A cyclotron consists of a circular device made out of two D shaped electrodes (called ‘dees’) placed in a magnetic field. The basic characteristics of all cyclotrons are the same. There is an ion source to produce ions, an acceleration chamber to accelerate them and a magnet to contain the ions on a circular path. In cyclotrons used for isotope production, the ion source is typically internal to the vacuum chamber; in high energy systems, the ion source is external and the charged particles are injected into a strong magnetic field. Owing to the combination of the magnetic field and the alternating electric field between the electrodes, the particles follow a spiral trajectory up to the maximum radius and are then extracted towards targets. The volume of the vacuum chamber inserted between the massive pole shoes of the electromagnet is often several cubic metres and the diameters of the poles can reach a few metres.

The use of negative ions has greatly reduced the level of activation of internal structures of cyclotrons compared with positive ion machines. The latter require specially shaped electrostatic deflectors for the extraction, which are typically hit by a significant fraction of the beam. In negative ions, extraction is made by stripping

FIG. 5. Example of a linear proton accelerator (courtesy of AccSys Technology, Inc).

electrons from the negative ions only in the last part (10–20 cm) of the acceleration path. The very high efficiency of this mechanism facilitates substantial reduction of activation.

However, negative ion cyclotrons require more complex ion sources and an improved vacuum system. The appropriate technology selection depends on the final use and the required beam current. Typically, in a modern cyclotron for radionuclide production, the choice will be for negative ions, whereas in relatively low current applications, positive ions are preferred owing to their simplicity.

In all cases, beam losses can never be totally avoided and will cause internal activation and generation of neutrons. The most common use of cyclotrons in the energy range up to 100 MeV is for the production of a wide variety of radionuclides that are typically used for medical diagnosis utilizing single photon emission computed tomography or PET imaging techniques [8].

In older cyclotrons, the dees will be activated in addition to the deflector and the septa; the dees tend to be heavy and bulky and may need to be cut for characterization and disposal.

The interaction of the beam with the targets and the collimation system will result in the production of secondary neutrons arising from (p, xn) (d, xn) reactions, and so on. These will result in activation of the structures of the accelerator itself as well as the surrounding infrastructures (the ancillary subsystems, perimeter walls or self-shielding present in some types of system).

3.6. CLASS 3 PARTICLE ACCELERATORS

Accelerators with energy ranging from 100 to several hundred mega-electronvolts are grouped within Class 3 and include cyclotrons, synchrotrons and synchrocyclotrons, as well as high energy linacs. Cyclotron accelerated protons with a maximum energy of 250 MeV and synchrotron accelerated carbon ions with a maximum energy of 400 MeV are usually utilized for radiotherapy of deep seated tumours.

High energy linacs are normally used for industrial material treatment and research. In the Class 3 energy range, significant activation of the accelerator and surrounding structures and infrastructure can be expected, due both to the primary and secondary radiation.

A synchrotron is an example of one type of cyclic particle accelerator. In a synchrotron, the magnetic field (which serves to rotate the particles, causing them to circulate) and the electric field (which accelerates the particles) are carefully synchronized with the travelling particle beam. Synchrotrons can be either proton or electron accelerators and are utilized to reach very high beam energies. The number of patients treated per year with proton therapy is increasing, and according to Ion Beam Applications S.A., this number is estimated to increase from 16 200 in 2015 to 300 000 by 2030. Figure 6 shows a 230 MeV proton synchrotron installed in 2015 being used

FIG. 6. First in-room proton synchrotron on rails installed at Trento Proton Therapy Centre, Italy (courtesy of Ion Beam Applications).

for therapy at Trento Proton Therapy Centre, Italy [30]. Electron and positron synchrotrons are mostly used in light sources.

To compensate for relativistic effects (which occur when the speed of the particle approaches the speed of light), synchrocyclotrons (whose design is based on cyclotron technology) operate using a variable frequency radiofrequency electric field. Modern azimuthally varying field cyclotrons utilize superconducting magnets to achieve a very high magnetic field in a compact volume to attain similar results.

In cyclotrons with a multigantry beam delivery system, the whole beam distribution system should be considered as subject to activation. The walls of the facility will also be subject to activation. Additional shielding used for the targets, energy selection system and beamlines will also be activated. Neutron spallation sources are associated with high levels of activation in and around the target area. Use of a mercury liquid target (as used at large spallation sources) poses specific challenges for decommissioning [31].

Detailed information on problematic materials, including mercury, resulting from decommissioning and guidance on their management are provided in Ref. [32].

3.7. CLASS 4 PARTICLE ACCELERATORS

3.7.1. Linacs, synchrotrons, storage rings and colliders

Very high energy Class 4 linacs, synchrotrons and storage rings are used to produce giga-electronvolt to tera-electronvolt proton or electron beams used for studies in fundamental particle physics or as sources of intense X ray beams (synchrotron radiation). The decommissioning of large Class 4 accelerators, such as storage rings and colliders, needs proper planning and documentation. It is a challenging activity in its logistic, operational and licensing aspects. Large quantities of massive components will arise during the dismantling (e.g. magnets can reach lengths of several metres and can weigh several tonnes), and therefore dismantling methods will generally need to involve size reduction to enable materials to be packaged and conditioned to the requirements of their final repositories or for characterization purposes.

The choice of the decommissioning strategy will largely depend on the level of activation, on the final scope of the decommissioning (greenfield or ‘unrestricted use’, or reuse of the shielding structures in another accelerator installation), on the requirements of the final repositories and on the regulatory framework in which the decommissioning work is carried out.

Synchrotrons are mostly post-accelerators using low emittance, monochromatic charged particle beams originating from lower energy injectors. The accelerators consist of a toroidal vacuum tube with diameters of several tens to hundreds of metres. Synchrotron radiation facilities provide synchrotron light for basic and applied science studies; worldwide information is listed in Ref. [33]. Figure 7 shows the large, modern 2.75 GeV SOLEIL synchrotron light facility located near Paris.

3.7.2. Storage rings

A storage ring is a type of circular particle accelerator in which a particle beam may be kept circulating for many hours. Technical solutions and efficiency of storage of a particle beam depend on the mass, energy and, usually, the charge of the particle to be stored. Most commonly, storage rings are used to store electrons, protons or positrons, either in continuous beams or in pulsed structures (bunches).

The most common use of storage rings is to store electrons, which then radiate synchrotron radiation. Several tens of facilities based on electron storage rings are in operation in the world today and are used for a variety of studies in many branches of science. Another very well known application is the storage of beams for large accelerator colliders.

3.7.3. Colliders

A collider is a type of experimental beam configuration mainly used for fundamental physics research. Colliders may either use ring accelerators or linacs to cause a head-on collision of the two beams. The beams can be accelerated in (a) a common beamline (a pipe-like vacuum chamber), as was the case for the electrons and positrons in CERN’s Large Electron–Positron collider (LEP) [34], currently decommissioned, or (b) two different beamlines, as for example in the CERN LHC, which accelerates protons in different directions. Figure 8 shows the CERN LHC.

Because of the loss of energy by radiation when following a bent trajectory, circular colliders are usually very big machines. The most powerful and the largest installation ever built is the LHC, which has a circumference of 27 km.

Two high energy proton beams travelling close to the velocity of light but in the opposite direction are made to collide with each other. Both beams are maintained in separate ultra-high vacuum pipes.

These beams are guided around the accelerator ring using a strong magnetic field generated by superconducting magnets. Beams are directed to bend using 1232 dipole magnets 15 m in length and focused using 392 quadrupole magnets, each 5–7 m in length.

Most of the accelerator parts are connected to a liquid helium distribution system for cooling the superconducting magnets, which are maintained at –271°C, and other supply systems. Collimators and focusing magnets ensure the high quality of the beam in the proximity of the collision points so as to increase the probability of collisions.

The Tevatron at Fermilab in Batavia, Illinois, USA (Fig. 9), accelerated beams of protons and antiprotons close to the speed of light around a 6.4 km circumference. This was the second most powerful proton–antiproton accelerator in the world; it was shut down in 2011.

FIG. 7. Aerial view of SOLEIL, a 2.75 GeV synchrotron light facility located near Paris (courtesy of SOLEIL).

FIG. 8. Large Hadron Collider at CERN (courtesy of CERN).

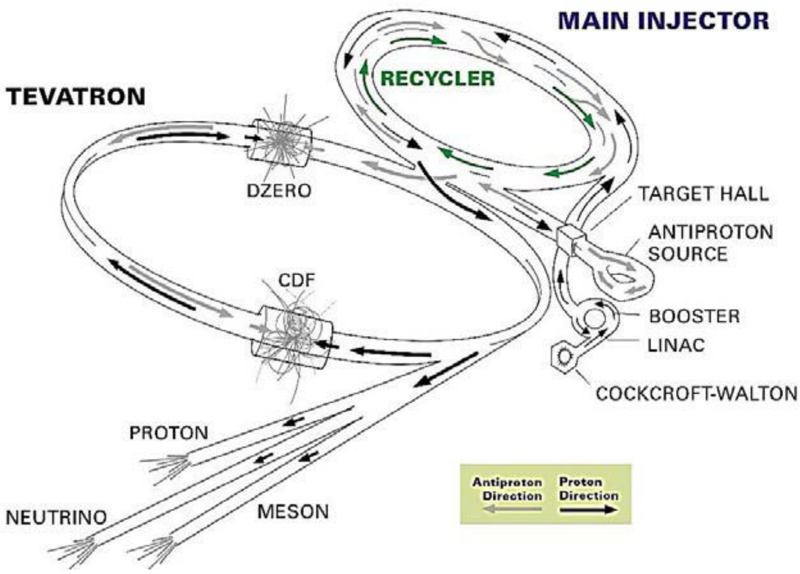

FIG. 9. Accelerator chain of Fermilab's Tevatron with injectors (courtesy of Fermilab).

The two beams collided at the centres of two 5000 t detectors positioned around the beamline at 'DZERO' and 'CDF' (shown in Fig. 9). The collisions reproduced the conditions similar to those of the early universe and enabled the probing of the structure of matter on a very small scale.

Unlike the Tevatron and the LHC, where particles spin in a circle until they collide, the accelerator at the SLAC National Accelerator Laboratory, California, USA, is a 3.2 km linac — the longest in the world — accelerating electrons and positrons at its peak of operation to a maximum energy of 50 GeV.

Figure 10 is a site view of the 3.2 km long accelerator at the SLAC National Accelerator Laboratory. Reductions in the high energy physics project at SLAC National Accelerator Laboratory have resulted in parts of the linac being disconnected; the maximum energy level has thus now been reduced.

FIG. 10. View of the 3.2 km long accelerator at SLAC National Accelerator Laboratory (courtesy of SLAC National Accelerator Laboratory).

3.8. NEW FACILITIES AND TECHNOLOGY

The technologies and facilities listed in the previous sections should not be taken as an exhaustive list of the complete range of accelerator facilities. New facilities and technologies are emerging at the time of writing, possibly creating new challenges at the time of their decommissioning.

A short, non-exhaustive overview of the emerging facilities and technologies is given in the following subsections, first listing facilities under construction and for which a detailed technical design is available, followed by the current trends in accelerator studies.

3.8.1. Emerging technologies

Plasma acceleration is a technique for accelerating charged particles, such as electrons, positrons and ions, using an electrical field associated with an electron plasma wave. The wave is created either through electron pulses or through the passage of very brief laser pulses [35]. The plasma accelerator is a relatively new technique of particle acceleration in which particles ‘surf’ on a wave of plasma. The plasma consists of a fluid of positively and negatively charged particles, generally created by heating a dilute gas.

Laser plasma acceleration is based on different physical principles than typical particle acceleration, which to date has relied on electric fields generated by radiowaves to accelerate electrons and other particles close to the speed of light. A variety of approaches has been proposed to accelerate particles by laser fields; of the other approaches considered, the laser wakefield acceleration in low density plasma is one of the most promising. It potentially allows the achievement of energies up to approximately 1 GeV in very small accelerator chambers with a dimension of centimetres, instead of hundreds of metres. Such a system could use a laser pulse to create a charge ‘wake’ in a low density plasma medium, where particles would ride the plasma wake (like a surfer who has caught a good wave) to achieve ever increasing speeds. Many technical challenges require resolution before tabletop accelerators and plasma driven turbochargers, as part of larger accelerators, are likely to become a reality.

Plasma based accelerators have been successfully used to accelerate electrons, protons, deuterons and other ions. The acceleration of electrons is obtained by hitting a gas jet with a very powerful laser beam. Electrons can be accelerated to energies of hundreds of mega-electronvolts and, after the interaction with the experimental chamber walls and surrounding material, will generate prompt radiation, as bremsstrahlung photons, neutrons and other particles (charged particles, ions, nuclear fragments and delayed radiation). The resulting prompt radiation is more complex the higher the energy of the accelerated particles [36, 37].

Rapid progress in the development of high intensity laser–matter interactions into the relativistic domain has provided several applications by generating intense particle sources [38]. Proton energies in the order of tens of mega-electronvolts have been obtained, and the possibility of producing medical radionuclides has been proven [39]. Some initial reports have been published on radiation protection issues with this type of accelerator and on the activation aspects that may be relevant to decommissioning [40, 41]. These estimates indicate limited activation of the system itself and of surrounding materials.

However, at the time of writing this publication, the amount of information available is very limited and mostly based on estimates rather than on experience collected in the use of the first prototypes. As research regarding this type of accelerator is still in development, and as technology for applications has not yet reached maturity, the decommissioning of the first experimental sites is far from being on the agenda. Nevertheless, the first experimental sites could undergo upgrades or partial modification that might lead to dismantling or recycling of at least some components. Accelerators of this type cannot yet be assigned to the classification system used in this publication (Classes 1–4) owing to the immaturity of design and the paucity of information that exists. Nevertheless, initial tests and plans involving powerful lasers hint that giga-electronvolt energy range is within reach. The Extreme Light Infrastructure Beamlines facility, which is under construction in Romania, plans to accelerate electrons to 1 GeV and protons to 100 MeV.

In the design of new facilities, a precautionary approach should be considered, which would take into account the options to facilitate future decommissioning given in this publication for other types of accelerator.

3.8.2. New facilities under construction

Other facilities under construction include:

(a) *The Facility for Antiproton and Ion Research (FAIR).* This is a new, unique international accelerator facility specifically designed for research with antiprotons and ions. It is already under construction near Darmstadt, Germany. Its core, a double ring accelerator (SIS100 heavy ion synchrotron) with a circumference of 1100 m, will be associated with a complex system of cooler and storage rings and experimental set-ups. The synchrotron will deliver ion beams of unprecedented intensities and energies. Thus, intensive secondary beams can be produced, providing antiprotons and exotic nuclei for groundbreaking experiments. It will provide unique accelerator and experimental facilities, allowing for a large variety of unprecedented forefront research in hadron, nuclear, atomic and plasma physics as well as applied sciences [42]. FAIR is expected to deliver beams for science experiments by 2025. Figure 11 is a schematic layout of the facility.

(b) *Kō Energī Kasokuki Kenkyū Kikō (KEK), High Energy Accelerator Research Organization, Japan.* The Super KEKB is under construction after replacing the KEKB. Two synchrotrons are being constructed for 7 GeV electron and 4 GeV positron colliding experiments. The luminosity of the Super KEKB will be 40 times greater than that of the KEKB.

(c) *The International Fusion Materials Irradiation Facility.* This is a joint nuclear fusion project between Japan, the Russian Federation, the USA and the European Union (EU) (Fig. 12), which is under construction in Aomori Prefecture in Japan [43]. The key objective of the facility is to study the behaviour of materials and components subjected to irradiation under conditions typically found in a nuclear fusion reactor. To achieve this, deuterium with a high beam current will be accelerated using two accelerators for 14 MeV neutron sources from a lithium target.

(d) *JT-60SA.* This is a fusion experiment designed to support the operation of the International Thermonuclear Experimental Reactor (ITER) (Fig. 13). ‘SA’ stands for ‘super, advanced’, since the experiment will have superconducting coils and study advanced modes of plasma operation [44]. The purpose of JT-60SA is to optimize the operation of fusion power plants that are built after ITER. It is a joint international research and

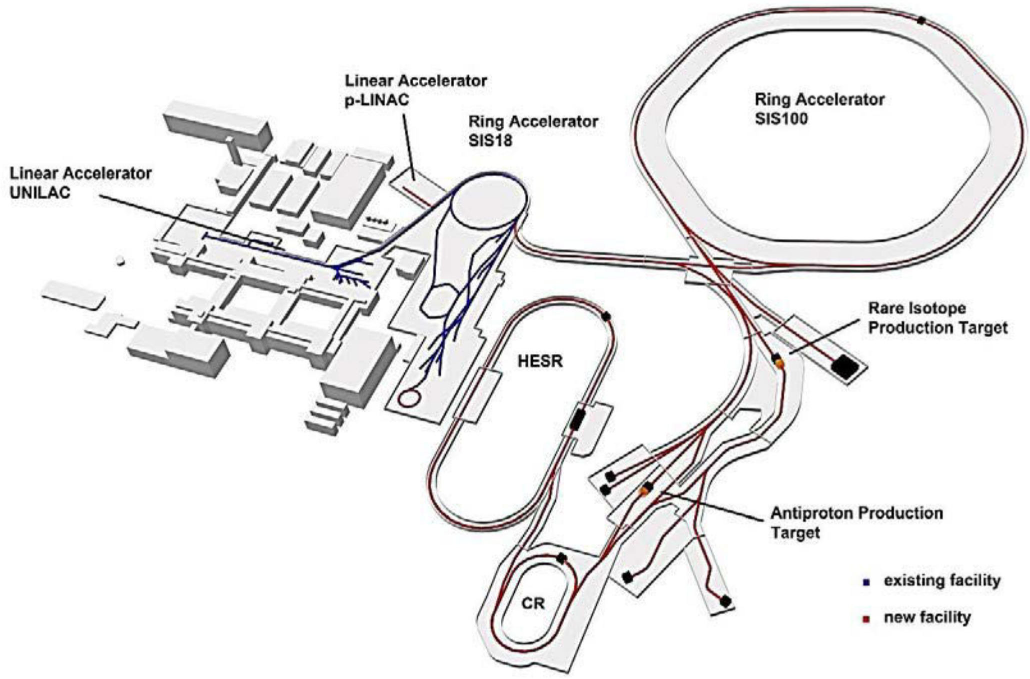

FIG. 11. Facility for Antiproton and Ion Research complex 2017 (courtesy of Facility for Antiproton and Ion Research/GSI Helmholtzzentrum für Schwerionenforschung).

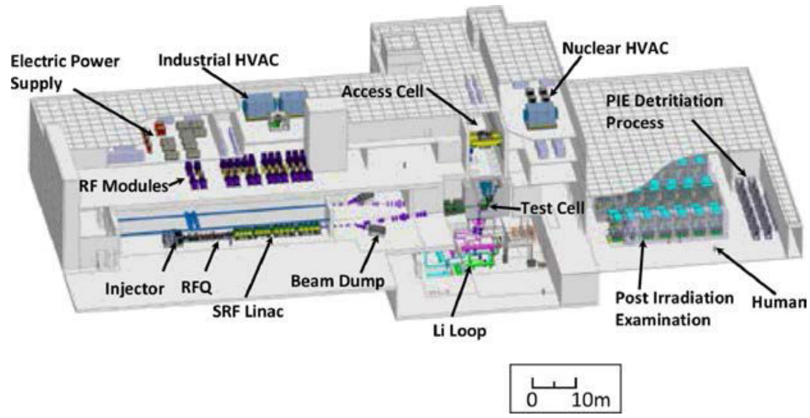

FIG. 12. Layout of the International Fusion Materials Irradiation Facility (reproduced from Ref. [43]).

development project involving Japan and the EU and is to be built in Naka, Japan, using the infrastructure of the existing JT-60 Upgrade experiment.

In addition to the above large facilities, many accelerator projects are planned in Japan, such as an energy recovery linac for future light source, high f1ux neutron source for boron neutron capture therapy, plasma acceleration, and so on.

3.8.3. Facilities for which a conceptual design report is already available

Conceptual design reports are available for the following facilities:

(a) *The European Spallation Source,* which will be the most powerful long pulse source of neutrons at 5 MW. It is a co-hosted Swedish and Danish project, built in Lund, Sweden, with a data analysis centre in

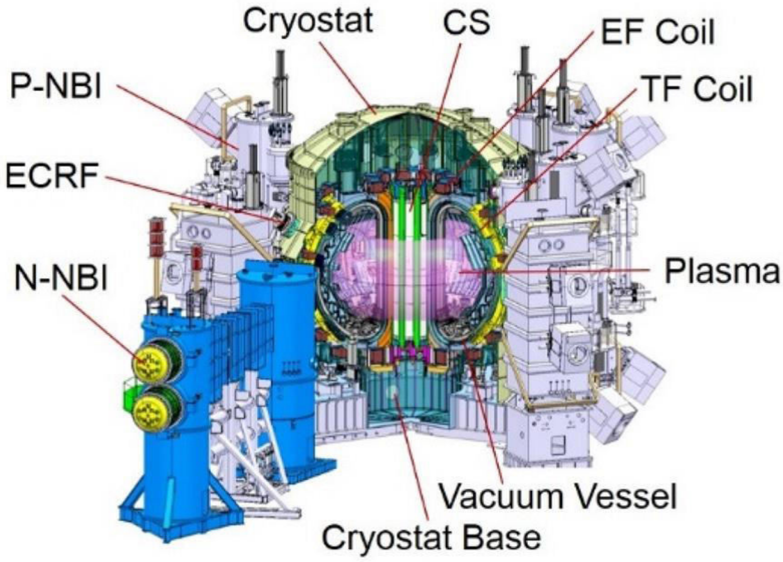

FIG. 13. The JT-60SA device (reproduced from Ref. [44]).

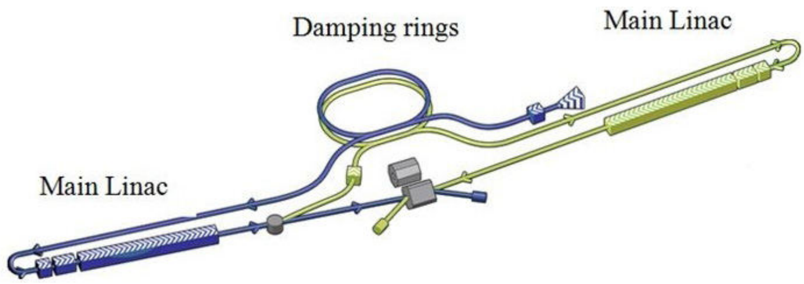

FIG. 14. Schematic layout of the International Linear Collider, not to scale (courtesy of the International Linear Collider project).

Copenhagen and a laboratory test facility and accelerator component factory in Bilbao, Spain. Preliminary decommissioning studies have been conducted and can be found in Refs [45–47]. The preliminary estimate of the decommissioning costs amounts to €300 million [48].

(b) *A future multitera-electronvolt $e^+ e^-$ collider* based on the Compact Linear Collider (CLIC) technology, which is under study. The CLIC concept is based on high gradient, normal-conducting accelerating structures, in which the radiofrequency power for the acceleration of the colliding beams is extracted from a high current drive beam that runs parallel with the main linac. The focus of CLIC research and development over recent years has been on addressing a set of key feasibility issues that are essential for proving the fundamental validity of the CLIC concept. The CLIC accelerator study is organized as an international collaboration with 43 partners in 22 countries. Several larger system tests have been performed to validate the two beam scheme; of particular importance are the results from the CLIC test facility at CERN (CTF3). Both the machine and the detector and physics studies for CLIC have primarily focused on the 3 TeV implementation of CLIC as a benchmark for CLIC feasibility. Specific studies for an initial 500 GeV machine and some discussion of possible intermediate energy stages have also been performed. The performance and operational issues related to operation at reduced energy, compared with the nominal, and considerations of a staged construction programme are included in the conceptual design report [49].

(c) *The International Linear Collider,* for which the schematic layout is shown in Fig. 14. This is a proposed high luminosity linac, based on a 1.3 GHz superconducting radiofrequency accelerating technique, for which the technical design report was prepared in 2012 [50]. It is planned to produce, initially, collision energy of 500 GeV, with the possibility for a later upgrade to 1000 GeV (1 TeV). The host country for the accelerator has not yet been chosen, and proposed locations are Japan, the USA (Fermilab) and Europe (CERN). The site specific design assumes a Japanese site, as a pre-project phase, to start operation around 2030. The International Linear Collider will make electrons collide with positrons. It will be between 30 and 50 km long, more than 10 times as long as the 50 GeV Stanford Linear Accelerator, the longest existing linac. This will be a Class 4 accelerator facility.

(d) *MYRRHA,* which is a multipurpose irradiation facility under study at the Belgian Nuclear Research Centre. It is a flexible, fast spectrum research reactor (50–100 MW(th)), conceived as an accelerator driven system and able to operate in subcritical and critical modes. It contains a proton accelerator of 600 MeV, a spallation target and a multiplying core with mixed oxide fuel, cooled by liquid lead–bismuth. It is the first prototype in the world of a nuclear reactor driven by a particle accelerator. This type of facility will pose challenges at the time of decommissioning as it combines both accelerator and reactor specific problems [51].

(e) *The International Fusion Materials Irradiation Facility*, which is an accelerator based neutron source that will use deuterium–lithium stripping reactions to simulate 14 MeV neutrons from deuterium–tritium fusion reactions [43].

3.8.4. Installations currently under study

The following two installations are currently under study:

(a) CERN has initiated a global Future Circular Collider study [52] as a direct response to the recommendation made in the Update of the European Strategy for Particle Physics [53], adopted by the CERN Council at a special session in Brussels on 30 May 2013. It addresses both approaches within a single, worldwide scientific project:
- Study of a circular hadron collider (protons, ions) with a centre of mass energy of 100 TeV at a luminosity of 5 to 10 × 10^{34} cm^2/s per interaction point;
- Study of a circular $e^+ e^-$ collider with centre of mass energies up to 350 GeV and luminosities ranging from 1.8 (tt) to 28 (z pole) × 10^{34} cm^2/s as a potential intermediary step towards an energy frontier hadron collider;
- Study of a high energy LHC with centre of mass collision energies up to 33 TeV in the LHC tunnel;
- Study of hadron–electron collider options, including an energy recovery linac at a collider in the LHC tunnel or an extension based on a new 100 km hadron collider.

Implementation schedules are oriented towards 2035 as the starting date for a stepwise launch of operation. Although the collider studies are considered site independent, geology, civil engineering, infrastructure and operation studies (including health and safety aspects) build on the experience gathered at CERN.

(b) The Chinese Institute of High Energy Physics announced plans for a domestic circular collider in September 2012. The envisaged facility would host an $e^+ e^-$ collider (Circular Electron Positron Collider with a centre of mass energy in the order of 250 GeV, acting as a Higgs factory). It could also include a proton–proton collider with a centre of mass energy in the order of 50–70 TeV [54].

4. RADIOLOGICAL CHARACTERIZATION OF ACCELERATOR FACILITIES

Activated materials are generated at accelerator facilities following a variety of processes:

(a) Interaction of the primary beam with targets, collimators or other materials that are intentionally (purposely) hit by the beam;

(b) Unintentional interaction of the beam with the structure of the accelerator caused by loss of control of the particle trajectories (beam losses) or the less severe but more frequent small beam losses due to scraping of the wide margins of the beam (‘halo’) in beamlines and their components;

(c) Interaction of radiation that is emitted when the beam is bent (i.e. synchrotron radiation or bremsstrahlung) within the structure of the accelerator or of ancillary components;
(d) Secondary radiation that is produced by all the above mechanisms that may be capable of producing activation (e.g. secondary neutrons, high energy photons).

A number of nuclear reactions can lead to activation; the most important are nuclear reactions produced by the beam particles within the absorbing material. Typical examples are (p, n), (p, α) and similar reactions produced by proton interactions with collimators or targets at proton accelerators.

Activation is also caused by secondary radiation such as neutron induced nuclear reactions, photonuclear reactions (γ, n) or hadronic interactions (spallation) occurring at high energies. Activation products in accelerators are different from nuclear reactors owing to differences in the primary and secondary particles, spectra and materials. In addition, at accelerators, no fission products are produced and very limited, if any, production of alpha emitters will arise (only in the case of activated high Z materials). Typical activation products are beta and gamma emitters with short to intermediate half-lives. Most of the activated materials contain low activity concentrations and can be considered as very low and low level waste [55]. Table 6 lists the typical activation products that are found in the components of an accelerator [7].

Provided mechanical treatments (cutting, sawing, filing, etc.) are not required and surface corrosion is avoided, accelerator waste does not present a significant contamination hazard (e.g. Class 1 accelerators). Although activated materials cannot be considered as sealed sources and appropriate measures to prevent contamination should be adopted, activated elements are mainly in a fixed form and as such will be non-removable.

Surface contamination may result from the deposition of airborne radioactive substances on accelerator components and nearby structures, but surface contamination is not the main concern during decommissioning. When tritium surface contamination occurs, it needs to be managed promptly so that it does not migrate and become a greater problem at the time of decommissioning. The formation of activation products at various depths in the shielding material could in the longer term become a decommissioning issue. The radioactive inventory requiring attention during the decommissioning of the facility is dependent on the type of accelerator and ranges from almost zero to being radiologically significant. The number of radionuclides produced is in principle very large, but in practice only a relatively small number of these radionuclides are of consequence in radiological protection and in the formation of activation products in the shielding and other solid material around accelerators [7]. The radionuclides with short half-lives are only of concern for radiation protection during operation and maintenance of the accelerator and not for decommissioning.

In most cases, accelerators are housed in thick walled concrete buildings that function as shielding. However, a large variety of situations is possible, according to the type and class of accelerator considered; these situations include (a) no fixed barriers (e.g. Class 1 industrial betatrons or linacs for intraoperative radiotherapy); (b) a combination of ‘self-shielding’, intrinsically part of the accelerator, together with a relatively thin walled bunker (e.g. Class 2 self-shielded cyclotrons for PET radionuclide production); and (c) thick walled containment

TABLE 6. RADIONUCLIDES COMMONLY IDENTIFIED IN SOLID MATERIALS IRRADIATED AROUND ACCELERATORS
(reproduced from Ref. [7])

Irradiated material	Radionuclides
Plastics, oils	^{3}H, ^{7}Be, ^{11}C
Concrete and aluminium	^{3}H, ^{7}Be, ^{11}C, ^{22}Na, ^{24}Na, ^{32}P, ^{42}K, ^{45}Ca, ^{152}Eu
Iron and steel	^{3}H, ^{7}Be, ^{11}C, ^{22}Na, ^{24}Na, ^{32}P, ^{42}K, ^{45}Ca, ^{44}Sc, ^{44m}Sc, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{48}V, ^{51}Cr, ^{52}Mn, ^{52m}Mn, ^{54}Mn, ^{56}Mn, ^{57}Co, ^{58}Co, ^{60}Co, ^{57}Ni, ^{55}Fe, ^{59}Fe, ^{63}Ni
Copper	^{3}H, ^{7}Be, ^{11}C, ^{22}Na, ^{24}Na, ^{32}P, ^{42}K, ^{45}Ca, ^{44}Sc, ^{44m}Sc, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{48}V, ^{51}Cr, ^{52}Mn, ^{52m}Mn, ^{54}Mn, ^{56}Mn, ^{57}Co, ^{58}Co, ^{60}Co, ^{57}Ni, ^{63}Ni, ^{65}Ni, ^{55}Fe, ^{59}Fe, ^{61}Cu, ^{64}Cu, ^{63}Zn, ^{65}Zn

(e.g. concrete walled bunkers for Class 1 linacs for radiotherapy, as well as bunkers, or concrete or earth shielding for higher classes of accelerators).

Shielding is required to reduce radiation to levels that are acceptable in terms of dose limits and optimization of staff or public exposure, with due regard for the intended level of human occupancy of the area. Shielding also helps limit damage to materials (thereby prolonging their working life), especially of electronic components, polymers used in pipes that supply cooling water and pneumatic gas pressure for operational purposes.

The shielding design is regarded as very important for protection purposes, but the secondary effects (e.g. generation of the activation products in the shielding material) are also to be appropriately considered.

During the operation of Class 2–4 accelerators, concrete walls become radioactive over time owing to the activation of traces of metals present in the concrete or reinforcement bars; this radioactivity needs to be fully characterized as part of early decommissioning planning.

The radiation resulting from the decay of radioactivity induced in the accelerator structure and its ancillary components remains significant even after shutdown of the accelerator. The precise characteristics of activation will depend on many factors, such as the type of particle, the acceleration energy, the beam current and intensity, and the isotopic and chemical composition of the materials irradiated by the primary beam and secondary radiation [55].

Fluids used in accelerator operation (cooling water and other liquids and gases) can become activated and contribute to the radiation dose to personnel if the accelerator enclosure is accessed during the first hours after shutdown or if the fluid is allowed to circulate outside the shielding during operation [55].

Releases of activated air and water, as well as activation of soil and groundwater by neutrons and other secondary particles, may also have an environmental impact, possibly extending beyond the boundaries of the accelerator site. The radioactivity levels are generally low. In some cases, such as for electron accelerators, the activity may be hard to measure. In such circumstances, sound modelling techniques can be utilized to predict activity in order to draw up an impact report as required by most national regulations and international guidance [55].

Several simulation codes have been successfully adopted and benchmarked for the assessment of the activation of prompt and residual (delayed) radiation as well as induced radioactivity [56–58].

Prior to decommissioning an accelerator, it is essential that a comprehensive characterization survey be completed to include all fluids and soil surrounding the accelerator facilities.

4.1. CHARACTERIZATION OF CLASS 1 ACCELERATORS

All particle accelerators in which the beam energy exceeds 10 MeV will produce some induced radioactivity. Until more recent times, medical and industrial accelerators (almost exclusively electron accelerators) operated at energies less than 10 MeV; however, the use of medical linacs in the energy region above 10 MeV is increasing [12].

Medical linacs operating below 10 MeV, particularly linacs used in radiation therapy, represent the greatest number of Class 1 accelerators in use, with many thousands being installed worldwide. Further information can be found in Ref. [59]. In this type of accelerator, activation is due to (γ, n) reactions arising from high energy photons and bremsstrahlung produced in the head of the units, specifically at the level of the bending magnet and in the target. When high energy photons interact with high Z material, the probability of production of activated nuclei is significant. These high Z materials (lead and tungsten) are found principally in the hardening filters and in the collimator system. Most of the activation products in tungsten will be short lived ^{187}W ($T_{1/2}$ = 23.7 h) and ^{181}W ($T_{1/2}$ = 121.2 d), while in lead alloys the content of antimony gives rise to ^{121}Sb (short lived) and ^{124}Sb ($T_{1/2}$ = 60.2 d). Gold may be present in foils or monitor chambers, leading to the production of ^{198}Au ($T_{1/2}$ = 2.7 d).

Other typical metallic components present in Class 1 accelerators are made of stainless steel, copper or aluminium. Impurities in the alloys of these metals can become activated [60–62].

Table 7 reports the most relevant beta–gamma activation products found in metal components arising from the dismantling of medical linacs. Radioactivity in these metals has three distinct components:

(a) *Decay of shorter half-life radionuclides.* The average half-life of most recovered metal will be in the order of one year.
(b) *Longer lived ^{60}Co.* This is expected to be present at lower levels in the range indicated owing to the lower yield of production.

TABLE 7. MOST RELEVANT RADIONUCLIDES FOR CHARACTERIZATION OF ACTIVATED METALLIC COMPONENTS OF LINACS

Nuclide	Half-life	Activity concentration in metal (Bq/kg)	Activated material
Zn-65	244 d	500–5 000	Machine parts
Co-60	5 y	500–5 000	Machine parts
Mn-54	312 d	500–5 000	Machine parts
Co-57	271 d	500–5 000	Machine parts
W-181	121 d	20 000–100 000	Machine parts
Sb-124	60 d	100 000–150 000	Machine parts

(c) *Individual activity levels in small pieces* showing higher amounts of activation, up to a factor of ten, with respect to the average values reported in the table.

However, while the total mass of waste expected is in the range of 1000–2500 kg, the size and mass of individual components can change significantly; small components could be significantly activated, or 'hot spots' could be detected in a single piece of considerable mass. As a consequence, an approximate and wide range of activity concentration levels is reported for each of the principal radionuclides. Relatively high activity of short lived radionuclides can be substantially reduced by an appropriate waiting time to allow radioactive decay after dismantling.

A lot of information exists that will help with planning the decommissioning of Class 1 accelerators, as many of these units have been decommissioned. This information can be used as the basis of costing for waste and materials management, but predicted activities need to be verified for each of the individual pieces by dismantling the relevant sections of the equipment after they have been checked for activation. There is also a need to consider the possibility of the use of non-standard materials in some units (i.e. tantalum or rhenium foils instead of tungsten). Suitable instrumentation for initial screening includes portable contamination monitors, and for more detailed assessment of materials, portable gamma ray spectrometry systems based on NaI (Tl) scintillation or on CdTe solid state detectors could be used. High resolution portable gamma ray spectrometry hyper-pure germanium (HPGe) systems, when available, can greatly assist in accurately identifying and quantifying the radionuclides present. Samples could also be collected for laboratory analysis, either by using facilities available in house or by sending them to an external measurement laboratory.

Dose and dose rate meters can be used to evaluate the emission from components and to assess the order of magnitude of activation, according to the gamma ray emission constant for the principal radionuclide identified.

Dose rate emission levels from activated components have been measured and have been found to be in the range of 1–5 μSv/h at 20 cm from the linac head and in the range of 0.1–0.3 μSv/h at 50 cm, shortly after use. The principal contributors to these dose rates are short lived radionuclides, such as ^{198}Au, ^{124}Sb and ^{187}W. Dose rates measured after dismantling can be significantly higher owing to the lack of shielding provided by the head. The highest activation levels will be found in target and hardening filters, with dose rates up to several hundred microsieverts per hour at a distance of 20 cm.

Depleted uranium parts were used in older models of linacs, as components of the head shielding or in the collimation jaws. These parts are typically labelled, so that their identification is normally easy. The mass is indicated or can be measured or estimated; the total mass expected is less than 150 kg. Depleted uranium is to be handled with particular care during dismantling owing to the possibility of contamination from eroded or worn out pieces.

4.2. CHARACTERIZATION OF CLASS 2 ACCELERATORS

This class includes a variety of different systems, such as 10–20 MeV proton cyclotrons for PET radionuclide production at hospital sites, 30 MeV proton–deuteron cyclotrons for industrial production of PET or single photon emission computed tomography radionuclides, research cyclotrons with energies of tens of mega-electronvolts, injectors installed at research sites, and other accelerators used for materials science, sterilization, and so on.

All the cyclotrons used for radionuclide production will generate substantial activation of the accelerator itself and of surrounding materials. In all types of system, the beam intentionally impacts targets and collimators.

There is a variety of target materials and target assemblies; in liquid targets (such as for the production of ^{18}F), a chamber frequently made of silver, niobium or titanium is sealed by foils, which can be composed of Havar (an alloy of 42.5% cobalt, 20% chromium, 20% nickel and traces of manganese, molybdenum, iron and others) or in titanium. The assembly containing the target chamber is frequently made of aluminium. The volume of the target chamber measures a few tenths of a cubic centimetre, while the whole target assembly is typically less than 1 dm^3.

Target assemblies for the production of radionuclides in gaseous form (as for the production of ^{11}C) are typically made of an aluminium body with a groove to host the target gas and are sealed again by Havar or titanium foils, the total volume of a target body being $\leq$3 dm^3.

Targets for efficient radionuclide production can be irradiated at beam currents ranging from 10 to 100 μA, depending on the type and efficiency of cooling. Moreover, in current day PET cyclotrons a dual target is a normal feature, so that, for example, production of relevant amounts of ^{18}F irradiating ^{18}O enriched water can be made using the ^{18}O(p, n)^{18}F reaction. Facilities for the commercial production of radiopharmaceuticals, such as fluorine-18 fluorodeoxyglucose (^{18}F-FDG), will run production cycles three to four times a day, whereas a hospital based cyclotron will typically dedicate part of the irradiation time to the production of very short lived radionuclides for internal use only or to the production of radionuclides for research studies; this will result in lower irradiation times than those in commercial facilities.

All the metallic components of the targets will become activated, in particular Havar foils (<5 cm diameter, <0.005 cm thickness) [63, 64]. The activation in the aluminium body target is expected to be mainly due to very short lived radionuclides and so is not of particular concern during decommissioning.

Collimators typically absorb roughly 10% of the beam current and will be significantly activated; the most used materials are tantalum (total mass <200 g) or graphite, the latter having the advantage of producing short lived radioisotopes.

In positive ion cyclotrons, where the deflector and septa are made of copper, the extraction system will absorb a significant part of the beam (up to about 40%) and will be highly activated. In negative ion machines, the extraction efficiency is much higher (>95%) and the components of the extraction system will be activated to a lesser extent; this typically includes aluminium components (frames and support for the graphite stripping foils) and some parts made of iron.

Beam losses in the acceleration process will produce activation in the walls of the vacuum chamber (typically in aluminium, with only short lived radionuclides produced) and in the dees (e.g. copper).

The production of secondary neutrons in targets and collimators is significant and will lead to activation of the accelerator itself and of the surrounding materials and shielding. The magnet yoke (iron with low carbon content) requires specific attention; in the case of a cyclotron for PET radionuclide production, the total mass of iron will be in the order of 20 t.

In the vacuum chamber (aluminium), activation will be limited to short lived radionuclides, while in cyclotrons with an internal ion source, the tungsten chimney of the widely used Philips ionization gauge type ion source is typically activated.

Moreover, in several models of cyclotron, lead alloy bricks or slabs are used to create partial shielding of some components, with potential for the production of ^{124}Sb.

Tables 8–10 list the main activation radionuclides that can be found in components of PET cyclotrons. Given the variety of possible combinations of materials, workloads, and types of target and production reaction, these tables do not claim to be fully exhaustive or to fully represent the range of possible activities that might be present. However, the most relevant radionuclides are reported. Data published in the scientific literature relate to both Monte Carlo simulation of the levels of activity expected or to experimental measurements made on samples from decommissioning. It is not always possible to directly compare simulated and measured data; when such a comparison has been made, agreement has been typically sufficient (within a factor of ten); however, the data

TABLE 8. RADIONUCLIDES PRODUCED BY BEAM PARTICLES IN CLASS 2 ACCELERATORS

Nuclide	Half-life	Activity in waste produced by direct proton irradiation[a] (MBq)	Activated material
V-48	15 d	<0.01–0.05	Target foils
Cr-51	27 d	5–31	Target foils
Mn-52	5 d	3–22	Target foils
Mn-54	312 d	0.3–1	Target foils
Co-56	77 d	6–49	Target foils
Co-57	271 d	2–10	Target foils
Co-58	70 d	15–100	Target foils
Re-183	70 d	0.2–2	Target foils
Re-184	38 d	0.01–0	Target foils
Ta-179	1 y	0.2–1	Collimators
W-181	121 d	8 000–20 000	Collimators

[a] Given the small size of the components considered, the activity is given as total activity and not in terms of activity per unit of mass.

TABLE 9. RADIONUCLIDES PRODUCED BY SECONDARY NEUTRONS IN CLASS 2 ACCELERATORS

Nuclide	Half-life	Activity concentration in waste produce by secondary neutrons in cyclotron components (Bq/kg)	Activated material
Zn-65	244 d	3E+06 to 2E+07	Dees, copper
Co-58	70 d	1E+03 to 1E+06	Magnet yoke
Co-60	5 y	1E+02 to 5E+03	Magnet yoke
Ni-63	100 y	1E+03 to 8E+04	Magnet yoke

showed substantial variability, which is reflected in the tables [65, 66]. More characterization studies are given in Refs [67–69].

Activation takes place in the concrete of the walls of the bunkers of Class 2 accelerators. Table 10 reports a reference range for activity per unit mass in concrete that can be expected at the time of decommissioning. As previously noted for activation of the components of the accelerators, the scientific literature reports both preventive evaluation made by Monte Carlo simulations and experimental data; in the case of walls, however, the collection of samples is relatively easy; several comparisons between simulated and experimental results have been

TABLE 10. EXAMPLE OF RADIONUCLIDES PRODUCED IN CONCRETE WALLS

Nuclide	Half-life	Activity concentration produced by secondary neutrons in concrete walls (Bq/kg)	Activated material
Na-22	2.6 y	1E+01 to 3E+01	Concrete
Sc-46	83.79 d	4E+01 to 2E+02	Concrete
Mn-54	312.3 d	1E+00 to 4E+01	Concrete
Co-60	5.27 y	4E+01 to 2E+03	Concrete
Zn-65	244.26 d	1E+00 to 6E+00	Concrete
Cs-134	2.06 y	2E+00 to 8E+00	Concrete
Eu-152	13.54 y	1E+01 to 5E+01	Concrete
Eu-154	8.59 y	1E+00 to 5E+00	Concrete

made, showing in general a good agreement. Variability in the data in this case reflects both the irradiation history of the equipment and the variety in shape and dimension of the vaults and in the composition of the concrete.

The blocks or ‘shells’ forming the self-shielding that are part of the configuration of many cyclotrons, in particular in the lower range of energies (10–11 MeV), but including also several systems in the 14–18 MeV range, merit special attention. The total mass of the self-shielding elements can reach 25–30 t.

In older PET cyclotrons (those built between 1980 and 2000), the self-shielding was mainly made of purpose built blocks of concrete; in later years, self-shielding has been integrated with elements or components specifically designed to reduce activation (e.g. slabs of borated polythene; boron loaded concrete; tanks filled with specially formulated mixtures of water, sand, iron and borate). This substantially reduces the presence of activated radionuclides in the self-shielding and simplifies disposal or recycling.

In summary, when PET cyclotrons are decommissioned, the characterization phase will require a well structured, comprehensive approach involving a combination of measurements, sampling and mathematical modelling.

All the principal activated components removed from the exterior body of the cyclotron should be disconnected and removed to a suitable secure location for further management to reduce irradiation in the vicinity of the accelerator. These components include targets: foil targets, targets installed on the cyclotron, spare targets and dummy test targets placed in the storage room or workshop. In addition, diagnostics, including Faraday cups, should be removed.

Dose rates from targets a few days after shutdown can still be in the order of 500 µSv/h at a distance of 50 cm; most of the activity will be concentrated in the front part, where the foils are located. Each individual target needs to be manipulated separately, bearing in mind the position of the foils, and transferred to shielded storage before the next target is removed. Portable shielded containers are useful and ought to be used to immediately store each target during transport to temporary storage rooms.

In the case of disassembly of the accelerator, all the internal components need to be clearly identified in advance, taking special note of the following most activated components and their position inside the vacuum chamber:

(a) Collimators;
(b) Extraction;
(c) Internal ion source.

These components have typically limited volume and can be dismounted and removed to minimize radiation exposure to workers and facilitate assessment of activation levels.

The risk of contamination when working inside the open vacuum chamber needs to be considered; a decision needs to be made about whether to proceed with disassembly of these components or perform in advance an accurate cleaning of the interior of the vacuum chamber. All the internal structures of the vacuum chamber need to be carefully inspected to identify hot spots of activation that may be present owing to accidents (e.g. loss of control of the beam during the use of the accelerator).

The dees may have different shapes and dimensions; disassembly is then an operation of variable complexity, depending on the type of cyclotron.

To assess the activation of the magnet yoke, sampling of bolts, screws or other small parts is sometimes possible.

Vacuum pumps can show limited activation; oil may be contaminated and has to be collected separately and checked prior to disposal. Similar consideration applies also to the cooling system. When the cooling system is installed inside the bunker, iron components can be slightly activated, the total volume of cooling water is normally limited to a few hundred litres or less, ^{3}H activity can be present, and some activated products can be contained in cylinders of the exchange resin of the water de-ionizing system.

The components of a helium cooling system may show a low level of contamination; valves, tubes and the compressor need to be checked prior to disposal or recycling.

All the metallic components installed inside the bunker of the cyclotron can become activated, in particular all items containing iron or copper. This can include tubes, valves, connectors, parts of the air compressing system, the ducting of the air-conditioning system, or frames and supports of a false ceiling or a raised floor.

An initial survey of materials requires the use of portable contamination monitors and dose rate meters. Portable gamma ray spectrometry systems (NaI (Tl), CdTe) are necessary to identify the radionuclides. In view of the wide range of activation products present and the resulting complexity of the gamma ray spectra, the use of high resolution portable gamma ray spectrometry HPGe systems is ideal. However, background radiation inside the bunker can make measurement with portable spectrometers challenging; small pieces or samples can be brought to a laboratory equipped with a shielded spectrometry detector for more accurate characterization.

Dose rate meters can be used to evaluate the radiation from components and to assess the order of magnitude of activation, according to the gamma ray emission constant for the principal radionuclide identified.

A German study compared dose rates and activation products found in four high energy medical linacs to evaluate the effects of utilizing different construction materials and methods [70].

Some Class 2 research accelerators (e.g. Van de Graaffs for proton and ion beams) may have used targets with tritium gas for low energy nuclear research. Tritium gas is supplied and retrieved into uranium beds that may contain in the order of 100 TBq of tritium.

In case of a target leak, long stretches of vacuum filled beamlines can be quickly contaminated. It is important to examine the history of operation for evidence of past tritium contamination before disassembling the beamlines and vacuum pumps. Extra precautions need to be taken by workers during disassembly before tritium contamination can be ruled out by sampling and surveys.

4.3. CHARACTERIZATION OF CLASS 3 AND 4 ACCELERATORS

Class 3 particle accelerators are high energy machines in the range of 100 MeV to less than 1 GeV. The types of accelerator in Class 3 are typically proton cyclotrons and synchrocyclotrons and high energy linacs. Proton therapy accelerators fall in this range, as well as accelerators for physics research, neutron spallation sources and light sources.

The first step of the characterization would be a radiological assessment by measuring dose rates at the accelerator and its surroundings. In parallel, activation needs to be assessed, preferably by measurement, or estimated by calculation. These measurements and calculations are used to identify the principal components that are likely to be activated. It is normal for decommissioning activities to be deferred for a defined period prior to the characterization to permit early decay of radioactivity. The appropriate period can be calculated from measurements made during operational activities. Drill cores of structures or samples of equipment parts will be collected for analytical measurement purposes, especially for assessing the depth of activation penetration.

A wide range of the radioactive nuclides produced at a high energy accelerator have an atomic mass number of less than 70. The most important radionuclides are listed in Tables 11 and 12.

TABLE 11. MAIN RADIONUCLIDES IN VARIOUS MATERIALS, AS ACTIVATED IN A LARGE ELECTRON POSITRON COLLIDER *(reproduced from Ref. [71])*

Material	Nuclide	$T_{1/2}$
Aluminium	^{22}Na	2.6 y
	^{54}Mn	312 d
Copper	^{51}Cr	27.7 d
	^{52}Mn	5.6 d
	^{54}Mn	312.2 d
	^{56}Co	77.7 d
	^{57}Co	271.8 d
	^{58}Co	70.9 d
	^{60}Co	5.27 y
Lead	^{105}Ag	41.3 d
	^{122}Sb	2.7 d
	^{124}Sb	60.2 d
	^{203}Hg	46.6 d
	^{202}Tl	12.2 d
Stainless steel	^{46}Sc	84 d
	^{48}V	16 d
	^{51}Cr	27.7 d
	^{52}Mn	5.6 d
	^{54}Mn	312.2 d
	^{59}Fe	44.5 d
	^{56}Co	77.3 d
	^{57}Co	271.8 d
	^{58}Co	70.9 d
	^{60}Co	5.27 y
	^{95}Nb	34.9 d
Iron-concrete	^{48}V	15.97 d
	^{51}Cr	27.7 d
	^{52}Mn	5.6 d
	^{54}Mn	312.2 d
	^{59}Fe	44.5 d
	^{56}Co	77.7 d

The activation varies with the type of accelerated particle, the irradiation history and the characteristics of the material (namely, chemical composition and size). It is not uncommon during the operation of a facility for components to be repaired and subsequently reused in other parts of the accelerator [45]. It would be beneficial if the radiological characterization took into account the different radiation fields to which the components may have been exposed during their operational life [73, 74].

In high energy accelerators, the regions with high residual activation depend on the main sources of radiation during operation. In areas where the beam interacts with the accelerator components and surrounding structures, the main irradiation channel in electron machines will be dominated by high energy photons and secondary neutrons. This radiation can propagate through ducts and shafts of the accelerator (if not properly shielded), thereby producing activation also in areas far from the accelerator tunnel. This is the case for wave guide ducts connecting the radiofrequency klystrons (usually located in auxiliary tunnels) to the cavities in the accelerator tunnel. In hadron machines, beam interactions in accelerator components create more complex radiation fields, but neutrons and photons also dominate radiation fields streaming through long labyrinths, ducts and apertures.

TABLE 12. MAIN PRODUCTION CHANNELS OF SELECTED RADIONUCLIDES IN DIFFERENT MATERIALS IRRADIATED AT HADRON ACCELERATORS
(adapted from Refs [57, 72])

Isotope	$T_{1/2}$	Copper	Stainless steel	Aluminium	Concrete
^{7}Be	53.3 d	Spall (Al, Cu)	Spall (C, N)	Spall (Al)	Spall (O, C)
^{22}Na	2.6 y	Spall (Al, Cu)	Spall (Fe, Ni)	Spall (Al)	Spall (Ca, Si, Al)
^{46}Sc	83.8 d	Spall (Cu)	Spall (Fe, Cr, Mn)	Spall (Mn)[a]	Spall (Fe)
^{44}Ti	60.4y	Spall (Cu)	Spall (Fe, Cr, Mn)	n.a.	Spall (Fe)
^{54}Mn	312.1 d	Spall (Cu)	Spall (Fe, Mn)	Spall (Mn, Fe)[a]	Spall (Fe)
^{57}Co	271.8 d	Spall (Cu)	^{58}Ni(n, pn)	n.a.	n.a.
^{58}Co	70.8 d	Spall (Cu) ^{59}Co(n, 2n)[a]	^{58}Ni(n, p)	n.a.	^{59}Co(n, 2n)[a]
^{60}Co	5.27 y	Spall (Cu) ^{59}Co(n, γ)[a]	^{60}Ni(n, p) ^{59}Co(n, γ)[a]	n.a.	^{59}Co(n, γ)[a]
^{65}Zn	244.3 d	^{65}Cu(p, n)[a]	^{65}Cu(p, n)[a] ^{62}Ni(α, n)	n.a.	n.a.

Note: n.a. — not applicable.
[a] Reactions on impurities of the material.

While activation by synchrotron radiation is not usually an issue, it is possible in circular electron accelerators with energy exceeding 100 GeV.

The residual dose rates in machine components after several years of operation and a few days of shutdown (allowing for decay of short lived radionuclides) are typically important in injection regions and in the acceleration regions (where radiofrequency cavities are installed). These residual dose rates can be in the order of 100 µSv/h up to several mSv/h, with higher levels possible in specific spots.

The majority of activated components in accelerators of both Class 3 and Class 4 are of a solid, metallic nature, including:

(a) Iron and zinc, especially for magnets and cable trays;
(b) Copper, used for the coils of magnets and for electric cables;
(c) Normal and stainless steel, used for supports, pipes for water cooling systems and machine components;
(d) Aluminium for power cables and pipes;
(e) Plastics and resins, used as insulators of electric cables or coating;
(f) Graphite, copper, tungsten, steel or aluminium for collimator jaws, beam absorbers and beam dumps;
(g) Resins from de-ionizing filters in cooling water circuits;
(h) Concrete, used for walls and as biological shielding from radiation;
(i) Earth, which is exposed to radiation in the case of underground facilities.

Within the same family (e.g. steel) there are many different types of material, which differ in density and the presence of trace elements. Trace elements are particularly important for neutron capture, in which high cross-sections can compensate for the small content. Care is to be exercised in the characterization of activated circuit boards, since these are frequently classified for disposal purposes as mixed waste owing to the inherent chemical hazard of the circuit board.

Oils in vacuum pumps and liquids from cooling circuits are the typical liquid activated materials from Class 3 or 4 accelerator decommissioning.

An electron accelerator will normally produce lower residual activity in the components of the accelerator than will hadron colliders. Even though most of the components will fall into the low level waste category, and some of the waste might even be suitable for clearance, some specific parts of large accelerators will have a sufficiently high level of radioactivity to be classified as intermediate level waste and will therefore require treatment and storage according to the level of risk they present.

Owing to the great variability of irradiation fields and of components, the range of variation of the residual activation in different components of accelerators is very wide. As an example, for an electron collider, the values reported in Ref. [75] give conversion factors from average beam power (in watts) to induced specific radioactivity at saturation for radionuclides in different materials [55].

High energy accelerators are normally installed underground owing to their large dimensions and the level of prompt radiation produced during operation. Assessment of residual activation of the ground and rocks surrounding the accelerator's tunnel is necessary when considering decommissioning. This can be substantial for proton and heavy ion facilities, while it is much reduced if not negligible in the case of electron facilities. Borak et al. [76] measured the radioactivity produced in soil by high energy hadrons around two high energy synchrotrons, the 12 GeV Argonne Zero Gradient Synchrotron and the 28 GeV Brookhaven Alternating Gradient Synchrotron. The radionuclides ^{3}H, ^{7}Be, ^{22}Na, ^{45}Ca, ^{46}Sc, ^{48}V, ^{51}Cr, ^{54}Mn, ^{55}Fe, ^{59}Fe and ^{60}Co were identified. A fraction of the activity induced in soil can be leached into and transported by groundwater [77]. In the study by Borak et al. [76], ^{3}H, ^{22}Na, ^{45}Ca and ^{54}Mn were observed in leached waters.

Soil and rock activation is mostly negligible around electron facilities, with a possible exception around high power beam dumps. For example, the radiological impact of CERN's LEP was evaluated before its construction and was extensively monitored during the 11 year lifetime of the installation. The result showed that the radiation areas accessible during the LEP operation were very low and that on the ground surface, the values of ambient dose equivalent were never discernible from the background [78].

Optimization of the design and material selection for accelerator components contributes significantly to minimization of the activation and therefore to minimization of the costs of decommissioning. One possible optimization technique is the preliminary simulation of the residual activation by Monte Carlo codes.

References [57, 79, 80] give a good overview of possible methods based on available codes. In Ref. [81], radionuclide inventories are calculated for a specific accelerator target. The particle transport code Monte Carlo N-Particle X (MCNPX) is used along with the transmutation codes CINDER'90, ORIHET-3 and SP-FISPACT (an inventory code for induced activation calculations in fusion devices). The results generated using the various codes and data libraries are compared with experimental measurements. For more than half the nuclides studied, the codes agree with the measurements within a factor of 2, and nearly all agree within a factor of 10 [55]. However, theoretical estimates need to be validated and improved by sampling. Concrete sampling strategies for the purposes of accelerator activation are described in, for example, Refs [82, 83]. Schumann et al. [84] expand on the radiochemical analysis of accelerator concrete samples.

Special precautions need to be addressed in the chemical characterization of the components: some toxic material (e.g. lead, beryllium, nickel, asbestos) could be present; such material is hazardous if in a friable, powdered or finely divided state. This is important information to be provided when planning decommissioning to ensure that appropriate personnel protection for handling, treatment and storage is accounted for.

5. PLANNING AND IMPLEMENTATION OF DECOMMISSIONING OF ACCELERATORS

The estimated life expectancy of accelerators and reasons for shutting down are almost as diverse as the type of accelerator. Accelerator facilities could be shut down owing to damage by extreme weather conditions, such as tropical storms or tornados, as was the case for the accelerator at the Texas Medical Center, operated by the University of Texas in Houston, USA, which became a victim of an extreme tropical storm in June 2001.

Research accelerators are commonly shut down after having completed their research and applicability scope. Finances, politics, market fluctuations, improved technology, institution goals and ageing of equipment could initiate the shutdown of an accelerator facility. For example, it is estimated that a therapy facility may be replaced after some ten years owing to technological progress (e.g. in beam control systems) or medical knowledge. The decommissioning of the tandem accelerator at the University of Minnesota, USA, as described in Annex I–1, was due to the safety of the building being questioned. Most accelerator facilities are routinely upgraded or refurbished during their operational lifetime. In many decommissioning projects, the components or accelerator facilities are reused, with a minimal amount of waste arising from decommissioning. In some instances, entire units are disassembled, transported to a new location and operated there for some period for the same or other purposes. At the same time, some portions of the particle accelerator may be disposed of while other parts may be reused or modified for use in a new machine in the same building or on the same site.

Planning for decommissioning will ideally commence at an early stage in a facility's lifetime, ideally during the design and construction phase. Early capture of data on design and construction can then be gradually improved during the facility's operation and finalized by the time of final shutdown [85]. The following sections expand on specific aspects of planning and implementation of the decommissioning strategy.

5.1. DECOMMISSIONING STRATEGY SELECTION

Two decommissioning strategies are defined in IAEA Safety Standards Series No. GSR Part 6, Decommissioning of Facilities [85]: immediate dismantling and deferred dismantling. Entombment is generally discouraged and limited to special cases. 'No action' is not regarded as an acceptable decommissioning strategy. Immediate and deferred dismantling are generic terms and do not necessarily mean that the decommissioning should include dismantling of building structures, as this is not essential for all particle accelerators, especially when reuse of a shielded room is anticipated [85]. Modifications of these strategies are possible in the decommissioning of some particle accelerators [21, 86].

An ideal process is for the operating organization to decide at an early stage in the life cycle of the particle accelerator on the most suitable decommissioning strategy and utilize this decision as the basis for future planning [24]. The selected strategy needs to be consistent with the national decommissioning and waste management policy and to take into account the graded approach relevant to hazards associated with the decommissioning of the particular type of particle accelerator.

A multiattribute analysis process can often be helpful in the decision making process and can facilitate justification of the selected decommissioning strategy and plan. Such multiattribute analysis includes consideration of facility specific conditions. The use of appropriate facility specific weighting factors can be made to achieve optimization of the plan. The selection of a decommissioning strategy needs to be based on and justified by both facility and national factors. This justification should be documented and maintained as the basis of the decision making process utilized for decommissioning planning throughout the life cycle of an accelerator.

Immediate dismantling would normally be the preferred strategy for Class 1 particle accelerators, for which typically no benefit will be gained from a 'delay and decay' approach. Conversely, a staged approach, including periods allowing for the decay of shorter half-life radionuclides, might be justified, typically for Class 2–4 particle accelerators. In deferred dismantling, security during the period of safe closure is an important consideration, especially in premises such as hospitals (e.g. with a Gamma Knife) where the public have access to the site.

In general, the staged approach adopted in the phased decommissioning strategy will permit time for access to the necessary resources, decay of short half-life radionuclides so as to reduce occupational exposures, provision of the required management arrangements, and resolution of outstanding technical issues. The staged approach would also provide a period during which radionuclide decay in buildings and materials might reduce the activity level to allow free release.

For particle accelerators, a combination of an immediate and deferred dismantling strategy might be appropriate, resulting in phased decommissioning. After characterization, parts of the machine and its activated components may be dismantled and segregated into radioactive and non-radioactive waste streams. Depending on the levels of activation, the accelerator hall and shielding and other activated materials may be left for an appropriate period of decay, after which clearance may be considered.

During the safe enclosure period, a responsible body, which may or not be the licensee, needs to be appointed to oversee (with appropriate support) the surveillance and maintenance programme to ensure that the required level of safety is consistently maintained and to take responsibility for ensuring that final decommissioning occurs at the soonest appropriate time.

When the finances essential to completing a decommissioning project are not available at the outset, a phased deferred decommissioning strategy could be a better strategy than failure to make progress due to lack of finances [24]. Future re-sale of cleared metals, such as copper, can provide substantial income towards the completion of further decommissioning. Deferred dismantling in a series of phases might be the optimized strategy, in which funds are released at defined intervals. This might be specifically relevant for particle accelerators at government funded establishments, such as hospitals and universities [24].

It is essential that the end state of the decommissioning process be defined at the outset. The most common strategy is to release the facility and site for unrestricted use (sometimes called 'greenfield'). However, other options are viable, including release restricted to specific site use or conversion of the former accelerator to another nuclear or radiological facility. The end state of the decommissioning process has an impact on parameters such as costs, waste generation and management, and duration of the project.

5.2. FACTORS INFLUENCING THE DECOMMISSIONING STRATEGY

The following factors need to be considered in order to define the decommissioning strategy of nuclear facilities, including particle accelerators:

(a) National policies and legal and regulatory framework:
  - Compliance with national policies for decommissioning.
  - Existence of a legal framework that details the regulatory functions and infrastructure, as well as regulatory requirements and the defined standards, to be applied to decommissioning.
  - Well established and understood national authorization/licensing processes to ensure regulation of the particle accelerators from the initial design stage, throughout the entire operational life cycle, through to a regulatory regime relevant for the planning and conduct of decommissioning.

(b) Financial assurance:
  - Availability and security of adequate financial provision, including robust arrangements to ensure timely release of the funds to achieve effective decommissioning.
  - Reliable cost estimate for the selected decommissioning strategy, to include suitable contingency finances to accommodate project uncertainties, so that the accelerator decommissioning strategy can be implemented and taken through to project completion.
  - Market availability and suitable regulatory oversight arrangements for the sale of recycled materials to support the decommissioning budget (e.g. copper pipes at clearance level sold to scrap metal recycling).

(c) Facility specific factors:
  - Complexity of the particle accelerator to be decommissioned.
  - Whether the particle accelerator is a stand-alone facility or part of a multifacility site and whether there are any interdependencies between the facility being decommissioned and other facilities on the site.
  - Historical or cultural values: whether parts of the equipment are suitable for preservation or documentation (e.g. as museum exhibits or historical archives).

(d) Conduct of decommissioning:
  - Reasons for permanent shutdown of the accelerator, if not consistent with the original anticipated operational lifetime of the accelerator (e.g. political, economic, due to an accident).
  - Current availability and ease of timely access to suitable decommissioning technologies and techniques, which may be especially relevant following sudden closure after an accident.
  - All possible redevelopment and reuse options for the particle accelerator (or its components) and adjacent areas.

(e) Waste management system:
  - Existence of an established and suitably regulated national waste management policy and strategy.

— Presence or absence of national clearance levels to facilitate disposal or recycling and reuse of materials (e.g. demolition rubble or metals).
— Amounts and categories of decommissioning waste, including any problem wastes with other chemical, physical or hazardous properties in addition to radioactivity.
— Facility specific waste management plans, including secure segregation and storage arrangements, supported by access to suitable waste management facilities and external disposal facilities. Often, production of the necessary documentation and demonstration of the required on-site control systems to gain acceptance of decommissioning waste at an external facility can be very demanding, resulting in possible delays in the decommissioning process.

(f) Health, safety and environmental impact:
— Safety and health impact, including a comprehensive consideration of how to demonstrate their optimization.
— Environmental impact assessment relevant to consideration of the graded approach to decommissioning, to include the impact of material or waste transportation.
— The physical condition of the particle accelerator facility (e.g. expected integrity of buildings over time and how well they have been maintained since the accelerator ceased operation).
— Impact of the characteristics of the radiological and hazardous material present as part of decommissioning.

(g) Knowledge management and human resources:
— Availability of suitably qualified and experienced personnel (from the particle accelerator or with past experience of other decommissioning projects).
— Knowledge capture, storage and retention from experienced staff prior to retirement or when changing employment.
— Relevance of any lessons learned from previous decommissioning projects.
— Operational history of the accelerator and adequacy of decommissioning related information (e.g. records, drawings), especially when changes to structures and facilities have been made during the operational lifetime of the accelerator.
— Availability of a competent and experienced project management team.

(h) Social impacts and stakeholder involvement:
— Impacts on local communities from the decommissioning process.
— Stakeholder concerns and perceptions and how effectively these can be resolved.

5.3. DECOMMISSIONING PLANNING

Paragraph 1.6 of GSR Part 6 [85] states that "Planning for decommissioning begins at the design stage and continues throughout the lifetime of the facility." The benefits of early planning for future decommissioning include the establishment of optimized procedures to minimize the exposure of workers and the public to radiation, the provision of maximum levels of protection of the environment necessitated by the decommissioning activities, the minimization of radioactive waste, and the timely release of the facility or site from regulatory control at the end of decommissioning activities. Other benefits of considering decommissioning of a particle accelerator at the early stage of operation arise from the establishment of suitable record keeping arrangements, knowledge retention to facilitate decommissioning and provision of both adequate financial and other necessary resources for when shutdown occurs.

For new facilities, an outline decommissioning plan is generally prepared at the time of the initial licence application seeking permission from the regulatory body for the construction and/or commissioning of the particle accelerator. This initial decommissioning plan can be kept updated, and more detailed information added during the facility's operational lifetime to assist in decommissioning [24]. The level of detail of the decommissioning plan will increase throughout the entire life cycle of the accelerator. A multifacility site needs to have an overall decommissioning plan, which takes into account the interdependencies of the individual facilities and activities, the associated constraints and the contents of the individual facilities' decommissioning plans. A standard format and content for safety related decommissioning documents is given in Ref. [87]. Often, particle accelerators have been operating for many years, and decommissioning may not have been considered at the design, construction and operational stages. Under such circumstances, urgent attention needs to be given to decommissioning planning around the time of final shutdown. In 1999, the European Commission carried out a study [14] and discovered that most particle accelerators in the European Union did not have an initial decommissioning plan and had no strategy to prepare one as there was no regulatory requirement for it.

For Class 1 and 2 particle accelerators, a brief decommissioning plan prepared in house by the operating organization will typically not require an environmental impact assessment and will involve, typically, limited decontamination and, often, no demolition, with limited controls and arrangements for waste management. Often, the accelerator room is reused for the installation of a newer model of accelerator [24]. On the other hand, Class 3 and 4 accelerators are likely to have extensive activation of materials and structures, and a more comprehensive decommissioning plan will be necessary.

External project management and external contractors will be required for the major dismantling and demolition work. Characterization may be performed by in-house staff or by contractors external to the operating organization. A complex facility, which is likely to be mainly for Class 4 accelerators, will require a lengthy decommissioning plan, typically requiring an extensive environmental impact assessment and often employing an external project manager because in-house expertise for complex decommissioning arrangements does not exist. The decommissioning strategy for complex Class 4 accelerator facilities typically involves extensive decontamination, demolition and, possibly, environmental remediation of adjacent areas performed by professional subcontractors.

The initial decommissioning plan needs to be reviewed and updated periodically during operation, as prescribed by the regulatory body [85]. A review may also be triggered by proposed changes in the design of the facility, the introduction of different waste management arrangements or alternative disposal routes, changes in the overall financial status, or specific modifications of the equipment or building that will impact the decommissioning plan (e.g. revisions to drainage arrangements, removal of hazardous materials such as asbestos). Revisions or amendments to the decommissioning plan need to also be made during the operational lifetime of the facility to reflect advances in operational experience, new or revised safety requirements, or the introduction of improved technology, as well as changes to the decommissioning strategy and proposed end state that have been agreed with the regulatory body. Such revisions or amendments need to be comprehensively documented and then stored in a suitable record retrieval system so that they will be readily available to facilitate future decommissioning.

The plan also needs to be reviewed and revised when significant accidents or incidents occur that could affect facility characteristics [85]. Comprehensive records of such events and their consequences will be necessary for future characterization of the facility.

Unanticipated shutdown of a facility can be due to a number of factors, such as (a) the owner declaring bankruptcy, (b) severe accidental damage occurring to the facility building structure (e.g. due to flood or fire), (c) the building having serious defects, (d) an ageing building being uneconomical to restore to present day standards, (e) problems arising with asbestos or other hazardous materials that it will be prohibitively expensive to remove or (f) it being no longer cost effective for the licensee to continue operation of the facility. After unanticipated shutdown, the regulator needs to promptly enforce the requirement to have available adequate financial provision for decommissioning, especially if the owner has declared bankruptcy. The regulator needs to seek early submission of the decommissioning plans so that the adequacy and security of the financial provision can be appropriately assessed. When drafting the early decommissioning plan for the accelerator, due consideration needs to be given to the actions that will be necessary if shutdown occurs before a final decommissioning plan is prepared. Suitable documented arrangements that are capable of prompt implementation are needed to ensure that the facility will be safely maintained until a satisfactory decommissioning plan can be prepared and taken forward. The following subsections give brief descriptions of preliminary decommissioning plans for selected accelerators.

5.3.1. Positron–Electron Project, USA

The Positron–Electron Project (PEP-II) facility at the SLAC National Accelerator Laboratory consists of two independent storage rings, one located on top of the other in the PEP tunnel. The high energy ring, which stores a 9 GeV electron beam, was an upgrade of the existing PEP collider; it reutilized all the PEP magnets and incorporated a copper vacuum chamber and a new radiofrequency system capable of supporting a stored beam of high current. The low energy ring, which stores 3.1 GeV positrons, was newly constructed. Injection is achieved by extracting electrons and positrons at collision energies and transporting each of them in a dedicated bypass line. The low emittance Stanford Linear Collider beams are used for the injection process. The collider was completed in July 1998. A preliminary decommissioning plan focusing on activation and waste disposal aspects is given in Ref. [88].

5.3.2. European Spallation Source, Sweden

The preliminary decommissioning plan for the European Spallation Source facility in Sweden proposes that it will be constructed and have an intended operational lifetime of 40 years. According to the Swedish Environmental Code, decommissioning plans need to be submitted when constructing such a facility [45]. Preliminary decommissioning studies, which also include measures taken to reduce activation and simplify decommissioning, are given in Refs [45, 46]. The operation of the facility is intended to produce neutrons for research purposes by utilizing mercury as a spallation source. The mercury will become activated, resulting in the production of a number of radionuclides. In addition, the accelerator system will become contaminated, and induced activity may be created in metals and concrete [45].

The European Spallation Source's main components are:

(a) Ion source;
(b) Linac;
(c) Storage ring;
(d) Target;
(e) Instrument facilities.

The lightweight metal parts (e.g. vacuum pumps, beam transport, pipes) can, after measurements of their activity, be cut using mobile hydraulic shears [45]. When use of such equipment is not possible, hand-operated band-saws or abrasive cutting machines can be used. The plan proposes that all equipment be cut up and compacted on the site. Parts that cannot be freely released will be packed into containers for waste disposal. The large instrumentation utilized in connection with the accelerator might require cutting with remote controlled band-saws. Concrete structures may be dismantled through techniques such as wire cutting, sawing, circular saw drilling, core drilling, cutting with special hydraulic pincers or thermal exposure utilizing electric resistance heating [45]. During decommissioning, some remote controlled equipment is necessary for dismantling, especially of the target system and systems connected to the target station, in order to reduce the radiation exposure of the workers [46].

The volume of activated material will depend to a great extent on beam losses. Decreasing the beam losses or the probabilities for their occurrence can reduce the volumes of activated material considerably [46]. Low level waste in the form of concrete and its reinforcements will be the main activated materials. Relatively short lived radionuclides are dominant, and the elapsed time between shutdowns and decommissioning will affect the residual activity amount. Radioactive waste can be disposed of in landfills or in bedrock repositories [45, 47].

5.3.3. Canadian Light Source, Canada

The Canadian Light Source (CLS) facility was launched in 1999 and started operation in 2004. The CLS research laboratory is a national centre for synchrotron research for the production of high brightness synchrotron radiation from the infrared, visible and ultraviolet through to the X ray region of the electromagnetic spectrum. The CLS facility is a major expansion of the existing Saskatchewan Accelerator Laboratory, located on a 3.3 ha area of land on the campus of the University of Saskatchewan, Canada.

This CLS facility currently incorporates [89]:

(a) Linac: the existing Saskatchewan Accelerator Laboratory 300 MeV electron accelerator.
(b) Booster: a 250 MeV to 2.9 GeV booster synchrotron accelerator.
(c) Storage ring: a 2.9 GeV storage ring and the source of the synchrotron radiation.
(d) Beamlines: for transport of synchrotron radiation to experimental target stations, where scientific experiments or processes requiring synchrotron radiation are carried out.
(e) Services.
(f) Support facilities: facility control, sample preparation, data collection and record archives, maintenance, and administrative areas.

The useful lifetime of the CLS facility is estimated to be 20–30 years from the date of routine operation. The preliminary decommissioning plan identifies that decommissioning of the CLS facility would not present any unique problems and could be done utilizing currently available technology. The 30 page preliminary decommissioning plan details the steps that would be involved in the decommissioning of the CLS facility. The objective described in the plan is to conduct decontamination and remove radioactively contaminated and radioactive materials, equipment and components to obtain release to unrestricted use by the regulatory body.

Box 1 shows the contents of the preliminary decommissioning plan for the CLS [89]. Although the structure of this preliminary decommissioning plan is different from the one suggested in Ref. [87], it is considered an interesting alternative example because it puts forward the conventional and radiological hazards that are to be tackled during decommissioning activities.

5.3.4. Paul Scherrer Institute, Switzerland

The preliminary decommissioning plan for the decommissioning of a 600 MeV proton, high intensity beam accelerator at the Paul Scherrer Institute, Switzerland, is summarized in Ref. [90], with a focus on decommissioning waste generation.

5.4. ENVIRONMENTAL IMPACT ASSESSMENT

An environmental impact assessment (EIA) is a structured process that helps to predict, identify and evaluate the potential impacts to ecological systems, natural resources and the biosphere of a proposal before any major decisions to proceed or commitments are made. The EIA for an accelerator facility is a comprehensive process that needs to consider the radiological and non-radiological hazards (e.g. asbestos, beryllium, polychlorinated biphenyls (PCBs)) and how these might impact decommissioning activities. The assessment also needs to consider and describe how compliance with national requirements for environmental safety will be achieved.

For the majority of particle accelerators, specifically medical linacs in Class 1, an EIA is not required for decommissioning. However, a brief environmental analysis could be included as part of the decommissioning plan. For complex particle accelerators, typically Class 3 and 4, a summary of the EIA and its conclusions need to be included in the decommissioning plan.

If required by national legislation, an EIA needs to be performed to determine whether the potential environmental impacts due to the accelerator decommissioning comply with national requirements. The EIA needs to evaluate both the impact of the decommissioning activities and the impact of any future restricted use of the facilities and site on the public and the environment once the agreed end state of decommissioning has been achieved.

The EIA includes evaluation of the environmental consequences to workers, the public and the environment. The EIA will typically include background information on the facility and its surrounding area, a description of the decommissioning tasks to be performed, a summary of any evaluated alternative methods for decommissioning, a justification for the rationale and impacts of selecting the preferred decommissioning strategy, and any mitigation measures that will be carried out to minimize the impact on the environment. The assessment might also state the likely impacts to the environment from the decommissioning activities. For large accelerator decommissioning projects, the EIA needs to also consider factors such as off-site transportation, geology and soils, water, the local ecology, whether there are any protected biota in the vicinity, impact on air quality, noise levels, historic interest in the site, visual impact resulting from decommissioning, socioeconomic impact, public and occupational health, waste management (pre-disposal), and any other cumulative impacts that might be relevant.

The results of the EIA could be used as the basis for the development of suitable environmental protection measures applicable to the decommissioning project. The conclusions of the EIA might also facilitate defined decommissioning mitigation measures to reduce the identified environmental impact. These mitigation measures need to be reflected in the environmental protection programme and decommissioning procedures. The EIA also needs to be considered during development of the radiation protection programme for decommissioning.

BOX 1. CONTENTS OF THE PRELIMINARY DECOMMISSIONING PLAN OF THE CANADIAN LIGHT SOURCE FACILITY
(*reproduced from Ref. [89] with permission*)

1. Overview
2. Purpose
3. Scope
4. Brief description
5. Principal hazards and physical conditions
   - 5.1 Conventional hazards
     - 5.1.1 Hazardous materials
     - 5.1.2 Electrical hazards
     - 5.1.3 Magnetic hazards
     - 5.1.4 Cryogenic hazards
     - 5.1.5 Oxygen deficiency hazards
     - 5.1.6 Mechanical hazards
     - 5.1.7 Vacuum and pressure hazards
     - 5.1.8 Asbestos
   - 5.2 Radiological hazards
6. Hazard reduction for decommissioning
   - 6.1 Conventional hazards
     - 6.1.1 Physical hazards
     - 6.1.2 Hazardous material hazards
     - 6.1.3 Electrical hazards
     - 6.1.4 Magnetic hazards
     - 6.1.5 Cryogenic hazards
     - 6.1.6 Oxygen deficiency hazards
     - 6.1.7 Mechanical hazards
     - 6.1.8 Vacuum and pressure hazards
     - 6.1.9 Asbestos
   - 6.2 Radiological hazards
7. Surrounding natural and social environment
8. Approach to decommissioning
9. Final end state objectives
10. Financial guarantee
11. Decommissioning work packages
    - 11.1 Administrative/regulatory
    - 11.2 Facility shutdown and deactivation
    - 11.3 Disconnecting and dismantling technical services
    - 11.4 Dismantling accelerator/beamlines
    - 11.5 Bulk shielding demolition and disposal
    - 11.6 Radiological measurements
    - 11.7 Radioactive waste management and disposal
    - 11.8 Site and facility final cleanup
12. Conceptual schedule
13. Cost estimates
14. Records
15. References
16. Appendices
17. Attachments

5.5. PREPARATION AND IMPLEMENTATION OF THE DECOMMISSIONING PLAN

The final decommissioning plan, along with prescribed applications required as part of the regulatory authorization of the accelerator, need to be submitted to the regulatory body for approval prior to commencement of decommissioning. All applicable requirements for the accelerator need to be appropriately maintained unless approved by the regulatory body on the basis of reduced hazards (e.g. the removal of radioactive material from the facility).

The approach to preparation and implementation of the decommissioning plan is generally consistent across the range of accelerators and normally includes:

(a) Applying a graded approach to decommissioning safety requirements according to the class of accelerator (see Section 3.3).
(b) Completing and submitting in a timely manner any necessary licence applications, and obtaining approvals to commence decommissioning from relevant regulatory bodies.
(c) Communicating early, as appropriate, with stakeholders and agreeing on an ongoing communication strategy, as well as establishing clear lines of communication for everyone who might be affected by the decommissioning project.
(d) Ensuring timely and appropriate communication and implementation of radiation protection and waste management measures.
(e) Assigning clear roles and responsibilities and ensuring they are well understood by all persons involved in the accelerator decommissioning project.
(f) When in-house expertise is not available, undertaking the timely employment of a suitably experienced project manager or external contractors to deliver specific decommissioning roles and tasks, and ensuring that their roles and responsibilities are fully documented and well understood.
(g) Providing appropriate training for in-house staff with no decommissioning experience who are intended to participate in the project, ensuring they are aware of the sequence in which their actions must be completed.
(h) Carrying out a comprehensive safety assessment and communicating its findings and conclusions to all those requiring this information. The safety assessment will identify what personal protective equipment (PPE) will be required during the various decommissioning activities; a responsible manager needs to be identified to ensure the timely availability and proper storage and maintenance of the PPE and the provision of any necessary training to ensure its correct use.
(i) Securing availability and advance booking of any equipment to be hired for key tasks during the project (e.g. lifting, cutting or demolition equipment). Ensuring in advance that the written specifications for the hired equipment will match those of the items as supplied.
(j) Reviewing and adapting on-site emergency arrangements, such as for fire or emergency preparedness measures. This will necessitate ensuring that all operators are familiar with any changes resulting from the review, that new signage for emergency evacuation is posted if required and that a mechanism is in place to update operators of any further changes that might be necessary as decommissioning activities progress.
(k) Agreeing and securing the appropriate tools and routes for the movement of materials, waste, containers, packages and equipment into or out of the decommissioning area.
(l) Communicating early with the regulator to secure agreement on clearance levels and the measurement method and calibration of equipment that will be used. Ensuring relevant operators and contractors are competent and in compliance with what has been agreed.
(m) Implementing a suitable management system to be in force throughout the duration of the project.
(n) Securing sufficient funds and resources and agreeing on appropriate timing for their release so as to avoid unnecessary project delays.
(o) Ensuring the availability of suitably qualified engineers to conduct thorough engineering surveys at key stages throughout the accelerator decommissioning project so as to ensure that the structural integrity of the accelerator and its building and infrastructure are preserved in a safe state throughout the dismantling operations.

5.6. ACCELERATOR DISMANTLING TECHNOLOGY

Dismantling techniques for accelerators generally do not differ from those applicable for the decommissioning of other nuclear and radiological facilities (see Refs [91–93]). The following provides examples rather than a comprehensive review of decommissioning techniques for use at accelerators.

Several important actions for implementing decommissioning strategies for a nuclear facility are discussed in Ref. [94].

Another technology selection process for the CERN synchrocyclotron accelerator dismantling is described in Ref. [95]. The conclusions identified as suitable for this decommissioning project are different from those mentioned in Table 13, which confirms that decommissioning technology is best evaluated on a case by case basis.

A technique widely used during decommissioning projects is diamond wire cutting. This method has the advantage of being able to cut with precision any thickness of concrete without producing airborne dust or spreading contaminated material. The main restriction of the method is that it requires a means of threading the wire behind the block to be cut. Reference [96] expands on the use of this technique for the dismantling of the Princeton–Penn Accelerator.

5.7. ORGANIZATIONAL AND MANAGERIAL ASPECTS

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 need to be represented within the project to respond appropriately and immediately to any unexpected occurrences. While quality assurance is an essential component of any decommissioning project, compliance with quality assurance standards and codes needs only to be commensurate with the complexity of the project as identified by the graded approach to decommissioning.

Management process systems and responsibilities are to be tailored to the complexity of the accelerator to be decommissioned, complying with the safety and quality assurance requirements. An integrated approach to project management is best applied throughout.

Management systems and processes are likely to be required to ensure compliance with:

(a) Project management, resource management and financial management;
(b) Legal requirements (to cover safety, environmental and labour legislation);
(c) Licensing and relicensing requirements;

TABLE 13. FACTORS RELEVANT TO THE SELECTION OF DISMANTLING TECHNOLOGIES

Thermal segmentation
• Required elaborate containment and filtration systems • Cutting was limited to approximately 18 inches (46 cm) • Heavy surveillance for contamination control and fire hazards • Safety concerns for gouging out tonnes of molten metal • Safety concerns for heat stress associated with hours of operating torch in full PPE
Mechanical segmentation
• Abrasive wire products at the time exhibited excessive glazing and wear • Stitch drilling provided unlimited cutting capability, however, set-up and operation were impractical and expensive • Cold sawing with hardened circular blades exhibited superior cutting, but, available apparatus was heavy and material had to be brought to the saw • Large band-saw was readily available, but expense and coolant requirements impractical • Milling hacksaw practical with minimal secondary waste generation, but no large delivery system available

(d) Quality assurance, roles and responsibilities, resource management, documentation and records or reporting arrangements, work procedures, events and non-conformance management (contingency procedure), management review and work flow.

References [97–99] provide supplementary information in this field. The overarching safety requirements for integrated project management can be found in Ref. [85].

Table 14 identifies typical mishaps that can occur owing to poor organizational management in decommissioning.

The application of management system requirements can be graded in accordance with the complexity of the accelerator facility to be decommissioned on the basis of:

(a) The significance and complexity of each product or activity;
(b) The hazards and the magnitude of any potential risks to the safety and health of the workers and to the environment, security, quality and economic elements of the decommissioning activity;
(c) The possible consequences, if there is a failure of operation due to the equipment or if an activity is carried out incorrectly.

5.8. STAKEHOLDERS

Generally speaking, accelerator decommissioning is subject to the same stakeholder pressure as any other nuclear decommissioning project. A general overview of stakeholder involvement is given in Ref. [100]. One accelerator specific issue that may arise is that the site owner may not be the same as the accelerator operator (e.g. university, research institute, local or national government) [24]. The site owner may want a guarantee that future redevelopment is not restricted [101].

On the other hand, the public will want a guarantee that all radioactivity and other hazardous materials will be removed with no detriment to public health from decommissioning activities. The public will generally not accept or understand ‘optimization’ of radiation protection. Often, anti-nuclear sentiment will have developed during the period of accelerator operation and will continue throughout its decommissioning.

An example of the involvement of anti-nuclear groups in an accelerator decommissioning project is the case of the Berkeley Bevatron, reported in Ref. [102]. The laboratory demolition plans accelerated a controversy

TABLE 14. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE IN ORGANIZATIONAL MANAGEMENT
(adapted with permission from Ref. [24])

Actions	Consequences
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 complexity of the project.	Confusion among the workers. Unnecessary costs and delays while workers cope with overly complex managerial arrangements.
Roles and responsibilities inadequately defined and communicated to all stakeholders.	Lack of overall control of the 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 under way, leading to delays and additional costs.

among local environmental activists concerned about the prospect of tonnes of radioactive material needing to be transported away from the Bevatron site as a result of decommissioning.

5.9. FACILITY DESIGN FOR DECOMMISSIONING

During the design, construction and commissioning phase of a new facility, the decommissioning requirements need to be considered [24, 85, 103]. Early consideration of decommissioning requirements may facilitate optimization of the design and operation of a particle accelerator that will later facilitate decommissioning. Examples of how decommissioning needs to be considered at the design phase include:

(a) Provision of easy access to areas of the particle accelerator to facilitate routine maintenance, decontamination procedures, performance of dismantling activities and operation of any equipment needed to carry them out, and removal of the accelerator;
(b) Design of the facility to avoid undesired activation of materials or to substantially reduce the likelihood of such activation as well as to facilitate in situ decontamination of pipes, ducts and so on;
(c) Selection of suitable materials or combinations of materials so as to provide a low reaction cross-sectional area to neutron and charged particle activation that will also be resistant to degradation by any chemicals in use at the accelerator and robust in terms of wear resistance to facilitate their decontamination at the end of their lifetime;
(d) Consideration of adequate ventilation so as to reduce or minimize ozone buildup and reduce the likelihood of operator exposure and equipment corrosion;
(e) Early consideration of lessons learned from previous accelerator construction and decommissioning projects so as to improve on the construction design;
(f) Consideration of the extreme range of experiments that might be conducted during the operational lifetime of the accelerator and avoidance of contamination and activation, which is especially relevant for research accelerators.

Although the design considerations detailed above can significantly facilitate easier decommissioning, the application of process and administrative control measures is equally important to ensure facilities are operated within defined limitations (safety envelope).

Often, accelerators are either removed and replaced with a more up to date model (especially at medical facilities) or partially decommissioned and upgraded. For early accelerator installations, ease of decommissioning is unlikely to have been comprehensively considered at the time of construction, so any scheduled upgrade or modification of the installation is an ideal opportunity to consider improvements that will facilitate future decommissioning.

It is important to clearly identify the circumstances during accelerator operation that will lead to activation of materials and to implement possible countermeasures to be taken during the design and construction stage to minimize them. An early in-depth study of machine and shielding activation will also allow better evaluation of the possible radiological impact on workers and the public that will arise as a consequence of decommissioning [14].

An appreciation of the magnitude of radioactivity levels and the associated radiation that will be produced when particles are accelerated to high energies is an essential requirement for the safe and efficient operation, maintenance and decommissioning of a particle accelerator. Although a number of models exist that will facilitate a relatively realistic assessment of all aspects of the activation that can occur in an accelerator during its life cycle, it must be remembered that this will be an inexact exercise despite it being an essential tool to use for early decommissioning planning.

In the design of accelerators, the only radiological considerations that are extensively considered are the shielding and perhaps the target handling mechanism. There are four other areas to be considered at the design stage to better facilitate decommissioning [12]:

(1) *Choice of materials.* The chemical composition of materials used in the facility and the setting of operational parameters can strongly affect the type and activity of radioactive waste and the occupational doses during decommissioning. The production of radioactive waste with a costly or no disposal pathway can be avoided by

a judicious choice of the material composition and the technologies used for the components that are directly exposed to the beam. Furthermore, a minimization of the radionuclide inventory of those components that are closest to the beam can be achieved by performing preliminary calculations and evaluation of alternatives in the earliest design stage. A software developed at CERN for this purpose is called ActiWiz, and it can be used to guide engineers in material choice [104]. The selection of metals, such as the use of aluminium instead of copper in magnet coils, will reduce the production of ^{60}Co. Various shielding materials are available on the market; tungsten alloy material is increasingly popular for making shielding to protect operators from radiation (e.g. for plasma accelerators). Tungsten is 60% denser than lead, which is very helpful for high radiation attenuation. The most important issues to consider are that tungsten material is environmentally friendly but is much more expensive than lead. However, care must be exercised to ensure that tungsten will not pose a higher risk of activation than lead. The advantages of operational safety should be weighed against the possible disadvantages that could be generated for decommissioning.

(2) *Physical layout of the accelerator components.* If there is the possibility to change the layout of an accelerator facility, components and equipment should ideally not be positioned near locations where a large fraction of the accelerated beam will interact [12]. This will shorten the operational life of electronic equipment and may result in the unnecessary generation of radioactive waste.

(3) *Method of assembly.* If the concrete shielding consists of individual removable blocks, it will be much easier to remove each block to perform characterization and separation of waste during dismantling. Some accelerator facilities use a combination of removable blocks and solid walls. This concept, often called modularization, is described in detail in Ref. [105], including advantages and potential drawbacks. An additional advantage of modular shielding is flexibility in configuration during operation of the accelerator. The modular maze pictures from the Hall D Tagger enclosure at Jefferson Laboratory (Figs 15–17) are such an example. If, in the future, a decision is made to rebuild the experimental configuration inside, it will be possible to dismantle the maze, allow access to large equipment, rebuild the experimental set-up and configure a new shielding wall, as needed. This flexibility would not be possible if the walls were permanently positioned.

(4) *Care in operations and maintenance of equipment.* Accurate beam tuning can help reduce the amount of unwanted beam losses that result in the activation of equipment and shielding (by the creation of hot spots). It is therefore important to continually aim for higher efficiency in the extraction of the beam from the accelerator and transport to the target with minimum loss [12].

Figure 15 shows an almost complete maze at the bottom of a truck ramp leading to the Hall D Tagger enclosure. The modular maze can be completely disassembled to allow access or removal of large experimental

FIG. 15. A maze under construction at the ramp leading to the Hall D Tagger enclosure at the Jefferson Laboratory (courtesy of Jefferson Science Associates, LLC).

FIG. 16. Modular shielding in use at the Jefferson Laboratory (courtesy of Jefferson Science Associates, LLC).

FIG. 17. Modular shielding of the maze leading to the electron beam dump in Hall D Tagger at the Jefferson Laboratory (courtesy of Jefferson Science Associates, LLC).

structures or beamline components. The maze structure also facilitates movement of smaller components by use of a forklift truck.

Figure 16 shows another view of the maze from Fig. 15, built of modular block shielding separating the Hall D Tagger enclosure at the Jefferson Laboratory (beamline is visible on the left) from the truck ramp behind the wall on the right. These blocks are also used as local shielding to protect sensitive equipment (far left in foreground of Fig. 16).

Figure 17 shows the modular shielding of the maze leading to the electron beam dump in the Hall D Tagger enclosure at the Jefferson Laboratory. Both concrete and iron blocks are used in this modular shielding, the latter of which are painted (green) to minimize corrosion.

Consideration of decommissioning during the design phase of an accelerator can decrease dismantling costs, minimize unavoidable activation areas and maximize the potential for reuse [12].

Reference [106] presents a study of a hypothetical cyclotron facility from conception to design and then through operation and, finally, decommissioning. The production of induced activity in the cyclotron pit walls was assessed using computer codes MCNPX, Monte Carlo N-Particle (MCNP) and FISPACT (an inventory code for induced activation calculations in fusion devices). These computer simulations highlighted the problems associated with neutron activation of the cyclotron pit walls and the need for special shielding materials, such as borated polyethylene. With these codes it was possible to design a vault for cost effective decommissioning through the use of sacrificial layers. This study [106] illustrates how particle transport codes to quantify the amount and spatial distribution of activation products can be used to arrive at an estimate for waste disposal costs.

The superconducting cyclotron at Variable Energy Cyclotron Centre, Kolkata, India, is at an advanced stage of commissioning and has successfully delivered many internal beams (light to heavy particles) up to the extraction radius. The FLUKA code ('fluctuating cascade', a Monte Carlo code for simulation of radiation transport) was used to estimate induced activity in accelerator components and resulting dose rates encountered by personnel during maintenance work. Simulations using a simple geometry consisted of a thick stainless steel target bombarded by 80 MeV protons, irradiating different common types of material — stainless steel, copper, aluminium and concrete — positioned downstream. Activities of generated radionuclides were calculated for an irradiation time of seven days and cooling times from 1 to 100 000 hours. Results of these simulations identified the long lived nuclides that will accumulate during the lifetime of the facility. The same approach and resulting data can also be usefully applied as an initial planning tool and then to achieve optimization of the decommissioning of the accelerator.

Loss of the primary particle beam is not the only possible source of activation in accelerators. The spontaneous field emission of electrons in high gradient radiofrequency cavities can generate a 'dark current' of electrons reaching energies of several tens of mega-electronvolts and beyond. Loss of these electrons generates activation in accelerator components during radiofrequency operation, with or without beam. In the Jefferson Laboratory, the FLUKA code was used to estimate such activation in cryogenic radiofrequency modules after years of operation, using measured dose rates after a three month commissioning run as a reference. Use of different materials, such as stainless steel, copper, aluminium and niobium, were explored for the most activated component in order to optimize future design. The comparison shows that while short term operations result in the lowest levels of activation in aluminium, stainless steel is the best choice for long term operations and decommissioning.

Other examples of activation studies are reported in Refs [55, 107–117]. Such examples point to the fact that with the continuously improving capabilities of modern particle transport codes it is increasingly easy to include decommissioning considerations at the design stage. The same codes used for accelerator shielding calculations can now be used to predict the nature and extent of generated radionuclide inventories. The first example shows a two step process, in which a general transport code (MCNP/MCNPX) provides input, such as particle spectra, to a special code (FISPACT) that provides information on generated radionuclide inventories, their evolution in time and associated quantities (e.g. gamma dose rates, heat deposition). A few of the general transport codes also have lately included tools for activation production, as illustrated in the two other examples above. While a description of general particle transport codes is beyond the scope of this report, brief details of several codes commonly used for design and radiation safety applications at accelerator facilities are included below:

— *MCNP 6:* Derived from a merger of MCNP and MCNPX codes, which were both developed at the Los Alamos National Laboratory (pointwise X sections vs. multigroup; vast array of predefined source and tally options; adjoint mode calculations). MCNPX addition meant vastly extending the energy range and number of transported particles, making it suitable for accelerator applications.
— *FLUKA:* This code was originally developed for high energy accelerator applications. The modern version has been developed at the Istituto Nazionale di Fisica Nucleare, Milan, Italy, extending particle transport to low energies and greatly extending the code capabilities overall. Lately, added features include tools for activation and radiation damage. FLUKA is widely used at CERN and other accelerator facilities throughout the world.
— *PHITS:* Developed in Japan in collaboration between the Japan Atomic Energy Agency (JAEA), the Research Organization for Information Science and Technology (RIST) and KEK, with additional collaborators in Japan and Europe. This code was originally designed for high energy space and accelerator applications but was later extended to be used for 'low' energies (below 20 MeV) and a wider range of applications. Specific

features include heavy ion transport, tallies for radiation damage and detailed microdosimetric tallies used in radiotherapy.
- *MARS:* This code was developed for high energy accelerator applications at the Institute for High Energy Physics, located in the former USSR, but was later used for the structures, systems and components (SSCs) project. Further development of the MARS code now continues at Fermilab. MARS has been coupled to the MCNP code to extend its energy range below 20 MeV. Early implementation of the MAD (methodical accelerator design) accelerator lattice description and use of the STRUCT (a complex data type declaration to define a group of variables in a block of memory) program for tracking particles in accelerator lattices are among its distinctive features. MARS found applications at major accelerator centres and for particle physics applications in space.

The common features of the above codes are their application to many-particle transport, a wide energy range (from thermal to giga-electronvolts or tera-electronvolts), combinatorial (or similar) geometry modules, sophisticated tools for input preparation, geometry display, and result analysis and display. Additional modules may be available to further enhance such functions or for additional specific purposes (e.g. to provide coupling with finite element analysis codes for heat stress effects calculations or to import geometry and magnetic field maps from specialized accelerator design codes). Since the transport codes are constantly evolving, the most relevant and up to date feature descriptions are likely to be found in more recently published code manuals and related web sites. A thorough, general description of the Monte Carlo method used for particle transport is given in Ref. [108].

6. REUSE AND REDEVELOPMENT OF REDUNDANT FACILITIES AND SPARE PARTS

The initial concept of decommissioning management for facilities generally entails the removal of equipment and the demolition of structures, with final disposal of waste and site restoration [118]. The reuse of both the equipment and the accelerator building after shutdown can be promoted as a decommissioning end point as far as practicable. Large quantities of metal, concrete and other slightly radioactive items from particle accelerator decommissioning could result in high waste management costs in cases where a regulatory provision for clearance is not in place. The activity concentration levels of material produced from accelerators varies considerably. In many cases (especially for Class 1 accelerators), the production of activated materials will be very low. Where activated items or bulk materials are produced that comply with clearance criteria, clearance for recycling and reuse are the preferred choice for further management [119].

It is important to always consider the benefits of reusing a facility for other radiological work. Financial benefits may accrue because it may not be necessary to remove some walls and supporting facilities and because waste disposal requirements are likely to be fewer [24]. Once a definite decision for reuse of a facility is agreed, it is important to carry out as accurate a characterization as possible to ensure suitability to meet the needs for this reuse, taking note of relevant compliance issues such as regulations and licence requirements for the new use. If the end point of decommissioning is not unrestricted use (without regulatory control), 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.

Even if a State makes provision for clearance of metallic waste by utilization of conventional decontamination methods such as melting, the result could still be an expensive solution for waste management when decommissioning accelerator facilities. There could also be a problem with the type of metallic waste generated after melting because it could fall outside the normal acceptance criteria for cast blocks, such that smelters and steel mills could refuse to accept it and it could be prevented from further dilution with other clean virgin metals. In those States where clearance is not implemented, the reuse of equipment and the facility might be possible only in radiological environments.

There are some examples of accelerator facilities that were decommissioned and reused. The Australian Nuclear Science and Technology Organisation's Camperdown facility is a recent initiative in which the Australian Nuclear Science and Technology Organisation and the University of Sydney have been working together to reuse the building that housed the redundant 30 MeV cyclotron to construct a new 18 MeV cyclotron and associated ancillary works. The 30 MeV cyclotron was successfully decommissioned in the beginning of 2011. An important lesson from the reuse of this facility is that it prompted the idea of design for decommissioning. An unshielded cyclotron was selected for various reasons, and one of the reasons was that a shielded cyclotron has the disadvantage of having to deal with an activated shield at the time of decommissioning.

In the safety analysis report for the new 18 MeV cyclotron, the decommissioning strategy and planning were addressed briefly but will only be addressed in detail towards the end of the cyclotron's service life. Historically, cyclotron operations have proven not to generate significant volumes of radioactive waste that would require management in the decommissioning phase. The factors that could influence the production of radioactive waste are known, and the facility will be well maintained and cared for over its lifetime.

Thus, it is likely that decontamination of dismantled equipment will be possible and that the building could be demolished or refurbished as required, after a suitable period for decay of any activated components [120]. The Camperdown decommissioning plan and schedule are given in Ref. [121]. Specific details of the Camperdown decommissioning plan are described in the safety assessment [122], the safety management plan [123], the radiation protection plan [124], the emergency plan [125], the security plan [126], the control plan [127] and the waste management plan [128].

Accelerators could be decommissioned to be transported and recommissioned at another facility. Examples of accelerators being sold and reused in another facility or State have been recorded. However, there is not a flourishing second-hand market for used accelerators because accelerator manufacturers protect their customer information to protect their own businesses. Users are also not comfortable with buying equipment without the appropriate guarantees and service upkeep that are included with the purchase of new equipment. Each decommissioning project needs to be handled as a unique project, and the reuse of equipment should not be assumed as part of the solution to waste minimization and overcoming of decommissioning constraints. Often, a used cyclotron that is still capable of operation is donated to another user to avoid the cost and administrative burden associated with radioactive waste disposal. Reference [129] provides comprehensive descriptions and numerous examples of the factors inherent in the removal and transfer of cyclotrons to other users. One project of this kind is described in detail in Ref. [130]. Focus on accelerator equipment reuse is given in Refs [12, 131].

Sometimes problems might be experienced in the reuse of equipment if some equipment parts were modified by the original user (e.g. coated with epoxy resin or fibre glass for specific purposes). The modifications may limit the reuse of such equipment by a new user and may also result in waste disposal issues during decommissioning.

One related example is given below. The TA-3, South Mesa site, is a large technical area and functions as the administrative centre of Los Alamos National Laboratory. The TA-3 site was developed during the Manhattan Project for use as a firing site. Facilities associated with the earliest use of TA-3 included a shop, magazine buildings and buildings for the storage and assembly of scientific hardware. The wartime technical area was decommissioned and cleared in 1943. The accelerators were regarded as historically important as they were key to the study of nuclear physics, and hence it was important to conserve and reuse them. In 1946, a van de Graaff was constructed at Los Alamos. The Ion Beam Facility, TA-3-16, on the Los Alamos National Laboratory site was built in 1951 and came into operation in 1952 to support essential post–World War II scientific research; it houses Los Alamos National Laboratory's original vertical and tandem van de Graaff accelerators. Over the years, the laboratory made upgrades to the Ion Beam Facility and added the powerful tandem accelerator in 1965. In 1970, the vertical accelerator received an upgrade, allowing it to work at 10 MeV. The US Department of Energy, National Nuclear Security Administration, Los Alamos Site Office, proposes to decommission, decontaminate and eventually demolish this historic accelerator facility. Between August 2002 and January 2005, several historic building surveys were made of TA-3-16. TA-3-16 is scheduled for cleanup and eventual demolition because it is an ageing facility that can no longer provide the level of support needed for crucial laboratory research functions. In preparation for these cleanup and demolition activities, the US Department of Energy has relocated the research formerly done at TA-3-16 to other facilities at Los Alamos and throughout other buildings in the Department of Energy complex. However, owing to the nature of past operations, the Ion Beam Facility is contaminated with tritium and other hazardous wastes and cannot be reused for another function [132]. The following provides a few case studies of reuse of accelerator buildings or their equipment for non-accelerator purposes.

In Canada, a van de Graaff particle accelerator building was converted after release from regulatory control into a high performance computing cluster known as Colossus [133]. In Pennsylvania, another van de Graaff particle accelerator, though decommissioned, is preserved as a local piece of history. The ‘atom smasher’ is on the List of Pittsburgh Landmarks, recognized by the Pittsburgh History and Landmarks Foundation [134].

At Chalk River, Canada, the Tandem Accelerator Super Conducting Cyclotron operated from the early 1960s through to 1997. It was used to conduct basic nuclear physics experiments. The 4200 m^2 facility housed the accelerator, beamlines, target areas, control room and service areas. The building consisted of one main level with a partial second storey and a basement area. This facility was specially built to house the accelerator and beamlines and is constructed of reinforced concrete and shielding up to 1.5 m thick. Attached to the cyclotron is a 1500 m^2, two storey office and laboratory facility with a partial basement constructed of wood with brick veneer siding. Following the cyclotron shutdown, decommissioning was completed with the removal of all process systems, equipment and components, leaving a serviced concrete cavern. The former cyclotron was delicensed and returned to operations for reuse. This vast space was difficult to retrofit owing to the odd angles and thick concrete walls. A number of small rooms were refurbished to house experimental loops, while larger areas with overhead cranes were used for fabrication shops, training rooms and laboratory space, and the former control and computer rooms were converted into office space and maintenance libraries. A project was carried out to expand the footprint of this facility for new laboratory space. The office section attached to the cyclotron was also retrofitted after the closure of the facility. A structural analysis of the building confirmed that it was structurally sound, and plans were developed for modifying the 1940 vintage building. Extensive renovations were completed, which included gutting the building to the outside walls and removing all former interior partitions. New electrical and mechanical services were installed, including an addition to the building to incorporate a fresh air and exhaust fan system. The building was converted into an open office concept to house staff from various groups on the site [118].

Although many facilities might be reusable, this is not always possible. Unsuccessful attempts to convert the Superconducting Super Collider in Texas, USA, to a different use (the last proposal considered was to convert it to a data centre) are given in Ref. [135].

7. COSTS

The cost of nuclear decommissioning cannot be viewed as a simple dismantling activity similar to conventional retired fossil fuel power plants and other industrial facilities. As labour costs have risen and radioactive waste disposal costs have soared, decommissioning costs have become a major consideration in the overall life cycle costs of this industry. In the mid-1980s, the nuclear industry in some States experienced severe construction cost overruns, driving several utility power companies to have severe financial problems. Regulators realized that should operating facilities suffer the same financial stress, the safe shutdown and decommissioning of facilities that have used radioactive material could become a financial burden on the owners, ratepayers and government agencies. Estimates of the cost to decommission these large nuclear facilities quickly escalated in some Member States, driven by the rapidly increasing costs of radioactive waste disposal, and the limited number of facilities licensed to receive this waste. Even in States enjoying more favourable waste management infrastructure, more accurate estimates of decommissioning costs were required by the growing maturity of the nuclear industry.

As part of a study carried out by Argonne National Laboratory in 1979, the decommissioning of four accelerators was examined in detail, and the associated decommissioning costs were recorded. Most of the decommissioned redundant equipment was shipped off somewhere or reused, and very little radioactive waste was generated [12]. The decommissioning costs can be summarized as follows:

(a) US $104 500 was spent in 1971 for the decommissioning of the 250 MeV synchrocyclotrons operated by the University of Rochester [12].
(b) US $735 200 was spent in 1973 for the decommissioning of the 6 GeV electron synchrotron at Harvard University [12].
(c) US $504 000 was spent in 1974 and 1975 during the decommissioning of the 440 MeV synchrocyclotron at the Nuclear Research Center at Carnegie Mellon University [12].

(d) US \$105 000 was spent in 1975 on the decommissioning of the Heavy Ion Linear Accelerator at Yale University [12].

More than four decades have passed since these projects were undertaken, and the costs detailed above will be totally unrealistic in the current market. Furthermore, the costs for these four projects did not include the requirement for disposal of radioactive waste as is common in many accelerator decommissioning projects. The typical present day all-inclusive cost to decommission a Class 1 medical linac is in the order of US \$20 000–40 000. These historical projects do not reflect present day costs for regulatory compliance, waste management and disposal, and labour.

Ameriphysics, an insured radiation health physics and environmental services company based in Knoxville, Tennesee, USA, is a service provider of radiological, environmental and waste solutions. Quite recently, Ameriphysics characterized, removed and disposed of a 50 t, 30 MeV Radiopharma Solutions Cyclone 30 cyclotron (Ion Beam Applications S.A.) and ancillary supporting equipment, two cyclotron vaults, four target vaults, four hot cells and three fume hoods. The cost was US \$6.3 million. This project involved decontamination as part of the decommissioning activities, with subsequent removal and disposal of more 6000 t of low level radioactive waste. Ameriphysics wrote and implemented the site's Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) based final status survey plan and developed release criteria using modelling codes, including residual radioactivity (RESRAD) computer code and MicroShield [136]. The cost estimate for the Tevatron accelerator was around US \$10 million; an accurate cost breakdown is given in Ref. [137].

It is important not to correlate decommissioning costs from one project to another, since a number of variables may significantly affect costs.

7.1. COST ESTIMATES

The cost of decommissioning accelerators is influenced by various factors common to all decommissioning projects, such as the selected decommissioning strategy, the time available for decay, the availability of repository sites in the State, the characterization capabilities of a facility, the resources available, the technology available, the storage facilities available and the national waste management policies. The end state of the decommissioning facility and site is an important factor affecting the costs.

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 under way.

Cost estimation can be one of the most difficult aspects of the project for the newcomer to decommissioning to get to grips with. Whereas an accelerator manager is all too familiar with the day to day running costs of the accelerator and the costs of support services such as waste management and disposal, underestimating the costs for a decommissioning project would mean that the project would be inadequately funded to reach completion. One option might be to provide excessive cost estimates to guarantee that sufficient funds are available. The problem in this case would 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 40% contingency fund), again the cost estimate may be rejected; this will need to be resolved to the extent possible prior to submitting a revised cost estimate [24].

The easiest way for the operator lacking specific experience in decommissioning to pull together a provisional cost estimate 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 [24].

For Class 1 facilities, the licensee will often contact a contractor to request them to tender a fixed price for the decommissioning project. It is quite common for the tender document to require modification once seen by the contractor as often not all the activities required to complete the project are well identified. A common shortfall in the first issue of tender documents is inadequate consideration of the waste and material management that will be required for recycling, reuse and disposal.

The IAEA and other international organizations defined a standardized list of decommissioning cost items [138]. The principal components of the cost projection for decommissioning of an accelerator include:

(a) Quantity of waste in each category that will be generated during decommissioning and the costs per unit for all phases of waste management, including segregation, packaging, transport and disposal. Opportunities to sell recycled materials need not be overlooked as a potential income source.
(b) Costs for document preparation, including the final decommissioning plan and, if required, a plan to access waste disposal facilities.
(c) Costs of any required regulatory permissions or licences for decommissioning, including document preparation.
(d) Labour costs per hour for dismantling.
(e) Costs to hire an external project manager, if required.
(f) Characterization of the facility, including costs of any external measurement facilities.
(g) Requirements to purchase additional instrumentation or equipment when decommissioning is to be carried out largely using in-house staff and facilities.
(h) Costs for remedial actions, including environmental restoration.
(i) Contingency allowance relevant to the project.

Labour costs ought to be based on the unit cost for hire of local labour. When specialist contractors or project management workers are required and such expertise is not available locally, the salary rates of the relevant State from which these workers will be hired will need to be used for the cost assessment. Breaking the decommissioning project costs down into smaller component parts facilitates comparison of the charges that an external contractor would make versus costs to retrain existing staff and complete the work in house for that aspect of the project.

It is important at the outset to ensure that sufficient funds will be available to complete the project, even if not all the funds are available at the start [24]. 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 under way. A 10–20% contingency is usually more than adequate for Class 1 accelerators. Where there are a greater number 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 on the basis of the available supporting data. This is relevant especially for Class 3 and 4 accelerator facilities. The IAEA has published information on the financial aspects of decommissioning [139].

For commercial organizations, such as industrial facilities producing saleable products with a regular cash flow, carrying forward ring-fenced funds for decommissioning from one financial year to the next is generally not a problem. This is often not the case for government funded establishments where money remaining in the facility budget at the end of a financial year will be forfeit. 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 that 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 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’ could usefully be revisited at suitable intervals (perhaps every two to three 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 United Kingdom utilized the provisional budget assigned for decommissioning to upgrade the radioactive facilities when work was projected to continue for a further 20 years instead of ceasing after another three 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 contamination from past incidents or historical sources, waste, or activated components), the larger the contingency fund might need to be. Even when it is thought that all the costs have been accurately quantified and no uncertainties exist, as an absolute minimum, a 10% contingency fund still needs to be allocated, so at least some provision for unexpected findings or cost increases for waste management can be accommodated. When the project is expected to extend over longer periods, it is wise to include an allowance for annual inflation increases.

7.2. COST STRUCTURE

In 2011, a joint publication of the OECD Nuclear Energy Agency, the IAEA and the European Commission [138] provided a standardized list of items for costing purposes for decommissioning (the International Structure for Decommissioning Costing). Cost considerations in this publication were broken down into 11 sections:

(a) Pre-decommissioning actions;
(b) Facility shutdown activities;
(c) Additional activities for safe enclosure or entombment;
(d) Dismantling activities within the controlled area;
(e) Waste processing, storage and disposal;
(f) Site infrastructure and operation;
(g) Conventional dismantling, demolition and site restoration;
(h) Project management, engineering and support;
(i) Research and development;
(j) Fuel and nuclear material;
(k) Miscellaneous expenditures.

Preliminary examination of this list of 11 generic groups for cost consideration might lead to the conclusion that they are irrelevant for accelerator facilities and only suitable for much larger facilities such as nuclear power plants and research reactors [24]. Perhaps this is a correct assumption for the many subgroupings of costs associated with each of the 11 cost groups, but it is likely that ten of the 11 cost groups (to exclude fuel) will be relevant to some extent for accelerator facilities. For Class 1 linacs, the costing exercise will be much simpler as there will be fewer individual cost items to consider under each of the generic cost groups. Furthermore, cost estimation by the licensee is often unnecessary for most Class 1 medical facilities as they tend to be decommissioned by contractors who have agreed a fixed price contract against a tender document to carry out the project. Where cost estimates must be prepared in house, this can be done utilizing simple spreadsheets or decommissioning evaluation software.

Every facility will need to allow some finance for pre-decommissioning actions 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 [24].

It is essential to consider the proposed reuse of the site or facility, as this will have a substantial impact on the decommissioning strategy and costs. It is uneconomical 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 accelerator hall is to be reused as a radionuclide facility. It would be beneficial for the potential for asset recovery to also be considered (e.g. 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, or surplus inventory equipment that has a viable resale market). These resaleable items show as an income stream in the financial spreadsheet for the project. All decommissioning facilities need to budget for radiological characterization and plant shutdown during this phase of the project. For Class 1 linacs, the cost of radiological characterization may be relatively low if all the sampling and measurements can be done in house using existing staff and resources, especially since there is unlikely to be any activated material to consider. 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.

Procurement of general equipment and material might not at first glance appear relevant as a cost consideration when decommissioning a Class 1 accelerator, but this assumption can be incorrect for the higher classes of accelerators.

It may be that the facility 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 need to 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 15 highlights numerous issues that can arise from inadequate assessment of decommissioning costs (not necessarily specific to particle accelerators) [24].

A wide range of costs are included in Ref. [24] for dismantling activities of items for costing purposes. For this reason, it will have cost implications for every decommissioning plan. Dismantling activities will be a substantial aspect of the budget for Class 3 and 4 accelerators, especially when limited depth cutting to remove activated concrete is required prior to demolition of the remainder of the non-activated structures. When decommissioning is to be staged over a protracted time period to allow decay of radioactivity, dismantling activities may be focused on achieving a safe state for decay storage. The generic aspect of dismantling cost assessment requires inclusion of cost estimates for the workforce and any other requirements to carry out a whole range of tasks of decontamination prior to dismantling, transferral 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, environmental remediation, decontamination for recycling and reuse, personnel training, asset recovery, and final radioactivity survey.

One of the costliest aspects of accelerator decommissioning, especially when activation is present, relates to the field of waste and materials processing, storage, transport and disposal. This aspect of the budget needs to meet the costs of preparing any dismantled components either for final disposal as radioactive waste or for restricted or unrestricted recycling or reuse. All 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, landfill or a specialist repository would ideally also be included, as well as costs of waste containers and fees levied by a waste storage facility.

TABLE 15. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE IN COST ESTIMATION [24]

Action	Consequences
Failure to adequately communicate regulatory end point requirements to the facility owner or operator when these conflict with the owner or operator’s 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 due to failure to recognize lack of skill in the field and seek the necessary training or employ the services of an external consultant.	Difficulties in delivering the project if underfunded or if 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 increased project costs, additional maintenance costs prior to dismantling, and possible safety issues. May result in pressure from regulator, donors or other stakeholders to progress with decommissioning.
Failure to establish adequate cost projections.	Insufficient funds to complete the project. Likely to result in regulatory action, especially if the holding point presents additional safety issues. Delays while additional funds are secured. Budget cost likely to increase with time.
Identifying an inflated cost projection to avoid being underfunded.	Management rejecting the data and requiring a resubmission, resulting in delay in funding provision. Overall project inertia as management are unable to fund the overinflated cost projection.

Site security, surveillance and maintenance will have a greater financial impact when decommissioning is staged to allow for decay of short lived radionuclides. This aspect of the cost assessment focuses on site protection, control and maintenance activities and might also include finance to pay for final cleanup and landscaping of a site. There may be a need to finance independent verification of cleanup standards when sites are to be reused, so this cost would be included here. Any perpetuity funding for restricted release of a building or site would 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 [24]. However, large decommissioning projects also offer opportunities for synergies in process organization, which will limit the cost increase. 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 service provider or demolition experts will depend on the type and complexity of the accelerator facility to be decommissioned [24]. In some projects, more relevance might be given to the costs of set-up arrangements, such as a temporary decontamination facility for personnel, an area to segregate clean waste from wastes requiring further measurement, and 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 in the cost assessment. Although it may not be immediately apparent that these processes will have a cost implication for the 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 the management of changing technology. For larger projects in which public stakeholder engagement is necessary, the costs of public relations might usefully 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 do cost implications for industrial safety.

Section 3.3.9 of Ref. [138] identifies that a cost assessment of the implications of research and development necessary to support the decommissioning plan needs to be considered and included, if appropriate. This is unlikely to be required for Class 1 or 2 accelerator facilities but may be required for untested decommissioning technologies, such as might exist for larger research accelerators. This aspect of decommissioning is likely to include costs to review available technical options and to select (or to adapt) the preferred way to complete specific tasks of the project, and any mock-up trials as part of as low as reasonably achievable (ALARA) planning.

Section 3.3.11 of Ref. [138] 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 insurance, 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 the sale of equipment purchased specifically for use during the project that has a resale value, as is frequently the case in accelerator decommissioning projects.

7.3. 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. When overspending has 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 to ensure that all 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). When decommissioning is not unrestricted, the regulator may require some funds to be held in reserve to meet the residual financial liability for the facility. Table 16 shows how poor management of financial reviews may lead to undesirable consequences [24].

The decommissioning costing ought to be done throughout the life cycle of an accelerator facility:

(a) The initial decommissioning cost could be determined on the basis of calculations.

TABLE 16. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICE FOR THE FINANCIAL REVIEW [24]

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

(b) The decommissioning cost could be refined during operations on the basis of measurements, and this would also encourage minimization of the total inventory.
(c) The estimated decommissioning cost will be periodically revised and adjusted and then, after shutdown, will be based on a final radiological survey and inventory [101].

7.4. FUNDING

A typical scheme that can be used to fund the decommissioning of particle accelerators is provided by the US Nuclear Regulatory Commission [140]. In the USA, any licensee that the regulatory body authorizes to possess radioactive material in excess of the limits specified in the legislation must submit a decommissioning funding plan and provide a certificate of financial assurance to demonstrate how the level of funding required to meet the costs of decommissioning has been assured.

The regulator needs to be convinced that the licensee will be well placed to carry out decommissioning requirements with minimum impact on both public and worker health and safety and without adverse impact on the environment, including secured provision of timely and adequate availability of funds. Most accelerator production facilities are required to submit a decommissioning funding plan and financial assurance certificate because of the activation materials that are produced during operation, which are likely to exceed the limits specified in the legislation (typically the stated limits for radioactive material of half-life greater than 120 days). These financial assurance requirements may specify that a licensee either set aside funds for future decommissioning and increase the financial provision as appropriate throughout the lifetime of operation of the accelerator or provide a financial guarantee, often through a third party, that funds will be available. The latter arrangement is more common for government owned and funded facilities. Reference [141] describes a case in which the Nuclear Regulatory Commission suspended the licensed activities of an accelerator facility because of lack of evidence that sufficient decommissioning funds had been allocated.

Even if a decommissioning funding plan is not a regulatory requirement for a Class 1 accelerator facility, licensees are required to maintain decommissioning records, in a suitable archive, that provide comprehensive information on the structures and equipment where radioactive materials will be present, including the storage of components previously removed from the accelerator.

The licensee is required to maintain records in an easily retrievable format in a secure location until the site is released for unrestricted use. In the event that the accelerator is removed and ownership is transferred to a new legal entity, relevant records need to be transferred to the new licensee prior to transfer of the licensed activities. The new licensee will then assume responsibility for maintenance of the records until the licence termination is agreed with the regulatory body. Comprehensive and suitably detailed record keeping will facilitate area release and licence termination.

The mechanism for financial guarantee of the future decommissioning of the TRIUMF accelerator facility in Canada is detailed and evaluated in Ref. [142]. Regulatory approval follows from a detailed examination of the facility's safety performance over several years. A case of lack of funds impeding reutilization or decommissioning of an accelerator is given in Ref. [143].

8. RADIOACTIVE WASTE MANAGEMENT

8.1. GENERAL ASPECTS OF RADIOACTIVE WASTE TREATMENT AND MANAGEMENT IN DECOMMISSIONING PROJECTS

In preparation for decommissioning, all operational waste (e.g. used targets, components of the accelerator or radioactive materials for ion sources or guns) will need to be removed and properly managed. If this cannot be achieved, the waste will need to be included as part of the overall decommissioning project.

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

(a) Minimize the quantities of radioactive waste at all stages of decommissioning;
(b) Prevent the combination of waste of different categories (e.g. radioactive waste, hazardous chemical waste);
(c) Comply with all applicable regulations in the handling, storage, processing and disposal of the waste.

The IAEA has issued numerous publications that provide information on the conditioning and packaging of waste for storage and disposal that is generated from non-nuclear power operations [144–146].

Many publications are also available to assist those wishing to quantify the level of activation products present in concrete and those wishing to understand the limits of detection of various instruments [147−149]. Publications relevant to the investigation of induced radioactivity, the validation of computer codes for predicting induced radioactivity and radionuclide characterization studies of radioactive waste produced at high energy accelerators include Refs [55, 58, 75, 79, 80, 109, 110, 150]. Record keeping is required for each stage in the waste management process. Relevant safety aspects are also dealt with in other IAEA publications [145, 151, 152].

Similar to that of many other radiological facilities, the bulk of the waste resulting from the decommissioning of accelerators will qualify for unrestricted (free) release owing to the insignificant level of radioactivity that will be present. Most IAEA Member States have enacted legislation that provides for clearance criteria to facilitate the release of waste that is in compliance with the numerical radionuclide values below which materials can be released from regulatory control. The situation is different in France, where there is no regulatory provision to permit the use of clearance criteria. The German Commission on Radiological Protection published specific guidance on clearance of accelerators and the removal of accelerator parts from controlled areas, which is given in Ref. [153]. Guidance on internationally agreed criteria for the clearance of solid materials was promulgated by the IAEA in 2004 [154]. In many States (e.g. Germany, Japan), release criteria depend on further use of the components or materials (e.g. within the nuclear industry or for unrestricted use).

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 under way. It is essential at an early stage to approach the operators of the waste management or waste disposal facilities that will be receiving each type of waste from the decommissioning project (including any opportunities that exist for recycling or returning parts, or even the whole accelerator, to a manufacturer) 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 (or other solutions can be identified).

Decommissioning activities should ideally not be initiated until well defined waste management arrangements, including any new or revised regulatory permissions, are in place and workers are fully trained in the implementation of the new procedures and any associated risks.

Problematic waste (e.g. mixed, chemical, toxic) needs to be properly identified and cleared for disposal to the appropriate route. Details of the IAEA waste classification scheme can be found in Ref. [155]. The IAEA scheme is based on disposal options, but it can be supplemented by other schemes based on, for example, dose rates or physical properties (combustible, compressible, etc.).

Waste management procedures for the decommissioning project need to be established and documented, if not already available [24]. Existing documented waste management procedures may require review 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 amendments identified through consultation with the regulatory body.

Consideration might usefully be given to the possibility of any biological hazards, including disease-causing organisms that may be present, especially when decommissioning medical premises.

The waste management procedures need to identify any PPE that may be necessary and is likely to be supported by a safety assessment [24]. When increased quantities of disposable protective clothing are required to safely conduct various decommissioning activities, their purchase and disposal needs to be considered, along with an assessment of the site capability for management of the resultant increased waste volumes that will need to be stored until the time of disposal [24].

Every decontamination technology will generate waste that will need to be managed. Careful planning and use of the most appropriate decontamination technique will minimize the production of secondary waste.

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 is more expensive than recycling the material. It is therefore essential to evaluate a cost–benefit analysis, comparing the costs of further decontamination with the benefits of clearance to recycling. This exercise is best 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 waste that either has no detectible radioactivity or contains 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. Waste characterization in volume is normally performed on the basis of gamma emitters only. Beta emitters may require ad hoc measurements or correlation to readily detectable gamma emitters. 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.

When the predicted waste volumes from a project are very small, the cost and effort required to demonstrate that regulatory clearance levels have been met might exceed those for disposing of the waste as very low level waste or very short lived waste. This needs to be considered as part of the decision making process when identifying the segregation and waste management options for the project.

Early consideration is to be given to all the categories of materials and waste likely to arise and their individual characteristics [151]. This point is a key component of early planning, which is essential for the smooth, timely and cost effective conduct of decommissioning.

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 issued a number of publications describing the different characteristics of the waste classes, but a particularly useful reference is Ref. [155], in which the IAEA has promulgated a standard categorization for use across 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 [155, 156]. These limitations often include the physical waste form, the activity level and the presence and concentration of other non-radiological constituents. The low level waste repository in the United Kingdom, located near the village of Drigg in Cumbria, provides its users with an extensive list of waste properties that are unacceptable, such as wet waste, biological materials and waste with corrosive or explosive properties. These factors need to be explored in full before any licence application is made to the regulator to accommodate the disposal of the waste streams arising from decommissioning.

Suitable instrumentation with a traceable calibration needs to be available for the measurement of waste and materials. In some cases, existing monitors available in the facility or laboratory will be suitable, but for more complex decommissioning projects, it may be necessary to purchase specific equipment, such as a germanium detector [24].

When identified single radionuclide (e.g. ^{60}Co) activity is present in structures, a dose rate instrument suitable for the measurement of that radionuclide can be used and a formula used to equate the measurement made to a dose rate equivalent, subject to agreement with the regulator. It is possible to derive a dose rate equivalent for the instrument that relates to the regulatory end point for that radionuclide in becquerels per gram and allows ready comparison with the waste acceptance or clearance criteria.

The expense of purchasing a germanium detector is rarely justified when decommissioning a simple facility, but the costs are worthwhile when decommissioning a more complex facility, such as a particle accelerator of Class 2–4. For a simple facility, like a Class 1 or 2 particle accelerator, often a sodium iodide detector is sufficient. Table 17 provides a long, if not exhaustive, list of examples of poor waste management practices [24].

TABLE 17. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES IN WASTE MANAGEMENT [24]

Action	Consequences
Failure to adequately categorize and segregate materials and waste.	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 waste.	Lengthy project delays while 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 waste.	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 owing to inadequate space to separate the different waste categories.
Failure to avoid the generation of problem waste.	Loss of confidence by regulator. Possible safety and security issues. Additional resource requirements. May be left with waste for which there is no existing disposal route, causing delays to licence termination. Mid- to long term radioactive waste storage may be required.
Failure to have available suitable instrumentation and formulas to identify, measure and quantify waste.	Shortfall in project budget when additional equipment has to be purchased or an external approved contractor has to be employed 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, and so on. As the cost of waste disposal increases constantly, disposal costs will be higher. The acceptance conditions for disposal could change, 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 owing 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, leading to delays to the overall project.

8.2. SPECIFIC ASPECTS OF RADIOACTIVE WASTE TREATMENT AND MANAGEMENT IN DECOMMISSIONING PROJECTS

Equipment and structure activation cause remnant ambient dose rates inside accelerator tunnels and target areas but also mean that when accelerator components are being removed at the end of their operational life they need to be treated as radioactive waste. The production of large quantities of activated material could thus arise when a whole accelerator complex of Class 3 or 4 is decommissioned [157].

Most of the radioactive material produced in accelerators consists of solid bulk components (e.g. vacuum chambers, pumps, magnets, other beam elements), mostly redundant metallic components with very low risk of contributing to any contamination. Over a service life that can reach decades, accelerators and shielding material become activated through the impact of both primary and secondary particles on equipment and structures. The level of induced radioactivity varies considerably from one accelerator to another and is dependent on factors such as the type or class of accelerator, the location of materials and components with respect to the beam losses, and the operational factors. Considerations for waste characterization are provided in Ref. [158].

It is expected that large quantities of waste can be generated in cases in which the facilities are extremely old and were not operated correctly and in which there was no prior consideration of adopting measures to minimize activation. If the accelerator beams are not aligned correctly, hot spots in the shielding material could be created, resulting in significant volumes of radioactive waste.

Waste quantities could really be an issue in cases in which the equipment and especially the building will not be reused for similar applications. Recycling within the nuclear industry is certainly a reasonable elimination pathway for at least a large fraction of material.

A specific problem that often is discovered at the time of accelerator decommissioning is that during the long operational lifetime of the machine, the range of experiments carried out has changed, resulting in alterations being made to the beam times, beam currents and materials within the accelerator; these changes are often poorly recorded. In addition, the suppliers of the construction materials might have changed over the years, and each of them might have been free to use different material sources. In such a situation, the material composition may be untraceable and it would be difficult to get a reliable nuclide inventory. This problem and other waste management issues are dealt with extensively in Ref. [159] in the context of accelerator decommissioning at the Paul Scherrer Institute, Switzerland. Radioactive waste could be cleared eventually, if sufficient time were allowed for the nuclides to decay, depending on the radionuclides present and the feasibility of holding the waste until it decays and of its being disposed of as unrestricted (free) release. The IAEA has developed standards that could be used when clearing radioactively contaminated material for unrestricted use [154].

Generally, radioactive waste generated during accelerator decommissioning, could be disposed of as low level waste or very low level waste in accordance with the IAEA waste classification scheme [155]. However, according to Ref. [155], a large portion of accelerator decommissioning waste can be classified as very short lived waste. This waste category consists of waste that, after a relatively short period of decay storage extending up to a few years, can be cleared from regulatory control according to arrangements approved by the regulatory body for uncontrolled disposal, use or discharge. This class includes waste containing primarily radionuclides with very short half-lives that typically have been used for research and medical purposes.

If a State has no generic clearance levels, as is the situation in France, the management of radioactive waste arising from accelerator decommissioning material could result in high waste storage or disposal costs. To address this problem, France has adopted a ‘zoning’ concept, whereby waste can be in principle released from regulatory control depending on its location in the accelerator and the operational history of the machine. Significant applications of the ‘zoning’ concept in the context of accelerator dismantling projects are given in Refs [160, 161]. See also Section I–5.

The management of radioactive material at a high energy accelerator facility is an ongoing process. For example, obsolete activated vacuum chambers or cables are transferred for radioactive storage as part of routine operations, while bigger parts like whole activated magnets are usually transferred to storage during longer shutdown periods [157]. Generally, materials requiring radioactive decay prior to further handling are left in interim storage.

The situation is more complicated for radioactive waste because national laws apply to final disposal, but regulators might also require measures to be taken to treat the material while it remains at the site of the accelerator facility [157]. The preconditioning of radioactive waste can result in great expense because the operator of the waste disposal facilities could require the use of specific containers for the waste to be accepted in the final repository.

At present, operational accelerator waste in most facilities is not conditioned for possible final disposal at radioactive waste disposal sites because it is believed that the waste can eventually be cleared. However, if a State does not accept waste clearance, all operational waste will be regarded as radioactive waste. In this case, it is of the utmost importance to reduce the activation at the source (by minimizing the beam losses and by performing an accurate selection of the materials of the components) as well as to limit as much as possible the creation and spread of contamination during the dismantling processes.

Waste from accelerator facilities that has been inadequately characterized, resulting in the radionuclide inventory not being fully identified, will become a problem. In particular, the national repositories could claim that unknown radionuclides resulting from high energy spallation reactions will add to the normal radioisotope inventory due to classical (n, γ) and (γ, n) reactions. Monte Carlo techniques and measurements are both used to quantify the radionuclides formed where simple gamma spectroscopy, in many cases, is insufficient [157].

Radiochemical methods are ideal for the determination of such radionuclides as ^{55}Fe, ^{63}Ni or ^{3}H in solid materials. The number of these cumbersome and expensive evaluations can be reduced by evaluating (by Monte Carlo methods or analytical methods) the activity ratio between a gamma emitter (normally ^{60}Co or ^{22}Na) and these radionuclides that are difficult to detect. The radiochemical analysis will result in a validation and scaling to absolute values of this ratio. In applying this method to radioactive waste, the assurance of traceability is most important [157].

Owing to the interaction of the primary beam or to secondary particles produced in a multitude of nuclear processes, induced radioactivity is unavoidable, and therefore accelerator components need to be treated as though they are radioactive until clearance activity can be proven. Characterization may often provide technical challenges, and incorrect characterization or improper methodology being applied might result in the wrong classification of waste. It is very important to have a well defined characterization plan agreed with the regulator, the waste disposal facility and the accelerator operator.

Normally, characterization methods and plans are not a regulatory requirement and are not subject to regulatory approval for accelerator facilities as is the case for nuclear facilities such as nuclear power plants and nuclear fuel cycle facilities. Furthermore, it would be prudent to discuss and have a clear understanding of the waste acceptance criteria and waste packaging requirements of the waste disposal facility such that waste is not rejected and does not require reworking.

As a rule, accelerator facilities do not generate a lot of operational waste. This, however, depends on the type of accelerator facility and the range of activities performed. Accelerator facilities with associated isotope production activities could generate more operational waste that will have to be managed. Accelerator decommissioning waste would be different from its operational waste and would require a detailed evaluation of the waste categories expected to be generated during decommissioning. Such evaluations would include the characterization of waste and assessment against the waste acceptance criteria of available waste disposal facilities. The waste acceptance criteria of a disposal facility will normally specify waste package requirements or processes for approval of non-standard waste packages or items. Close liaison with the regulator and the disposal facility operator would be required to establish a waste management plan that caters to accelerator decommissioning waste.

Another example is the van de Graaff laboratory in Studsvik, Sweden. This laboratory was used for neutron physics experiments from 1962 to 1989. The laboratory was never classified as a nuclear facility during its operational lifetime, but subsequently it was discovered to be extensively contaminated with tritium.

A comprehensive characterization was performed to identify the contaminated material and surfaces. After thorough decontamination, the building was released from regulatory control and demolished in 1999. Three drums and one steel box containing tritium contaminated waste are held in a radioactive waste storage facility [162]. Further unexpected contamination problems such as this will likely still be identified in the future and will result in the generation of historical radioactive waste that has been unaccounted for.

An example of accelerator material characterization in the light of decommissioning is given in Ref. [150]. Measurements and other procedures intended to segregate accelerator waste into different categories for the purposes of waste storage and disposal are described in practice for the Deutsches Elektronen-Synchrotron centre in Germany in Ref. [163].

9. HEALTH AND SAFETY

9.1. IAEA SAFETY STANDARDS

Radiation and conventional safety are as intrinsic to decommissioning as to routine work activities. There are a number of relevant publications in this field (e.g. refs [52–55] of Ref. [24]). The safety requirements of a management system for facilities and activities are detailed in IAEA Safety Standards Series No. GSR Part 2, Leadership and Management for Safety [164]. Safety requirements specific for decommissioning are given in GSR Part 6 [85]. IAEA safety guidance on safety assessment for decommissioning, including descriptions of hazards and accident scenarios, is given in Ref. [165]; Ref. [166] details the graded approach to safety assessment.

During decommissioning, the workers, the public and the environment need to be properly protected from radiological and non-radiological hazards. The relevant dose limits for the exposure of workers and for the exposure of members of the public need to be applied during decommissioning [85]. National regulations on protecting the environment and the environmental protection requirements of the current basic safety standards of the European Union need to be complied with during decommissioning, and beyond, if a facility is released from regulatory control with restrictions on its future use [85]. Compliance also needs to be demonstrated with the environmental discharge limits detailed in the licence granted by the regulatory body. A comprehensive radiation protection programme is necessary to ensure that the radiation protection of workers and the public is optimized during decommissioning. Optimization needs to take into account the specifics of the decommissioning project. The radiation protection of persons who are exposed as a result of decommissioning actions needs to be optimized with due regard to the relevant dose constraints [85].

Although the principles and aims of radiation protection during operations and during decommissioning are fundamentally the same, the methods and procedures for implementing these principles may differ. During decommissioning, different work scenarios are likely to arise that may require the use of specialized equipment and the implementation of certain non-routine procedures.

During decommissioning, adequate controls need to be applied through the use of a comprehensive integrated management system. The integrated management system will provide a single framework for the delivery of decommissioning activities, including safety procedures that will ensure the protection of workers against, or mitigate the impact of, potential exposures from incidents or accidents during decommissioning. Other IAEA publications give guidance for such situations [86, 165, 166]. The licensee is responsible for all aspects of safety, radiation protection, and protection of the environment during decommissioning [85].

The operating organization of a facility that is undergoing decommissioning needs to appropriately manage and control activities so as to mitigate any impact on the environment of the site and the surrounding area. These arrangements should be adhered to through the time of decommissioning, and beyond if a facility is released with restrictions on its future use. The end state conditions of the decommissioning project need to be demonstrated to the satisfaction of the regulatory body before a site or accelerator facility can be released with no restrictions [24].

Decommissioning tasks have the potential to create new hazards. Therefore, an important objective of decommissioning planning is to be fully prepared and able to assess and manage any new safety implications that might arise during decommissioning operations. A safety assessment needs to be conducted to define protective measures, utilizing an optimization approach for radiological protection with due regard for radiological safety [85]. There are many safety functions and related SSCs (e.g. ventilation, electrical safety, drainage) that need to be considered to ensure the safe operation of accelerator facilities during the normal operational lifetime. Many of these SSCs will be disconnected once the accelerator moves into the decommissioning phase; however, some of them will continue to be required, and the loss of some SSCs might result in the identification of requirements for new safety functions as decommissioning progresses.

Moving from operation to decommissioning can best be facilitated when all the necessary planning and preparatory work has been undertaken during the lifetime of the facility, especially in relation to careful recording of accelerator modifications or changes in use. Such actions will reduce the potential for adverse impacts on human health and the environment that can occur during the active and passive processes undertaken during decommissioning (see Section 5). Careful planning and implementation of the decommissioning of accelerator facilities and management of the resulting radioactive materials can be accomplished without undue risk to or radiological impacts on workers, the public or the environment [24].

Both the licensee and the regulatory body need to foster and maintain a safety culture in order to encourage a questioning and learning attitude towards safety, and to discourage complacency [85]. The licensee needs to ensure that properly trained, qualified and competent staff are available for the decommissioning project [85]. Timely and appropriate training on health, safety and environmental matters needs to be provided to individuals engaged in decommissioning activities with training updated at appropriate intervals. Records of training need to be maintained.

During decommissioning, the generation of radioactive and non-radioactive effluents needs to be carefully controlled and managed as it would routinely be during operations. In some cases, this may involve a period of storage on the site in compliance with radioactive waste storage procedures and the site licence. Discharges to the environment need to be controlled in compliance with appropriate national regulations and the licence granted by the regulatory body. Normally, the discharge licences are limited to the operational lifetime of the installation. Specific decommissioning licences often need to be applied for prior to the commencement of decommissioning activities, as the discharges associated with decommissioning may be different from those that occur during the operation of the facility [24]. Furthermore, there may be a vast increase in the volumes of waste during decommissioning, which can be a problem when there are only a limited number of storage facilities. In such circumstances, arrangements to cope with the increased volumes of waste, specifically ensuring adequacy of space for segregation and measurement of the waste at source, need to be fully considered and included in the waste management plan of the final decommissioning.

Guidance on waste management and the regulatory control of discharges of radioactive effluents to the environment is provided in the Safety Reports Series and IAEA Safety Standards Series (e.g. Refs [165, 167]). Radioactive waste management is further discussed in Section 8. Guidance on radiological criteria for the removal of regulatory control from materials, equipment and sites is provided in IAEA Safety Standards Series No. RS-G-1.7, Application of the Concepts of Exclusion, Exemption and Clearance [154], and IAEA Safety Standards Series No. WS-G-5.1, Release of Sites from Regulatory Control on Termination of Practices [168].

Guidance on the transport of radioactive material is provided in IAEA Safety Standards Series No. SSR-6, Regulations for the Safe Transport of Radioactive Material, 2012 edition [169].

9.2. GRADED APPROACH TO DECOMMISSIONING SAFETY

The range of decommissioning activities for medical, industrial and research facilities is broad, and the scope, extent and level of detail for planning; safety assessment and demonstration; and preparation, review and update of safety related documentation needs to be commensurate with the types and magnitude of hazards and their potential consequences to workers, the public and the environment [24]. Requirement 2 of GSR Part 6 [85] states that: "**A graded approach shall be applied in all aspects of decommissioning in determining the scope and level of detail for any particular facility, consistent with the magnitude of the possible radiation risks arising from the decommissioning.**" This graded approach can be appropriately applied to accelerator facilities according to their complexity and will influence all aspects of planning, conduct and completion of decommissioning through to release of the site for unrestricted or restricted use.

The conduct and regulatory oversight of decommissioning actions need to be applied in a manner that is commensurate with the hazards and risks associated with the accelerator facility [85]. A graded approach [166] is a process by which the level of analysis, documentation and actions necessary to comply with the safety requirements are commensurate with the factors below. The graded approach needs to be applied in a way that does not compromise safety and ensures compliance with all relevant safety requirements and criteria. The application of the graded approach in the context of decommissioning of particle accelerators should take into account factors such as [24]:

(a) Class of accelerator and type of accelerated particles (including the accelerator's complexity, operational use, and past accidents or incidents).
(b) Physical state of the facility, specifically the integrity of the SSCs, and, in particular, the extent to which ageing or abandonment may have compromised building structures or SSCs, for example, owing to a long period of poor maintenance.

(c) Radiological (source term), biological and chemical inventories and hazards associated with the decommissioning of the facility.
(d) Life cycle stage of the facility (design, construction, commissioning, operation, shutdown or decommissioning), such as the preparation of an initial decommissioning plan at the design stage or preparation of a final decommissioning plan prior to planned shutdown.
(e) Scope of the assessment (e.g. for an upgrade of the accelerator, for outright replacement of the accelerator with reuse of the constructed building, for decommissioning of one part of a facility without planned replacement or total decommissioning). It is essential to consider the extent to which the proposed decommissioning operations could adversely affect ongoing operations with safety significance elsewhere at the facility or at nearby facilities.
(f) Uncertainty of information (e.g. the quality and extent of the characterization of the facility) and the reliability and availability of relevant supporting information (e.g. drawings and records of modifications or past accidents and incidents) to be used as input data for the safety assessment as part of an integrated management system.
(g) Complexity of the decommissioning tasks.
(h) Final end state of decommissioning of the facility (e.g. unrestricted or restricted use).

All individuals performing decommissioning actions have the responsibility to inform management of any concerns about safety [85]. This is particularly relevant if the written procedures for a new decommissioning work activity are perceived to be overly complicated such that the workers believe they are inadequately trained to comply with them or are concerned about other aspects of their safety. The licensee needs to foster a safety culture that encourages a questioning and learning attitude towards safety [85], such that the workers have the confidence to raise such concerns through their line management structure.

9.3. CONSEQUENCES OF THE GRADED APPROACH

The application of a graded approach needs to support effective use of resources and help optimize efforts. In the context of accelerator decommissioning, a graded approach is a process by which the type of information and the level of detail in the decommissioning plans and supporting documents, including the safety assessments and actions necessary to comply with safety requirements, are commensurate with the class of accelerator to be decommissioned.

Successful decommissioning depends on adequate and organized planning and systematic implementation of the decommissioning activities in accordance with the licence conditions. Documentation (e.g. the scope of the decommissioning plan, its content and the degree of detail necessary, including the safety assessment) may vary, depending on the complexity and hazard potential of the accelerator facility and the actions necessary to meet national regulations. Grading has an impact throughout the decommissioning project, specifically in the following areas:

(a) Identification of SSCs and control requirements.
(b) Control of decommissioning work activities.
(c) Authorization process.
(d) Appropriate review of activities when they are completed.
(e) Project management (e.g. organizational structure). The management of the decommissioning project should be tailored to the project's complexity and size and to the potential hazards associated with it [164]. Specific organizational information for facilities decommissioning is presented in Section 5.
(f) Staffing and training.
(g) Oversight (i.e. surveillance, inspection, control).

9.4. RADIATION PROTECTION

The principles of radiation protection and safety for practices are provided in the IAEA Safety Standards Series and are based on the radiation protection system established by the International Commission on Radiological Protection [167]. A radiation protection plan needs to be included as part of the decommissioning plan and be based on the national requirements for radiological protection.

During decommissioning activities, the principal focus of radiation protection is the protection of workers against normal and potential occupational radiation exposure. The safety management system needs to also provide arrangements for the protection of workers undertaking interventions in the event of an emergency. Emergency response arrangements for decommissioning, commensurate with the hazards, need to be established and maintained, and events significant to safety need to be reported to the regulatory body in a timely manner [85]. The licensee is required to prepare and implement appropriate safety procedures, including emergency plans [85]. Radiation protection of workers and members of the public exposed as a result of decommissioning activities needs to be optimized with due regard to the relevant dose constraints [85].

The operating organization may establish an organization for radiation protection that functions independently in matters affecting the health and radiation safety of workers and the public. This will necessitate that appropriate procedures are drafted and implemented, supported by additional training as required. These procedures for decommissioning may be the same or only slightly different from those already in use during the operation and maintenance of the facility, but this does not mean that the situation should not be fully reviewed, and additional safety procedures drafted, as required. Particular emphasis needs to be placed on mitigating the following hazards:

(a) Decommissioning activities that place workers in closer proximity to radiation sources (due to the removal of shielding or interlocks to gain access to the accelerator for decommissioning) and hence increase the potential for radiation exposure.
(b) New activities that occur during dismantling activities and may result in greater potential for the creation of airborne radionuclides (e.g. cutting, sawing). Removable contamination may also be spread (i.e. from contaminated oil from the vacuum system).
(c) Introduction of new techniques and written procedures that necessitate specific controls and adequate training of personnel.
(d) Redesignation and zoning of areas with appropriate posting of notices. Care needs to be exercised where radiation redesignation closes off an emergency evacuation route [24].

As part of planning for decommissioning, the following issues need to be considered:

(1) Ensuring that the radiation protection of workers and the public is optimized;
(2) Having the appropriate number of skilled radiation protection personnel to assist in ensuring the safe conduct of the decommissioning tasks;
(3) Ensuring that the decommissioning personnel have the appropriate skills, qualifications and training with respect to radiation protection techniques and requirements;
(4) Using protective equipment for shielding to limit internal or external exposure and doses (e.g. lead shields, tents, local ventilation and filtering systems);
(5) Applying good housekeeping practices to reduce doses and to prevent the spread of contamination;
(6) Dismantling never accessed areas of highly activated equipment (e.g. beam dumps) by remote control and applying other techniques to minimize workforce external exposure;
(7) Zoning the occupational activities as a function of the levels of radiation and contamination, as well as appropriate rezoning as decommissioning work proceeds, according to the radiological hazards involved;
(8) Documenting all radiation protection measures and survey results.

The operating organization needs to review the classification of radiation areas implemented during operation and determine their ongoing relevance during decommissioning activities by taking into consideration the magnitude of the expected normal exposures, the likelihood and magnitude of potential exposures, and the nature and extent of the required protection and safety procedures during decommissioning activities.

The operating organization may consider the end state of the facility and associated site. Consideration needs to be given to the protection of workers and the public from exposure, not only during decommissioning but also as a result of any subsequent occupancy or use of the decommissioned facility. Radiation protection is discussed in more detail in IAEA Safety Standards Series publications. A description of (minor) radiological incidents during dismantling of an accelerator is given in Ref. [170].

9.5. ENVIRONMENTAL PROTECTION

The licensee has to discharge responsibilities to ensure adequate protection of the environment. This is best achieved through a comprehensive integrated management system to facilitate efficient management of decommissioning operations and define the controls to ensure that any impact to the environment, both on the site and in the surrounding area, is mitigated. Environmental protection needs to be maintained during the entire decommissioning process, and beyond if a facility is released with restrictions on future use [85]. As part of the preparation of the final decommissioning plan, an appropriately updated EIA is carried out, if required, taking due account of the graded approach [24]. Usually, for Class 1 accelerators, an EIA is not required, although a brief statement identifying that environmental impacts have been considered can usefully be included in the final decommissioning plan.

When collecting information to produce the EIA, records of the environmental monitoring carried out during the operational lifetime of the accelerator need to be carefully considered alongside the characterization of the accelerator site and surrounding areas prior to decommissioning. Furthermore, any records of plant modifications or past accidents or incidents also need to be reviewed. Past releases of activated air and water, as well as activation of soil and groundwater by neutrons and other secondary particles, can also have impacted the environment, possibly extending beyond the boundary of the accelerator site. At electron accelerators, the radioactivity levels are generally low and in some cases are very hard to measure; however, reliable predicting techniques are essential to enable an impact report (or equivalent document) to be drawn up, as required by most national regulations [55].

Environmental monitoring needs to be conducted throughout decommissioning. All potential radioactive and hazardous material releases need to be prevented or controlled at source and kept within regulatory authorized limits [85]. Where releases are expected and authorized, the releases through identified release points need to be monitored and recorded. Off-site monitoring may be conducted to demonstrate the adequacy of the control over releases of radioactive and hazardous materials to the environment [24].

9.6. RADIOLOGICAL AND NON-RADIOLOGICAL HAZARDS

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 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 for visitors to the site. These hazards might be the direct result of the physical state of the building, especially when demolition of structures is under way, or might arise from a component of the accelerator currently subject to dismantling as part of decommissioning. Additional hazards might arise from the technologies in use or changing environmental conditions; for example, airborne contamination might arise as cutting of concrete or large components of the accelerator gets under way. 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 the dismantling of accelerators, various radiological or conventional safety hazards may arise either in isolation or jointly, such as:

(a) Hazards of radiation;
(b) Hazards of work place contamination;
(c) Hazards of environmental contamination;
(d) Conventional hazards (biological, physical or chemical).

An integrated approach to the management of hazards is essential to work safety. This is especially relevant when decommissioning Class 1 accelerators, where the hazard from radiation may be less than conventional hazards, such as lifting or trip hazards.

Radiological hazards can stem from a number of causes, such as:

(1) Radioactivity not having been included in the inventory (e.g. stored foils previously removed from the accelerator);
(2) Leaking coolant fluid or loss of shielding;
(3) Leaks of fluid or contamination incidents that have occurred during the operation of the accelerator that were inadequately dealt with at the time;
(4) Piping systems containing activated liquids;
(5) Buried pipes with activated liquids, which might be broken;
(6) Tanks with activated coolant;
(7) Accumulation of radioactive dust present in ventilation and filtration systems;
(8) Accumulation of a significant radioactive inventory during dismantling and demolition, typically in the form of activated components and structures;
(9) Clean areas that have become contaminated owing to loss of containment (e.g. inadequate segregation at source of clean and contaminated accelerator components and construction materials as decommissioning proceeds);
(10) Decontaminated zones that have been recontaminated owing to inadequate control of personnel movement and material handling.

Not all of the hazards connected with 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, as is the case at accelerator facilities, it may be a requirement of the Member State that each of the hazards be assessed separately. In some Member States, there is a requirement for a consolidated hazards assessment. The project manager should have identified which option is relevant to the decommissioning project. The regulation of each of the above may be handled by a different regulatory body, so it will be essential to consult with each of them in advance to ascertain their preferred method of calculating and combining hazards. When explicit standards do not exist in a Member State, the regulator may operate under certain constraints, so it is essential to have a clear understanding of how to comply with them.

Hazards of environmental contamination and activation of structures are generally not a problem for Class 1 accelerators but need to be assessed on a case by case basis [24]. 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 procurement of any identified protective clothing and equipment; these tasks should be supported by relevant staff training and rehearsals of contingency plans. The preparation and communication of a relevant and appropriate radiological and conventional 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 roles and responsibilities in implementing the procedures, and the mechanisms that exist for workers to raise health and safety concerns with their supervisor. Hazards are assessed so that they can be eliminated, if possible. If elimination of hazards is not possible, administrative controls need to be put in place to minimize their impact.

General measures of worker protection from hazards include:

— Appropriate use of engineering controls (e.g. shielding, ventilation systems);
— Planning the work in detail to reduce the exposure levels and time (ALARA review or dose budgeting);
— Training personnel about working procedures and specific hazards;
— Surveys and sampling for individuals and defined working areas;

— Compliance with all relevant health and safety standards and written procedures;
— Appropriate use of PPE, with reusable PPE subject to proper cleaning, storage and inspection arrangements;
— Work practices aimed at minimizing exposure levels in the work place (e.g. storage of waste in isolated areas and its frequent removal);
— Avoidance of contamination through appropriate signage, zoning and access–egress control.

When various options exist to execute a particular part of the decommissioning plan, the benefits of each method need to be evaluated (an ALARA assessment) and the most appropriate technique adopted for use. The final choice of method 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 might necessitate a slightly increased radiation exposure. In addition to the non-radiological hazards that exist while the facility is operational, decommissioning activities will likely create new non-radiological hazards from activities such as cutting, drilling and sawing, and these also need to be considered. Completing a comprehensive characterization survey may require investigating areas that operators do not usually access. This might involve the drilling and removal of cores of construction material to investigate the depth of penetration of activation products. Decontamination can involve the use of chemicals or equipment that may never have been used on the site. Demolition may introduce a whole host of physical hazards, not the 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 number of potential accident scenarios that will need to be appropriately considered [23]. Issues such as extending utilities to the new work areas; erecting platforms, scaffolding or other structural supports; providing adequate lighting (which might mean an enhanced level of lighting above that in existence or a new lighting supply where none exists); providing simple communication equipment such as a two way radio; and supplying breathable air in a restricted space, supported by heating/cooling methods, will all be important.

Some examples of poor management of radiological and conventional safety and their possible consequences — not necessarily related solely to particle accelerators — are given in Table 18 [24].

Despite the low intensity of the early cyclotrons, many were constructed underground to avoid anticipated but unquantified radiation problems. Furthermore, the safety and ease of decommissioning of the underground structures and equipment were never considered at that time, particularly in relation to ease of movement of equipment and materials into and out of the facility.

In many instances, especially when there has been a delay in preparing the decommissioning plan after shutdown of the accelerator, records of past use and accident or incident reports that could impact safety during decommissioning have been lost. In 2008, the IAEA published a Technical Report that provided useful information on the long term preservation of information for decommissioning projects [171]. When a lengthy period has elapsed since shutdown, and maintenance of the facility has ceased, it is essential not only to ensure a comprehensive characterization of the radioactive inventory but also to fully explore the status of electrical, ventilation and other systems that might be essential to safety and ensure any ongoing concerns are reflected in the safety planning. Many of the large Class 3 and 4 present day accelerator facilities are largely constructed underground (e.g. the LHC at CERN), so the project manager needs to be experienced in managing the overall safety of working below ground level.

Two examples will now be given of non-radiological incidents at accelerators. Although they did not actually occur during decommissioning, these two cases are representative of typical decommissioning conditions.

In the first example, a contractor was working inside an accelerator tunnel moving heavy steering magnets with a cart. While pulling the empty cart to pick up additional magnets, the contractor encountered a puddle of water and tried to jump over it. However, his foot slipped and he sprained his ankle. The accelerator tunnel was 25 years old and there were roof penetrations caused by corrosion, which allowed water to seep into the tunnel. This had been an ongoing issue for several years. Previous corrective actions were to only clean up the water, since repairs might be costly. The corrective action for the described event was to hire a contractor to reline and waterproof all penetrations. The water penetration had existed for a while, but the injury provided the incentive to correct the problem properly. The generic lesson learned here is to consider safety first. In this specific case, the organization in charge should not have allowed structures to deteriorate to the point of being hazardous to access [172].

TABLE 18. ACTIONS AND CONSEQUENCES ASSOCIATED WITH POOR PRACTICES IN HEALTH AND SAFETY [24]

Action	Consequences
Failure to adequately integrate health and safety 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 after any agreed changes to work procedures, etc.	Safety assessments may not be inclusive, resulting in possible accident or incident scenarios previously not envisaged.
Failure to draft a comprehensive safety assessment that integrates 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 when 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 inadequate control that is inconsistent with ALARA. There may be additional radiation protection requirements, such as radiation passbooks for contractors working in the operator controlled areas.
Failure to adequately communicate revisions to risk assessments or health and safety procedures as the project progresses.	Workers may be 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 the 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.
Failure to identify 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 for the selected work procedures.	Staff may be subject to unnecessary additional risks or doses may not be ALARA.
Failure to adequately appraise the physical conseqences 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 or incidents.

Note: For long term decommissioning projects, consider establishing an on-site laundry service for coveralls instead of using single use disposable coveralls in order to reduce waste volume and disposal costs. Pay particular attention to ensure that, where airborne contamination, especially alpha radionuclides, is present, operators are provided with isolated air supply suits rather than full face respirators, which provide a lower level of operator protection.
ALARA — as low as reasonably achievable.

In the second example, on 21 June 2001, a construction sub-tier contractor employee at Fermilab received serious head injuries requiring hospitalization when he was struck by part of the drilling rig that he was operating. The equipment involved in the accident, known as a tong, was an 80 cm steel bar with a handle essentially used as a pipe wrench to connect and disconnect the drill pipe. The accident occurred when a welded connection in the hydraulic system used to apply force to the tong failed as the two man crew was removing lower sections of the drill assembly (a maintenance activity similar to one during decommissioning). A comprehensive illustration of the incident, the measures taken and the lessons learned is given in Ref. [173].

10. CONCLUSIONS

The decommissioning of accelerators can more easily be undertaken if it occurs soon after permanent shutdown. Full consideration of decommissioning requirements, including all technical, legal, safety and financial provisions, is best done as early as at the time of licensing. However, such early consideration does not often take place.

In general, the decommissioning of an accelerator facility is relatively straightforward, compared with many other types of nuclear facility, particularly when operations have not resulted in contamination.

There is substantial worldwide experience in the decommissioning of accelerators, and many projects have been successfully concluded. Experience has shown that these projects can be undertaken with no adverse effects on the public, the workers or the environment. Benefits can be gained from the transfer of knowledge from those having undertaken these projects to the novice.

This publication (including its appendices and annexes) also identifies certain constraints and challenges, namely:

(a) Shortage or absence of funding or infrastructure to undertake decommissioning (due to, for example, changes in political priorities);
(b) Lack of end of life waste management options, including disposal sites;
(c) Failure to plan for decommissioning during the early stages of the accelerator life cycle;
(d) Absence or inadequacy of records (especially as-built drawings) to facilitate decommissioning;
(e) Difficulty of detecting and evaluating radiation and contamination levels close to clearance criteria.

Requirement 10 of GSR Part 6 [85] states that:

> **"The licensee shall prepare a decommissioning plan and shall maintain it throughout the lifetime of the facility, in accordance with the requirements of the regulatory body, in order to show that decommissioning can be accomplished safely to meet the defined end state."**

The following also need to be considered by licensees:

(a) A suitable, robust funding mechanism needs to be established when the accelerator facility licence is granted and then revisited periodically to ensure that adequate financial resources are available when required. This mechanism needs to account for the cost of removal from buildings, plus packaging and transportation costs and disposal or recycling costs, if applicable.
(b) Planning for decommissioning needs to be included in the design, construction and operational phases and could cover, for example:
    — Modularizing shielding to facilitate dismantling and sorting (removable individual blocks rather than solid walls, as described in Section 5.9);
    — Selecting construction materials for shielding and equipment that minimize activation;
    — Optimizing operational parameters (e.g. in order to minimize beam losses).

To decrease future dismantling and waste management costs associated with the decommissioning of accelerators, it is important to clearly quantify the extent of activation that is possible by the type of accelerator to be installed. In any case, the activation estimates need to be carried out well in advance of final shutdown and be incorporated into the decommissioning plan.

Proper documentation regarding all aspects of the accelerator facility, including any modifications or customizations, needs to be kept in a safe and secure manner. The institutional knowledge of these records also needs to continue for the life of the facility and beyond [24].

High energy accelerators (above 1 GeV) are very likely to require remote handling techniques if they are to be dismantled immediately after the shutdown of such a facility. A cooldown period prior to disassembly of highly activated components could result in sufficient reduction of the radiation levels so as to permit dismantling without the need for remote handling equipment [12]. Most medium energy accelerators can be dismantled using hands-on methods with some localized shielding [12]. Low energy accelerators (below l0 MeV), such as van de Graaffs and linear electron accelerators used in medical and industrial applications, generally will not produce radiation levels that would affect the decommissioning procedures [12]. Therefore, for small accelerators, decommissioning needs to be undertaken as soon as the accelerator operation ceases.

Appendix I

EXAMPLES OF ACCELERATORS SORTED BY TYPE

The following list of types of accelerator facility and their location is taken mostly from Ref. [22].

I.1. ELECTRON: STRETCHER RING OR CONTINUOUS BEAM FACILITIES

ELSA (University of Bonn, Germany); JLab (Thomas Jefferson National Accelerator Facility, USA); MAMI (University of Mainz, Germany); MAX-Lab (Lund University, Sweden); SLAC (SLAC National Accelerator Laboratory, USA).

I.2. ELECTRON: SYNCHROTRON LIGHT SOURCES, STORAGE RINGS

ALBA (Synchrotron Light Facility, Spain); ALS (Lawrence Berkeley Laboratory, USA); ANKA (Ångströmquelle Karlsruhe, Germany); APS (Argonne National Laboratory, USA); AS (Australian Synchotron, Melbourne); ASTRID & ASTRID2 & ELISA (ISA) (Institute for Storage Ring Facilities, Denmark); BESSY II (Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Germany); CAMD (Center for Advanced Microstructures and Devices, Louisiana State University, USA); Canadian Light Source (CLS) (University of Saskatchewan, Canada); CeBeTeRad (Institute of Nuclear Chemistry and Technology, Poland); CHESS (Cornell University, USA); DELTA (Zentrum für Synchrotronstrahlung, University of Dortmund, Germany); ELBE (Helmholtz-Zentrum Dresden, Germany); Elettra (AREA Science Park, Italy); ELU-6e (Technical University of Lodz, Poland); ESRF (European Synchrotron Radiation Facility, France); HASYLAB (Das Hamburger Synchrotronstrahlungslabor, Germany); HLS (University of Science and Technology of China, Hefei City); INDUS (Centre for Advanced Technology, India); LNLS (Laboratório Nacional de Luz Sincrotron, Brazil); MAX-Lab (Lund University, Sweden); MLS (Metrology Light Source, Physikalisch-Technische Bundesanstalt, Germany); NSLS (Brookhaven National Laboratory, USA); PAL (Pohang Accelerator Laboratory, Republic of Korea); SESAME (Synchrotron Light for Experimental Science and Applications in the Middle East, Jordan, under construction); SLS (Paul Scherrer Institut, Switzerland); SOLEIL (Gif-Sur-Yvette, France); SPEAR (SLAC National Accelerator Laboratory, USA); SPring-8 (Super Photon Ring, Japan); SRC (Synchrotron Radiation Center, University of Wisconsin, Madison, USA); SSRF (Shanghai Synchrotron Radiation Facility, China); SURF III (National Institute of Standards and Technology, USA); TPS (Taiwan Photon Source, Taiwan, China); TUNL (Triangle Universities Nuclear Laboratory, USA).

I.3. ELECTRON: OTHERS

BATES (Massachusetts Institute of Technology, USA); IAC (Idaho Accelerator Center, USA); PBPL (Particle Beam Physics Laboratory, USA); PEGASUS (Photoelectron Generated Amplified Spontaneous Radiation Source, USA); PITZ (Deutsches Elektronen-Synchrotron, Germany); S-DALINAC (Technische Universität Darmstadt, Germany); UNAM (National Autonomous University of Mexico); WMU (Van de Graaff Accelerator, Physics Department of Western Michigan University, USA).

I.4. PROTON

88 inch Cyclotron (Lawrence Berkeley Laboratory, USA); ARRONAX (Accelerator for Research in Radiochemistry and Oncology, France); CNA (Centro Nacional de Aceleradores, Spain); CNL (Crocker Nuclear Laboratory, University of California, Davis, USA); COSY (Cooler Synchrotron, IKP, Germany); ININ (National Institute for Nuclear Research, Mexico); ISIS (Rutherford Appleton Laboratory, United Kingdom); iThemba (Laboratory for Accelerator Based Sciences, South Africa); IUCF (Indiana University Cyclotron Facility, USA); KEK (National

Laboratory for High Energy Physics, Japan); Large Hadron Collider (LHC) & PS & SPS (CERN, Switzerland); RHIC (Relativistic Heavy Ion Collider, Brookhaven National Laboratory, USA); TRIUMF (Canada's National Laboratory for Particle and Nuclear Physics, Vancouver); TSL (Svedberg Laboratory, Uppsala University, Sweden).

I.5. LIGHT AND HEAVY ION

88 inch Cyclotron (Lawrence Berkeley Laboratory, USA); AGOR (Accélérateur Groningen-ORsay, KVI, Netherlands); ANSTO (Australian Nuclear Science and Technology Organisation, Lucas Heights); ANU (Australian National University, Canberra); ARRONAX (Accelerator for Research in Radiochemistry and Oncology, France); ASTRID (Institute for Storage Ring Facilities, Denmark); ATLAS (Argonne National Laboratory, USA); CENPA (Center for Experimental Nuclear Physics and Astrophysics, University of Washington, USA); CMAM CNL (Centro de Microanálisis de Materiales, Universidad Autónoma de Madrid, Spain); CRYRING (Manne Siegbahn Laboratory, Sweden); CYCLONE (Cyclotron of Louvain-la-Neuve, Belgium); ESSB (ESS-Bilbao, Spain); FRIB (Facility for Rare Isotope Beams, Michigan State University, USA); GANIL (Grand Accélérateur National d'Ions Lourds, France); GSI (Gesellschaft für Schwerionenforschung, Germany); HISKP (Helmholtz-Institut für Strahlen- und Kernphysik, Germany); ININ (National Institute for Nuclear Research, Mexico); ISNAP (Institute for Structure and Nuclear Astrophysics, Notre Dame University, USA); iThemba (Laboratory for Accelerator Based Sciences, South Africa); IUCF (Indiana University Cyclotron Facility, USA); JYFL (Jyväskylän Yliopiston Fysiikan Laitos, Finland); LAC (Louisiana Accelerator Center, University of Louisiana at Lafayette, USA); LAFN (Laboratório Aberto de Fisica Nuclear, Brazil); Large Hadron Collider (LHC) (CERN, Switzerland); LHE Synchrophasotron / Nuclotron (Joint Institute for Nuclear Research, Russian Federation); LNL (Laboratori Nazionali di Legnaro, Istituto Nazionale di Fisica Nucleare, Italy); LNS (Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare, Italy); Maier-Leibnitz-Laboratorium (Munich, Germany); MIBL (Michigan Ion Beam Laboratory, University of Michigan, USA); MIC (Microanalytical Centre at Jožef Stefan Institute, Slovenia); MPI-HD (Max Planck Institut für Kernphysik, Germany); NCSL (National Superconducting Cyclotron Laboratory, Michigan State University, USA); ORNL (Oak Ridge National Laboratory, USA); OUAL (John E. Edwards Accelerator Laboratory, Ohio University, USA); PSI (Villigen, Switzerland); RHIC (Brookhaven National Laboratory, USA); RIBRAS (Radioactive Ion Beam in Brasil, São Paulo); RUBION (Zentrale Einrichtung für Ionenstrahlen und Radionuklide, Universität Bochum, Germany); SNS (Spallation Neutron Source, USA); SPS (CERN, Switzerland); TAMU (Cyclotron Institute, Texas A&M University, USA); TANDAR (Tandem Accelerator, Buenos Aires, Argentina); TSL (Svedberg Laboratory, Uppsala University, Sweden); TUNL (Triangle Universities Nuclear Laboratory, USA); U-400 / U-400M (Joint Institute for Nuclear Research, Russian Federation); UAC (Inter-University Accelerator Centre, India); UMASS (University of Massachusetts Lowell Radiation Laboratory, USA); UNAM (National Autonomous University of Mexico); Variable Energy Cyclotron Centre (India).

I.6. COLLIDERS

BEPC (Beijing Electron Positron Collider, China); CESR (Cornell Electron Positron Storage Ring, Cornell University, USA); DAFNE (Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, Italy); Large Hadron Collider (LHC) (CERN, Switzerland); RHIC (Brookhaven National Laboratory, USA); Stanford Linear Collider (SLAC National Accelerator Laboratory, USA); TESLA (Deutsches Elektronen-Synchrotron, Germany); Tevatron (Fermilab, USA); VEPP-3 & VEPP-4M & VEPP-2000 (Budker Institute of Nuclear Physics, Russian Federation).

Appendix II

MISCELLANEOUS EXPERIENCE AND STUDIES ON ACCELERATOR DECOMMISSIONING PROJECTS

This appendix briefly describes actual experience or theoretical estimates regarding specific accelerator decommissioning projects. Other decommissioning projects are extensively described in the annexes. The reader is invited to consult the experience given below for applicability to new decommissioning projects.

II.1. UNITED STATES OF AMERICA

The decontamination and decommissioning of the Argonne National Laboratory 60 inch (152 cm) cyclotron facility was completed in 2001. Characterization, planning and documentation began in June 1997 and was completed in December 1998. Decommissioning field work began in January 2000, and the final report was issued in February 2001. The total duration of decommissioning field work was 13 months. The total exposure to project personnel was 0.436 person-rem (4.36 person-mSv). The total cost of the cyclotron decommissioning project, including labour, management and waste disposal, was US $3.9 million. A total of 197 m^3 of low level radioactive waste, with a total activity of 1900 MBq was packaged for off-site disposal. Additionally, 3.3 m^3 of mixed waste, including liners, was packaged for disposal, with a total activity of 1070 MBq. In February 2001, the cyclotron facility was formally decommissioned and transferred to the landlord.

Following completion of the independent verification survey, the cyclotron facility was released for unrestricted reuse. Although the facility was subject to unrestricted reuse, the independent verification survey did record the fact that elevated activity remained in some inaccessible areas:

> "The upper floor of the Cyclotron vault contains readily measurable radioactivity from neutron activation of the concrete and other structures resulting from Cyclotron operations. In accessible areas, the exposure rate criteria in DOE Order 5400.5, i.e., ≤20 μR/hr, was met. No Radiation Work Permits (RWPs), radiation monitors, or other radiological controls are needed to enter the area" [170].

Reference [174] discusses the main elements of policies and strategies to facilitate systematic, safe, timely and cost effective planning of decommissioning nuclear and radiological facilities.

In the summer of 2011, the University of Iowa's 20-year-old 17 MeV Scandatronix cyclotron underwent decommissioning. The project is described in Refs [175, 176]. Waste was classified into two categories: that associated with the cyclotron and targets, and that associated with the concrete vault wall that needed to be removed to remove the old cyclotron and bring in the new one.

The cyclotron itself was stripped of useful spare parts, which were sent to sites with operating 17 MeV Scandatronix cyclotrons. Accumulated radioactive waste from 20 years of operation was bagged and placed in the cyclotron vacuum chamber. This included target foils, which were first placed in lead containers to minimize gamma-shine from the cyclotron. The tank was then released for the last time. Assessment of the identity and the quantity of radionuclides associated with the cyclotron was required before cyclotron shipment to the waste disposal site in Clive, Utah (Energy Solutions).

Residual radioactivity from the cyclotron and cyclotron parts comes from direct proton and deuteron bombardment of materials (foils, target bodies, and internal components from stray protons and deuterons), and from neutron activation primarily of the magnet steel and copper coils.

The project metrics included the following:

(a) Low level radioactive waste shipped for disposal: 22 t.
(b) Time: 324 person-hours over a three day period.
(c) Cost: ~ US $200 000.
(d) Dose: 0.53 person-mSv.

At the Lawrence Berkeley National Laboratory, decommissioning work included relocation of van de Graaff and biomedical programs, radiation measurements, planning, estimate preparation, tooling design and procurement, scheduling, shipping arrangements, rigging studies, obtaining of permits, waste disposal coordination, and cleanup. All these activities are described in Ref. [177].

II.2 NETHERLANDS

A brief description of the dismantling of the Amsterdam 700 MeV Linear Electron Accelerator is given in Refs [178, 179]. The year 1998 marked the end of the scientific programme. In 1999–2000, the facility was transferred to Dubna, Russian Federation. The removal of activated materials was carried out in 2001, with the final survey of residual radioactivity in 2002–2003. The material management policy consisted of the following approaches:

(a) Reuse is preferred over recycling (much equipment was transferred to Dubna).
(b) Recycling is preferred over disposal as waste.
(c) Release criteria are:
    — >100 Bq/g: dealt with by the Central Organization for Radioactive Waste (the Dutch radioactive waste management company).
    — >10 Bq/g: chemical waste.
    — <10 Bq/g: controlled recycling.
    — < 1 Bq/g: uncontrolled recycling (but scrap metal, even <1 Bq/g, was not accepted for recycling; lead was recycled).

The material flow included 8 t as radioactive waste, 23 t as chemical waste, 60 transports to Dubna and 31 t of lead recycled. The total cost was US $295 000.

II.3. FRANCE

The decommissioning of two French accelerators is described in Ref. [180]. The two facilities were the linac at Saclay (electrons, 700 MeV) and the Synchrotron Saturne (ions, 3 GeV protons). Reference [180] extensively deals with reactor modelling and categorization of materials generated from decommissioning. It is remarkable that out of a total mass of 12 700 t, 83% was recycled as radiological material, 10% was recycled as conventional material and only 7% was disposed of as very low level waste. The paper expands on the savings due to the very low level versus low level waste disposal, the costs per cubic metre of the former being one tenth of those of the latter in France. An overview of the decommissioning projects for nuclear facilities and accelerators in France is given in Ref. [181].

II.4. BELGIUM

Activation modelling and decommissioning strategies for a variable energy, multiparticle (protons, deuterons, and alpha and ^{3}He particles) cyclotron at the Vrije Universiteit in Brussels are described in Refs [182, 183]. Optimization of occupational exposures in this project through the use of VISIPLAN software is described in Ref. [184].

II.5. UNITED KINGDOM

At Harwell Laboratory, a substantial decommissioning programme has been under way for the past 20 years. The variable energy cyclotron was built in the mid-1960s to study radiation damage, radiochemistry and solid state physics. In later years, its primary function was to produce radioisotopes (e.g. ^{123}I) for medical use. The variable energy cyclotron comprised a large reinforced concrete shielded structure (approximately 2500 m^3 above ground) containing four areas: the cyclotron vault (which housed the variable energy cyclotron machine, including the 250 t main magnet) and three separate target rooms. Several large mechanical and electrical plant rooms, a control room and cooling water systems were positioned around the cyclotron. The variable energy cyclotron was the first facility to be fully dismantled within the Harwell programme (1994). Details of the main elements of the project to decommission the 250 t cyclotron and demolish the 5 000 t of concrete shielding and external building structure are discussed in Ref. [183]. The actual demolition took six weeks.

Information on recent accelerator decommissioning projects in the United Kingdom is given in Ref. [184]. The projects include an MC40 cyclotron, cyclotron services, an 8 MeV yoke magnet and a PET cyclotron.

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Annex I

EXAMPLES OF NATIONAL EXPERIENCE

The examples provided in this annex address a wide range of technical and organizational aspects of accelerator decommissioning. They are intended to provide practical information on how accelerator decommissioning projects are planned and managed in various countries. The examples given are not necessarily best practices; rather, they reflect a wide range of national legislation and infrastructure, site conditions and nuclear programmes. Although the information presented is not intended to be exhaustive, the reader is encouraged to evaluate the applicability of these schemes to a specific accelerator decommissioning project.

I–1. TANDEM ACCELERATOR DECOMMISSIONING AT THE UNIVERSITY OF MINNESOTA, USA

I–1.1. Introduction

The purpose of this project was to demolish the Tandem Accelerator Building (or ‘Tandem Building’) located on the east bank of the Mississippi River adjacent to and just north of the Interstate 35 West bridge. When the bridge collapsed in 2007, the issues and condition of the Tandem Building were brought to the forefront. At that time, the majority of the building was vacant except for the Center for Interdisciplinary Application in Magnetic Resonance research laboratory. In the aftermath, it quickly became apparent that the laboratory had to be moved out of the Tandem Building owing to the close proximity to the bridge demolition and reconstruction activities and the resulting risks posed to staff and equipment. The laboratory has since been relocated to a new leased space off campus.

I–1.2. Decommissioning project

The tandem accelerator at the University of Minnesota (Fig. I–1) was housed in a research building located on the eastern bank of the river, next to Interstate 35. Details of the tandem accelerator are given in Ref. [I–1]. After

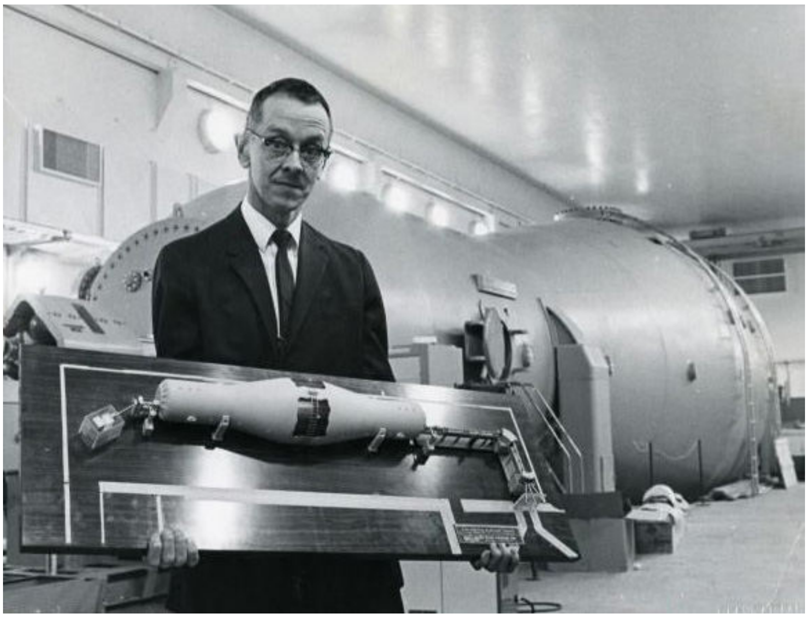

FIG. I–1. Tandem accelerator at the University of Minnesota with J.M. Blair (reproduced from Ref. [I–1] with permission courtesy of the University of Minnesota).

the Interstate 35 West bridge collapsed in 2007, potential accident scenarios resulting from the close proximity of the accelerator to the freeway were re-examined. Following this safety analysis, a decision was made to remove all operations from the research building and to demolish the building.

The project required total demolition and environmental remediation of the Tandem Building. The project was awarded to an external contractor. The significant aspects of this project were the heavily fortified accelerator vessel, which was built with 50 mm solid steel, and the 0.9 m thick solid concrete structure surrounding the vessel.

The decommissioning included the dismantling of the tandem accelerator, which posed a new challenge to the university. The university did not have personnel qualified for the task and therefore hired decommissioning contractors. The initial decommissioning plan and schedule were compiled on the basis of information given by the accelerator staff and additional observations made in the accelerator building. The plan was then reviewed and refined as needed during the execution of the project. The great potential for reuse of accelerator equipment was recognized at an early stage and considered during the compilation of the decommissioning plan. Equipment that did not comply with statutory requirements and that would be costly to reuse, such as the pressure vessel shell, was regarded as waste.

Multiple challenges were identified during the planning process. It was decided that seismic monitoring would be necessary during demolition to ensure there was no damage to the existing utility tunnel feeding the University of Minnesota and the newly constructed Interstate 35 West bridge, which was directly overhead. The project's close proximity to the Mississippi River necessitated that extensive erosion control measures be implemented.

The floor areas surrounding the 24 m long pressure vessel were used for equipment storage; a large portion of the accelerator was not visible at all during the planning stage. Cleanup of these areas was necessary for proper access to the accelerator. The accelerator itself was contained within a large 24 m long steel pressure vessel; between each end of the vessel spanned a glass and aluminium truss support structure under approximately 75 t of compressive force. After the pressure vessel was opened, testing for the presence of hazardous gases, used as dielectric medium, was necessary. Disassembly and removal of the heavy and fragile inner structure was accomplished using a system that included access walkway scaffolds, a cart on a light rail system to wheel pieces of equipment from the inside, and hydraulic rams to neutralize the 75 t stress force on the inner isolated truss structure that supported the central beamline. Additional safety measures were implemented, such as a webcam within the vessel to monitor the hydraulic rams and the progress of stress release.

In total, 100 t of reusable components were removed from the building. The project was scheduled to be completed in four weeks. The planning was done over 50 hours, engineering work took 160 hours and direct labour in the field took another 160 hours. No special decommissioning tools were required, and most of the necessary hand tools and equipment were already available at the facility. Safety received high priority because there was a potential for catastrophic failure of the fragile inner structure. The decommissioning project was assessed as successfully completed.

I–1.3. Conclusions

The University of Minnesota Purchasing Department assessed the decommissioning project as highly successful. It was completed on time and within the agreed budget. The application of additional safety measures, including the use of seismic monitoring to ensure there was no damage done to the existing utility tunnel feeding the university or to the newly constructed interstate bridge, proved beneficial. The great potential for reuse of 100 t of components removed from the building was considered in the early planning stage and hence substantially reduced the cost of the waste and materials management aspect of the budget and demonstrated best practice.

I–2. BEVATRON (CLASS 4), LAWRENCE BERKELEY NATIONAL LABORATORY, USA

I–2.1. Introduction

The Bevatron, a proton synchrotron at Lawrence Berkeley National Laboratory (LBNL) began operation in 1954 and was capable of accelerating protons to 6.2 GeV. In 1971, it was connected to the Super-HILAC linear accelerator (linac) as an injector for heavy ions; the combination was called the 'Bevalac'. It was used to accelerate any nuclei in the periodic table to relativistic energies. Operations ceased in 1993, the allocation of funding for decommissioning started in 2008 and the cleared site was returned to the laboratory for reuse in early 2012. The history of the facility is given in Ref. [I–2].

I–2.2. Decommissioning project

The project consisted of the deactivation and demolition of Building 51, Building 51A and the Bevatron accelerator. Building 51, which housed the Bevatron, was an approximately 1.16 ha steel frame structure built in the early 1950s. The building was located in the west–central part of LBNL and occupied approximately 0.9 ha. The project scope also included the disposal of approximately 30 000 t of radiologically activated material, remediation of contaminated soil within the building footprint and engineered enforcements of containing walls. The objectives of the project were to demolish the largest building at the laboratory, remove hazards posed by the structure and the accelerator, reduce the burden on laboratory resources, and make the Building 51 site available for future reuse. The project was completed on schedule in February 2012, and was able to return more than US $2.4 million to the Office of Science (the approved total project cost was US $50 million at Critical Decision (CD)-2/3, and the final total project cost was US $47.6 million at CD-4). The project also met the waste diversion goal of more than 75% of recyclable waste. Although Building 51 was a decaying facility and there were inherent demolition hazards, more than 230 000 hours were worked with no lost time and only one recordable injury.

Further details on the Bevatron project are given in Refs [I–3 to I–5]. Figure I–2 reflects an early stage of the project. More information on the Bevatron decommissioning project is given in Ref. [I–6].

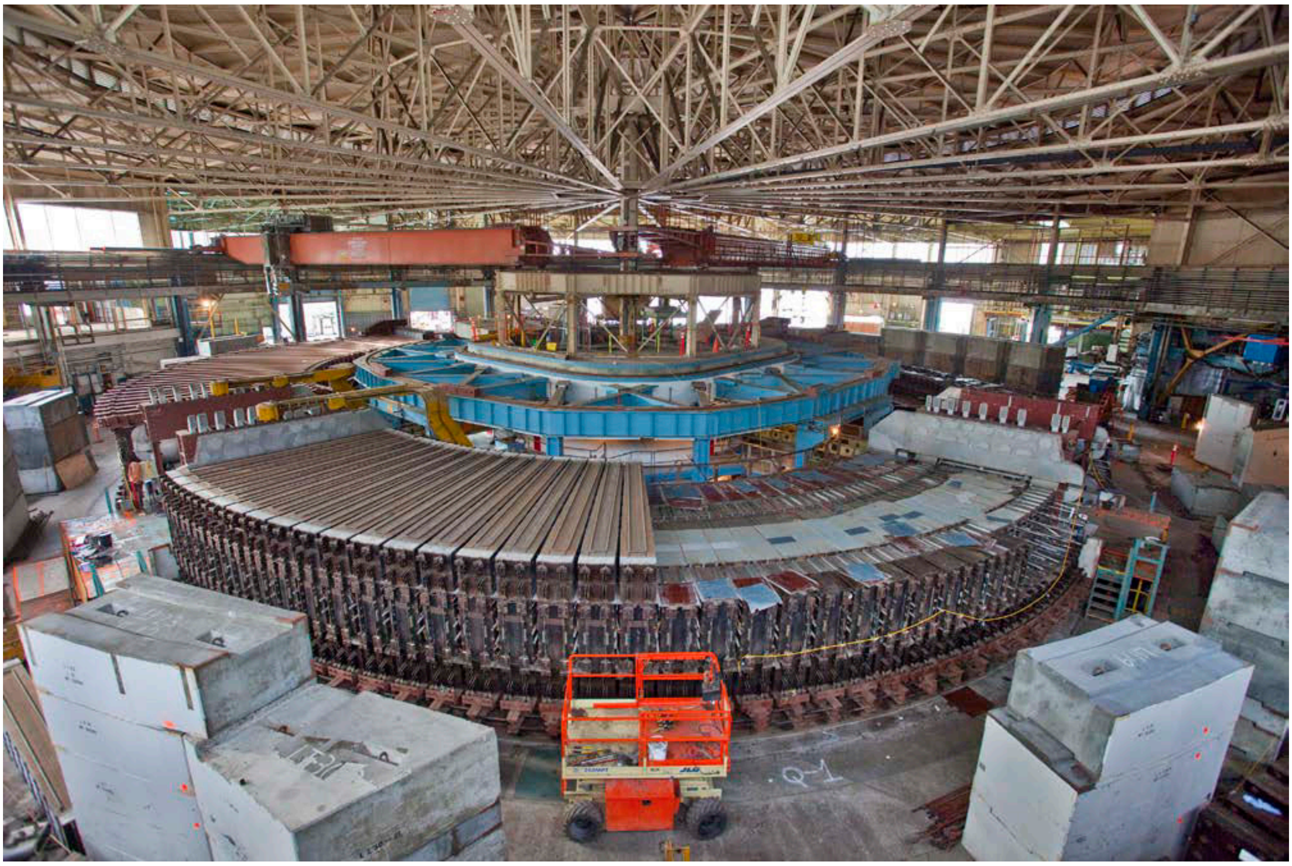

FIG. I–2. Bevatron in the process of disassembly, 14 January 2010. (Photo © 2010 The Regents of the University of California through the Lawrence Berkeley National Laboratory.)

I–2.3. Achievements

As outlined in a report by the United States Department of Energy [I–7] [1,2], the three biggest successes of this project were the following:

(a) Threshold and objective values: Using threshold and objective values for the key performance parameters for project completion criteria, as allowed by US Department of Energy (DOE) Order 413.3B and defined by DOE Guide 413.3-5A, provided a means to achieve success without definitive knowledge of the level of environmental remediation that was required. Threshold and objective values were established as part of the project execution plan and included as key performance parameters. The project key performance parameters set 1900 yd^3 (0.75 m^3) of soil cleanup as a threshold value, while an objective value was set for cleaning all soil to institutional reuse standards. The project met the key performance parameter of 1900 yd^3 (0.75 m^3) of soil clean and was not held to further remediation. Had further remediation been required, the project schedule and budget might have been at risk.

(b) Retired personnel involvement: The use of personnel who are experienced with the facility and its operations, specifically the part-time involvement of a retired Bevatron operations manager, was an excellent strategy for both LBNL and the subcontractor. The involvement of the former operations manager resulted in increased efficiency owing to his knowledge of assembly and disassembly processes, methods and tools. Had this former employee not been involved, the subcontractor would have required additional time to determine the most efficient means for demolition. Potential hazards regarding disassembly were also outlined, likely resulting in improved safety during the project. It is good practice to establish a relationship with similar experienced personnel early in the project, during characterization, if possible, for all demolition projects.

(c) Unit rates for unknowns: Addressing unknown quantities in bid documents with unit rates reduced the risk and contingency the bidders would have been required to include within the required fixed price bids. The request for a proposal required that bidders include unit rates if waste quantities were outside the predicted range (i.e. more or less activated concrete shield blocks, more or less activated steel, and more or less polychlorinated biphenyl (PCB)-contaminated or volatile organic compound-contaminated soil). If unit rates had not been used, bidders would have included additional contingency to cover the added risk, resulting in increased costs. The unit rates were used when the variation did not result in a cardinal change to the project; this process reduced the number of change orders needed.

I–2.4. Areas for improvement

Three significant areas of potential improvement and how they might have adversely impacted the project are described as follows:

(a) Improve sample analysis limit expectations: Although there were clearly defined minimum detectable activity levels in effect when the proposals were requested, the contractor collected a sample that was not required, did not discuss it or have it approved by the project management, and sent it to a laboratory without providing that laboratory with clear guidance on the minimum detectable activity levels required. The lack of project approved minimum detectable activity levels on this sample resulted in testing to standards more rigorous than required and ultimately declaring some materials as radiological waste when it might not have been necessary to do so. If the subcontractor had been clear about what the expectations for minimum detectable activity levels were, the largest cost and schedule changes for this project could have been avoided. The project management needs to be involved with reviewing and approving sample collection to ensure that the sample is needed, properly collected and properly analysed to ensure data quality objectives are met.

(b) Improve hazard characterization: A reconnaissance level characterization report and hazard maps were created under the original project team several years earlier, during an earlier phase in the overall demolition project of the facility. Prior to the start of this final phase, several project team member changes occurred,

[1] Some of the text in Sections I–2.3 to I–2.5 appeared in earlier reports, including the project closeout report posted on the United States Department of Energy Office of Scientific and Technical Information (OSTI) web site.

[2] Available as a supplementary file on this publication's individual web page at www.iaea.org/publications.

leading to the loss of much of the undocumented knowledge and associated information. Because this is a specialist field and because of staff workloads, the reconnaissance level characterization effort was now provided by subcontractors. One firm was not able to handle both the radiological and the non-radiological characterization, as such work is a specialty. An important aspect of interacting with a qualified subcontractor is to get a plan that follows a prescribed method that is tied to the historical use of the buildings and to include internal subject matter experts in the development of any such sampling plan. A reconnaissance level characterization is not intended to provide a complete picture of the material hazards present. Due diligence on the part of the demolition subcontractor when the actual work is done is expected and needs to be noted in both a request for proposals and contract documents. Further sampling, specifically for sub-slab foundations and soils, early in the planning or demolition phase of the project, would have been advantageous. Access for this type of sampling may have been difficult, but earlier characterization would have resulted in less impact during subcontractor demolition activities, resulting in fewer cost and schedule changes.

(c) Improve subcontractor submittal expectations: The quality and timeliness of submittals ought to be clearly set out in the contract documents. The ground rules for document preparation and submittal expectations need to be set before issuing the notice to proceed. Poor performance on document submittals resulted in increased effort by the reviewing and approving organizations, with associated costs and schedule impacts. The project permitted inadequate subcontractor work products to pass during the review for notice to proceed based on verbal agreements, and that same lack of document preparation and sophistication set the tone and standard for documents produced by the subcontractor throughout the life of the project. Not having to repeatedly review, comment and frequently rewrite substandard subcontractor documents would have resulted in cost savings for the contractor. Solutions could have included specifying that the subcontractor could not proceed with a particular phase or task until the specified documents had been submitted and approved. Firmness with the subcontractor on these contractual commitments is needed. Setting payment milestones to ensure quality submittals and work could usefully be considered, as could requiring sample documents as part of the bid package or within the contract and award process to allow evaluation of the standard of documents. The importance of quality and timeliness of documents needs to be expressed, for example, by providing samples to the subcontractor of deliverables that meet expectations.

I–2.5. Other lessons learned

Many other lessons can be learned from this project:

(a) Hazard documentation: In reviewing documents and requirements, do not assume all historical information is still accurate. Information collected needs to be reviewed, approved and researched further before accepting and incorporating it into request for proposal documents. Err on the side of asking questions about historical information. The reports used should have been only a starting point for further investigation with the new project team leads. On the positive side, the hazard maps were updated and included in the request for proposals. The maps were also useful in obtaining Department of Energy approval to proceed with the project. Future projects may consider interviews with previous team members if projects are split among various phases that could result in team member changes.

(b) DOE requirements: The project was able to take advantage of the DOE Order 413.3A requirements. Utilizing the design/demolition approach, the project was able to work within the tailored approach, as defined in DOE Order 413.3A, and combine the CD-2 and CD-3 reviews. This allowed for savings in the time needed to conduct the review and to prepare for a separate review.

(c) Order compliance verification: The project team failed to identify that the quantity of stored radioactive material required the development of authorization basis documents or justification that the authorization basis documents were not required. The decision was made to prepare the authorization basis documents, which necessitated a safety assessment document and an accelerator safety envelope before the CD-2/3 review; the preparation of these documents became a critical path activity. It would have been beneficial to verify DOE order compliance early to ensure all required documents could be adequately prepared and approved. Independent DOE order compliance cross check would have been beneficial.

(d) Differences in working with small businesses: Contractors need to recognize that demolition subcontractors and/or other small businesses often have a different approach, resources and level of sophistication than general construction contractors. Recognizing these differences could have helped to ensure that contractors and DOE expectations in these areas were established early in the project.

(e) Interdepartmental communications: Contractor groups, departments and divisions should work together to improve interdepartmental communications. Hiring the dedicated project radiological control technician took longer than anticipated. The hiring process was delayed because of last minute decisions not to use contract radiological control technicians to augment the LBNL Radiation Protection Group staff and to hire a term employee. There were few résumés submitted for the position, as other DOE sites, such as Hanford and Savannah River, were hiring numerous radiological control technicians at the same time. The first candidate selected used the LBNL offer to leverage more money from his current employer and backed out at the last minute; the second choice candidate had found another job by that time, so more résumés had to be collected before filling the position. Because the interviewing and selection process was slower than planned, there was a change in the assigned radiological control technician personnel after the initial phases of the project. Although the loss of consistency and partial coverage did not create long term problems, they could have been avoided entirely. Improving communications would have ensured sufficient time to hire appropriate project support personnel.

(f) Schedule development: The schedule provided by the subcontractor did not sufficiently plan for potential weather impacts. An allowance for weather impacts needs to be included within the subcontractor's schedule, for example, including rain days for each of the winter months. The subcontractor's schedule did not break out a schedule contingency; rather the subcontractor's risk planning was included within individual activities. Although having the subcontractor specify contingency was not required in the project contract documents, defining the risk and documenting the amount of remaining schedule contingency would have improved understanding of the laboratory's risk. Also, if the schedule risk had been explicitly documented in the schedule, then negotiation of several of the change orders for which the subcontractor was seeking schedule variance would have been easier.

(g) Safety oversight planning: Environment, health and safety oversight was scheduled into the project from early in the planning phases; the type and quantity of the estimated effort was addressed in the project's environment, health and safety oversight plan. Commitments were provided for the project by the Environmental Services, Fire Services, Industrial Hygiene, Occupational Safety, Radiation Protection and Waste Management groups of the Environment, Health and Safety division. Support and services provided by the respective environment, health and safety groups met or exceeded expectations, in some cases requiring efforts greater than estimated. The early recognition and concurrence regarding the anticipated environment, health and safety effort aided planning and provided additional assurance that support would be available.

(h) Authorized release limits: The use of authorized release limits was suggested for this project; however, the approval of authorized release limits could not be assured within California and even if it had been, likely would have resulted in a schedule delay. A possible benefit to future projects would be to evaluate whether authorized release limits (as opposed to the default 'no human-made radiological material added') would benefit the project and if so, to seek authorized release limits early. Owing to the restrictions currently in place within the state of California, this would likely be a benefit only in other states.

(i) Funding strategy: The strategy used with the funding profile, specifically the way money was accumulated, and the project was put on hold in order to accumulate enough funds to proceed with the project without multiple phases and interruptions of mobilization and demobilization, worked very well. Although risky, it was beneficial for LBNL to go to the DOE to adjust and suggest the above method. Prior to implementing this strategy, the project was not able to make any significant progress and encountered numerous personnel changes and inefficiencies.

(j) Subcontractor selection process: The subcontractor was selected on the basis of the 'best value' criterion. This resulted in the bid selection process being completed without any complaints filed. Only one bidder requested a debriefing. There was a sufficient turn-out of bidders providing fair and comparable bids. Several companies called after the close of the bid period, indicating the possibility for broader advertisement in future bids. Use of the best value selection criterion should continue for this type of contract.

(k) Subcontractor training: LBNL successfully provided project and site specific training courses for the subcontractor. Initial training of project personnel, specifically in the areas of radiological worker and general employee training, was accomplished by LBNL on a project favourable schedule. Subsequent training was provided by the subcontractor, after their training material received a substantial review by the Radiation

Protection Group, and the Radiation Protection Group determined that the revised training was LBNL equivalent. Establishing sufficient contractor training resources as part of project planning can help ensure subcontractors meet training expectations and requirements.

(l) Full-time safety professional: The decision to have a full-time safety professional on the LBNL team was a great benefit. Although the subcontractor's safety professional was also a benefit, the subcontractor's safety personnel had a potential conflict between job safety and customer satisfaction. The additional safety oversight from the contractor, including both the full-time, project based personnel and the part-time, off-project Environment, Health and Safety division personnel, helped to reinforce job safety.

(m) Incorporation of bidder proposal into contract documents: By including the bidder proposal and the request for proposals in the contract, several subsequent scope questions would have been avoided. Importantly, without the unit rates, contract negotiations were required when additional activated shield blocks were identified.

(n) Key personnel requirements: More levels of key personnel, their roles and the percentage of time to be spent on the project identified in the subcontract need to be included and the 'best value' approach considered. The relatively few key personnel requirements established in the bid documents allowed the subcontractor to change personnel or reduce personnel involvement. It was discovered after the selection was made that the subcontractor had a noted lack of project control and planning expertise. Contractor specifications could have been improved by more clearly identifying expectations regarding key project personnel, project controls and scheduling products and resource requirements.

(o) Safety incentive programme expectations: The safety incentive programme required by the contract was not implemented as anticipated. Although the contractor provided safety milestone awards to the entire team in the form of some workday safety luncheons and some after-work events, the application of safety incentive funding towards individual or spot awards was limited. The implementation of individual and spot awards on another LBNL project, the User Support Building, was a better example of a good practice. If future programmes are established, then LBNL should consider self-administering the programme or defining the programme expectations more thoroughly in contract documents.

(p) Budget for site support services: Some site services and work orders should be anticipated throughout the course of the project. Examples include utility location services, work orders for lockout or tagout and for maintaining peripheral systems and components affected by demolition activities. It is impractical to plan every detail for every phase of the project; accordingly, sufficient budget should be set aside for laboratory support of these in-scope activities.

(q) Plan of Day meeting format: The subcontractor's Plan of Day meetings proved useful and were acknowledged as the expectation for all LBNL capital projects. Although the initial Plan of Day meetings were adequate, feedback and subcontractor experience produced improvement over time. The Plan of Day meetings are recognized as a vital element in the implementation of integrated safety management; the continued use of the Plan of Day meetings, similar to those used on the project, will aid safety awareness at the laboratory.

(r) Penetration (dig) permit process: Preparation of penetration (dig) permits improved over time; initial permits placed significant restrictions on the work that could be accomplished in view of abandoned or de-energized lines. Dig permits were prepared with specific allowances to improve workflow; for example, a permit might specify that abandoned lines were expected and that after receiving LBNL construction manager concurrence, work could continue without changing the permit, or specify that minor damage to a de-energized (or non-hazardous) system was acceptable provided the damage was repaired before penetration operations were completed. Obtaining individual dig permits for each excavation could have been a time consuming and expensive process. In lieu of multiple dig permits, the project successfully demonstrated that the building was isolated from all live utilities and that excavations within the building footprint could be performed safely. On the basis of this demonstration, the project obtained a variance from typical permit restrictions for both duration and affected areas. The global dig permit was approved for all work that was contained within the building and was issued for the planned duration of the project.

(s) Sharing of approved vendor list: Providing the subcontractor with LBNL's approved vendor list, or similar, at the commencement of the project could be beneficial. LBNL project requirements state that sub-subcontractors must be approved by LBNL; however, the sub-subcontractors that were known to be acceptable were not identified. Also, a few sub-subcontractors selected by the contractor team were marginal. Sharing the approved vendor list and other LBNL feedback prior to contractor selection could have saved the contractor from the issues resulting from below par sub-subcontractors.

(t) Subcontractor involvement with risk planning: The subcontractor may identify risks, mitigation strategies and potential impacts not considered by the contractor. Quarterly or semiannual input from the subcontractor could be beneficial. Projects should consider involving the subcontractor once in a while during risk planning. This needs to be done in a separate session in which confidential risks are not shared with the contractor.

(u) Early vetting of project requirements: To the extent possible, a clear definition of the project requirements prior to or early in the project can greatly enhance the chance of success. The project needs to thoroughly vet the project criteria, including applicable code, standards and regulations. It is beneficial to involve appropriate subject matter experts for advice and counsel early in the design phase. This requires care, as it can be unproductive to attempt too much detail in a specification. A robust process needs to be established for selecting firms for architectural and engineering services. The review and evaluation of potential architect and engineering firms should be based on qualifications of key personnel, relevant recent experience, performance on previous projects and ability to perform requested services.

(v) Definition of subcontractor role and responsibilities: Roles, responsibilities and expectations should be clearly identified at the onset of the project. For example, the percentage of time that subcontractor personnel are to be assigned to the project should be clearly identified during the subcontractor interviews and then documented in project documentation. For this project, it was sometimes unclear which individuals within the subcontractor team were responsible for activities, requiring multiple communications among the subcontractor's management team. One means to achieve this would be to require a subcontractor document analogous to the LBNL oversight plan that would delineate the roles, responsibilities and percentage of effort planned for different phases of a project.

(w) Subcontractors' project planning: The statement of work for a large construction project needs to include a requirement for the preparation and implementation of an integrated work plan utilizing an activity based, resource loaded schedule. The baseline construction schedule needs to be agreed to early in the construction phase. Continual attention and regular updates to the resource loaded schedule is critical since not all general contractor subcontracts will have been awarded at the time of the baseline. Also, the minimum level of effort by the scheduler during specific phases of the execution should be specified to ensure schedule updates are produced in a timely fashion. Without proper and consistent updates, risks associated with the subcontractor's plan may not be recognized in sufficient time to develop corrective actions or contingency plans.

(x) Scheduling for characterization: When it is not practical or practicable to complete site characterization prior to the preliminary design stage (e.g. the underslab soils being inaccessible owing to the accelerator), allowance should be made to complete characterization activities when areas became accessible. Although project contract documents required some time to be set aside to perform soil characterization, the time was not sufficient to allow completion of the characterization when new contaminants were identified. The project risk planning included possible cleanup of previously unidentified underslab contaminants but should have also included allowance for the characterization; specifically, risk planning should have acknowledged that subcontractor activities may need to be paused while characterization is completed. Future contract documents should consider a longer duration for characterization than the five days allowed for LBNL characterization on this project.

(y) Change order timeliness: When change order work cannot be avoided, every attempt needs to be made to resolve cost and schedule impacts as soon as practicable. The project needs to ensure substantiating documentation is received in a timely manner for change order resolution. Contract provisions establishing the process for change orders need to include a time frame for submitting the information as well as options that the project team may consider if the information is not forthcoming. This is especially important for change order work that deletes scope and results in a credit to the owner. Change order work should be forward priced to the greatest extent possible. The cost and schedule impacts need to be negotiated prior to releasing the work. When change order work is scheduled as critical and must be done immediately owing to unknown field conditions, a field change order process can facilitate the progress of the work and mitigate potential schedule delays.

I–3. INTENSE PULSED NEUTRON SOURCE, ARGONNE NATIONAL LABORATORY, USA

I–3.1. Introduction

The Intense Pulsed Neutron Source (IPNS) was the first spallation slow neutron source based on a proton synchrotron. It was in operation for 26 years, between 1982 and 2008, when the closure was announced [I–8]. The accelerator complex consisted of a pre-accelerator, a proton linac and a rapid cycling synchrotron. From there, the 500 MeV protons were brought through a transport line to a scattering target in the large IPNS experimental hall, which contained 12 experimental beamlines. Figure I–3 shows the layout of the IPNS accelerators and experimental hall.

IPNS established itself as a very successful user facility for condensed matter research. In spite of its successful programme, IPNS operation was stopped abruptly and irrevocably on 27 December 2007 owing to cuts in government funding. Two workforce reductions occurred in 2008, but workers with the skill and experience needed to conduct a safe shutdown were retained. By the end of September 2008, only six workers remained to plan and proceed with deactivation and decommissioning. A transition plan was developed and submitted to the DOE with a request for funding, which was ultimately provided until the end of fiscal year 2011.

I–3.2. Deactivation activities

Because of the sudden and unplanned shutdown, the facility was left in a working configuration, with scores of experimental samples, plus equipment and supplies. Many of the samples did not have proper identification or labelling. During deactivation, energy sources such as electrical power, vacuum, pressure, gases and water were removed or secured with administrative lockout/tagout. Fire protection, lighting, heating, ventilation, air-conditioning, building electrical power, safety and security systems remained functional.

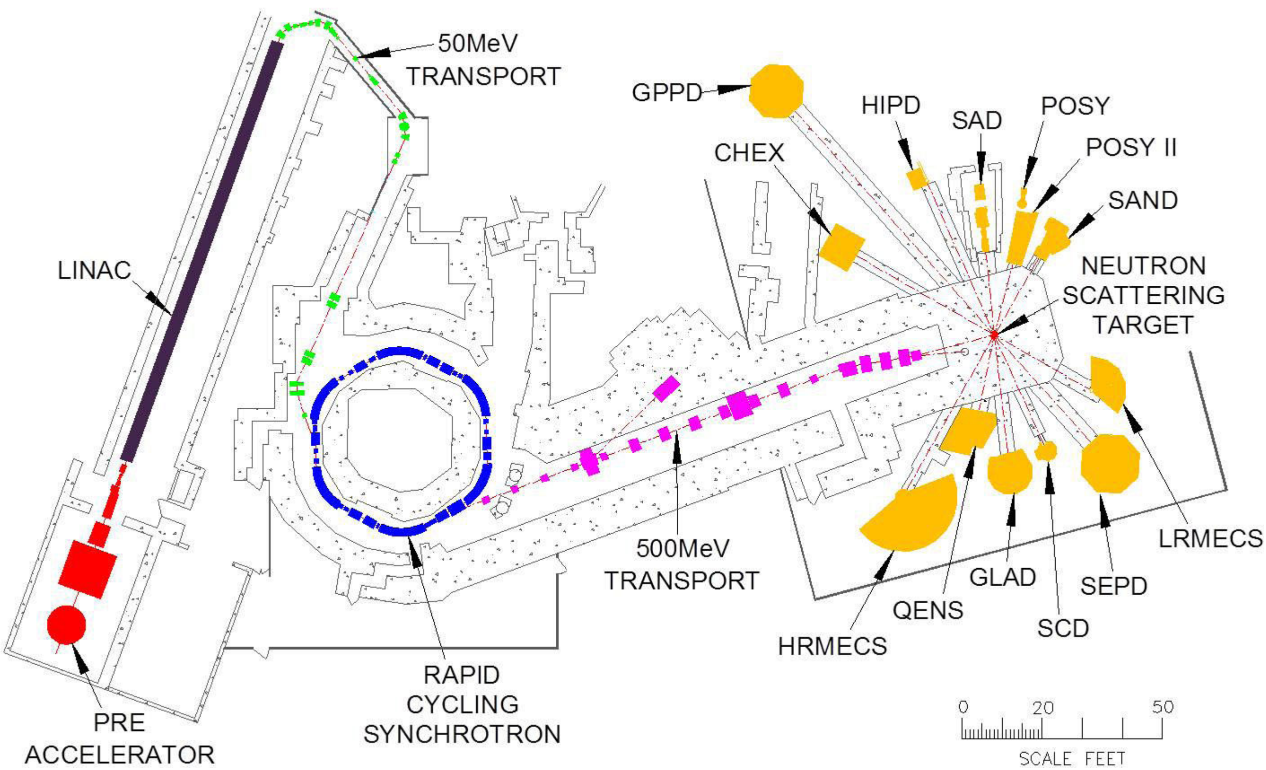

FIG. I–3. Layout of the IPNS accelerators and experimental hall (courtesy of Argonne National Laboratory).

I–3.3. Removal and disposal activities

To make the building acceptable for transfer to the DOE Office of Environmental Management, all materials had to be removed except for structural and beamline components. Initially, all remaining hazards were removed or identified. All electrical wiring was tested and labelled, and non-essential power was de-energized and removed. The building was cleared of all excess equipment and materials, which necessitated disassembly of large experimental setups and disposal of chemicals, PCB-containing transformers, hazardous metals (e.g. beryllium, lead), and accessible radioactive materials. A large amount of usable equipment (e.g. vacuum pumps, computers, detectors, electronics, ancillary equipment) was distributed to other DOE programmes for reuse.

I–3.4. Lessons learned

The following lessons can be learned from this project:

(a) Upper management of the facility needs to be involved promptly in order to raise awareness of upcoming challenges and provide support in securing funding.
(b) The most qualified and experienced staff need to be selected, because special knowledge and skills are necessary. Human memory proved to be more valuable than stored information in this project. Argonne's Human Resources department was helpful in selecting the proper staff for retention.
(c) Multiorganizational teams need to be formed early. IPNS teamed with the Facilities Management and Services and the Waste Management Organization divisions. IPNS became the responsibility of the Facilities Management and Services division. All hazardous waste was disposed of through the Waste Management Organization division.
(d) Holding a daily group meeting for discussions of planned work, controls and safety topics can be effective for a decommissioning group of approximately ten people.
(e) Supervisors need to keep a daily work journal, preferably in a solid bound format for durability. In this project, knowing the chronological order of the numerous activities was later helpful.
(f) Programmatic divisions typically do not dispose of excess equipment and materials during operations in order to save money. Institutional housekeeping programmes, such as Argonne's 'Clean Sweep' programme, can be helpful.
(g) Surveillance and maintenance are more time consuming after shutdown owing to reduced staffing levels. This is another reason to involve staff with the required expertise.
(h) Photographing all items disposed of can be useful (see Fig. I–4). Identification tags need to be added for reference. A thoughtful and logical labelling system is necessary to manage thousands of photographs.
(i) For lifting of heavy legacy items — such as accelerator magnets — bolts and shackles might be an issue. Securing qualified suppliers and performing qualification calculations by engineers may be time consuming. Starting early and allowing for long lead times would be beneficial.

FIG. I–4. All items disposed of were photographed and catalogued. Note the placement of a unique inventory identification label in the photo to avoid having to insert or label the many photos afterwards (courtesy of Argonne National Laboratory).

(j) Simplifying necessary systems helps to reduce maintenance. For example, in this project, the electronic accelerator security system was replaced with a key lock entry and crash bar exit system that was easy to maintain.
(k) So-called simple tasks should not be underestimated. Clearing of offices, small laboratories and paper files can be onerous. Personal identity information checks and document shredding require time. There are legal requirements for the retention of records, and they need to be evaluated by institutional record managers.
(l) Experimental sample disposal is a time consuming task. Samples should have been returned to scientific users. Identification is required before disposal, but some samples remained unknown. It is important to analyse the hazards and consider the knowledge and skills of the workers; here, an outside vendor was used for the neutralization of some highly reactive samples. The ability to acquire sample inventories would have been useful.
(m) Large quantities of unused industrial chemicals such as oil, paint and acetone are difficult to give away or dispose of. The use of a commercial disposal vendor could be considered for efficiency.
(n) The institutional on-line excess material system was inadequate because it was not designed for processing large quantities of equipment and materials. Data entry of individual components was tedious.
(o) Shipping materials for transfer to other institutions may be problematic. The requester is often not aware of transportation and administrative requirements and costs. Management and requesters do not always agree. A management signature from the receiving facility needs to be obtained before shipping.
(p) Advance notice may need to be given to those interested in pictorial documentation and gathering of historical information before facility dismantling begins.
(q) It is better to avoid considering borderline cases as mixed waste as opposed to simply chemical or radioactive waste. This can result in substantial cost savings.

I–4. EXPERIMENTAL EQUIPMENT DECOMMISSIONING DURING UPGRADE OF CEBAF AT JEFFERSON LABORATORY, USA

The Thomas Jefferson National Accelerator Facility (Jefferson Laboratory) is a nuclear physics research facility funded by the DOE. Its 4 GeV electron accelerator, CEBAF, began delivering beam to its original three experimental halls (Halls A, B and C) in 1994. The accelerator consists of two linacs using superconducting radiofrequency acceleration technology, arranged in a racetrack set-up. In 2000, the first facility upgrade extended the accelerator energy to 6 GeV. A second, major upgrade was executed between May 2011 and September 2013. The purpose of this upgrade was to increase the electron beam energy to 12 GeV and build a new experimental hall (Hall D).

The 12 GeV upgrade was conducted in two major phases, with a six month period of operations separating the two periods of demolition and modifications [I–9]. In the accelerator tunnels, modifications included removal, refurbishment and reinstallation of dozens of large dipole magnets and associated equipment, plus installation of a large number of new magnets with associated beamline. The upgrade of the accelerator proper produced about 20 t of waste (almost entirely metals) consisting of dipole magnets and their supporting structures, cabling, piping, cable trays, and so on. Two of the original experimental halls underwent significant reconfiguration. Hall B was entirely eviscerated of its original target–detector package. Most of the equipment in Hall B was cleared as non-radioactive. In Hall C, the short orbit spectrometer (see Fig. I–5) was demolished and removed. Restructuring of the experimental halls yielded large amounts of activated concrete as well as massive metal structures, which all required disposal. The short orbit spectrometer alone produced over 180 t of waste, a portion of which — about 43 t of concrete — was cleared as non-radioactive. The final tally of radioactive materials requiring management as waste includes approximately 150 t of metals and over 230 t of concrete. Of these materials, approximately 136 t of lightly activated concrete was stored for decay and eventual release. The rest (about 250 t in total) is being managed under a five year plan, approved by the DOE, which includes the development of specific authorized release limits for a portion of the waste. Examples of radioactive material collected during the decommissioning process are illustrated in Figs I–6 to I–8.

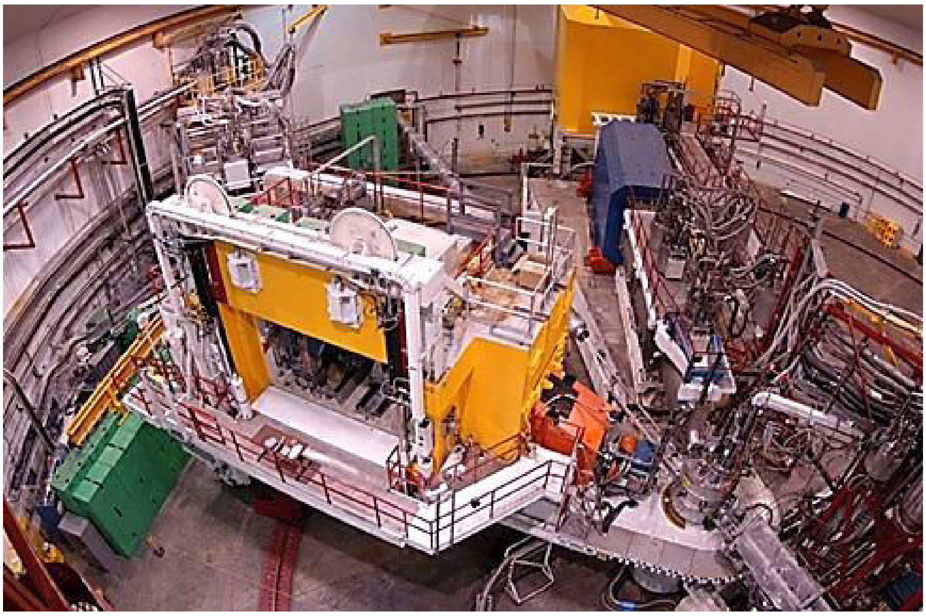

FIG. I–5. Experimental Hall C before the 12 GeV upgrade, showing the short orbit spectrometer and high momentum spectrometer (courtesy of Jefferson Science Associates, LLC).

FIG. I–6. Short orbit spectrometer frame from Experimental Hall C, with weight marked in pounds (courtesy of Jefferson Science Associates, LLC).

FIG. I–7. Target pivot from Experimental Hall C, with weight marked in pounds (courtesy of Jefferson Science Associates, LLC).

FIG. I–8. Excess dipole magnets in the foreground, concrete shielding blocks in the background and fragments of the concrete floor slab from Experimental Hall C on the right in the background (courtesy of Jefferson Science Associates, LLC).

The experimental hall is a cylindrical structure that has an inner diameter of 46.4 m and is 15 m in height at the apex. Electrons arrive from the accelerator in the beamline that crosses the hall from lower right towards upper left, pass through the cylindrical target chamber and continue towards the beam dump beyond the wall of the hall. A short orbit spectrometer and a high momentum spectrometer are on the left and right side of the beamline, respectively. The short orbit spectrometer and high momentum spectrometer frames can be rotated around a pivot under the target chamber.

I–5. DISMANTLING A CLASS 4 ACCELERATOR: THE LARGE ELECTRON–POSITRON COLLIDER, CERN (2000–2001)

I–5.1. Introduction

The Large Electron–Positron collider (LEP) at the European Organization for Nuclear Research (CERN) started operation in 1989. Until 1995, it was operated at 45.6 GeV per beam to study the production of the Z^0 particle. At the end of 1995, the LEP2 phase began, with the progressive upgrade of the collider energy above the W pair production threshold. The goal was 100 GeV per beam in 1999, which was exceeded in 2000, the last year of operation, when the LEP reached 104 GeV per beam. In the LEP2 period, the major modifications to the machine were the addition of (a) a new acceleration system employing superconducting radiofrequency cavities and (b) a dump system.

The accelerator, which was installed underground at a depth between 50 and 170 m, had eightfold symmetry, with eight arcs, eight long straight sections and a circumference of 26 658 m (Fig. I–9). The four experiments, L3, ALEPH, OPAL and DELPHI, were located at the interaction points in the centre of the straight sections.

The installation of the Large Hadron Collider in the LEP tunnel required the dismantling of the LEP after 11 years of operation. Decommissioning started early in 2001 and was completed by February 2002. Extensive information on this dismantling can be found in Ref. [I–10].

Before dismantling could start, a complete characterization of the expected amount of low level radioactive material to be removed during the accelerator decommissioning had to be undertaken.

The Swiss regulation in radiation protection does not provide unconditional clearance levels (i.e. threshold values below which the material can be regarded as non-radioactive) for activity concentration (activity per unit

FIG. I–9. Example of LEP accelerator structure experimental hall (courtesy of CERN).

mass) in materials to be released into the public domain. Release of material may only be allowed after a detailed theoretical study supported by experimental measurements is performed.

A major constraint imposed by the Swiss legislation is that material or equipment classified as ‘radioactive’ in the zoning study cannot be declassified as ‘conventional’ after a measurement, no matter how accurate the latter is in showing no traces of induced radioactivity. Material can be ‘declassified’ only by revising the zoning of its area of origin. Out of over 30 000 t of material removed from the accelerator itself, only about 3% was classified as radioactive.

I–5.2. Decommissioning planning

The project of decommissioning the LEP started several years before the actual shutdown of the installation. The project was organized in 1999, after identification of the major technical and logistical problems associated with the removal of equipment from the underground areas. The major constraints identified at the beginning of the project were:

(a) Conformity with the national (Swiss) regulations;
(b) Project schedule (fitting in with the Large Hadron Collider construction);
(c) Limited resources.

Over 140 major activities were identified, and the project plan and preliminary schedule were established and kept updated throughout the project. A steering committee monitored the different phases of the decommissioning.

Safety was monitored throughout the project, with the objective of keeping the doses to personnel as low as reasonably achievable. The radiation controls applied at several progressive stages of the evacuation and disposal of material were aimed at assuring the highest level of confidence in the verification of predicted activity. The dismantling project included:

(1) Preparatory phase;
(2) Studies and documentation;
(3) Tendering and procurement;
(4) Planning;
(5) Infrastructure;
(6) Traceability, zoning, radiation protection and recycling;
(7) Security and temporary storage;
(8) Execution;
(9) Safety, training and transport;
(10) Coordination and follow-up.

About three hundred pages (and a substantial resource deployment) were necessary for preparing the safety documentation, the general operating procedures and specific (e.g. radiation protection) procedures, as well as for the risk analysis.

I–5.3. Project execution

Owing to the repetitive nature of the structure of the accelerator (eight arcs, eight straight sections, four major experimental halls, etc.), the project was conducted using a phased approach, with a limited number of teams following each other through the tunnel and progressively removing the accelerator components and services.

The accelerator was divided into 50 sections, based roughly on the electrical sectors. For each zone a procedure was established.

The list of tasks for the dismantling was as follows:

— Make areas safe from beam.
— Perform detailed radiological survey to confirm the preliminary estimate.
— Make equipment safe in readiness for dismantling.

— Remove radioactive items.
— Disconnect vacuum components.
— Cut vacuum chamber and bus bars.
— Remove beamline components.
— Remove cables.
— Remove cooling pipes.
— Clean up remaining small items.
— Perform radiological survey and reclassify zones.

A total of around 30 000 t of equipment had to be removed from the LEP machine areas and a further 10 000 t from the experiments. This material was divided into four categories: equipment to be stored for future reuse, either conventional (i.e. free from activation) or radioactive, and material to be eliminated as waste, again either conventional (sold as scrap) or slightly radioactive (stored on the CERN site).

Characterization of the material took into consideration the possible activation phenomena:

(a) Localized beam losses (predominant in most parts of the ring):
   — Irradiation of samples and analysis by gamma spectrometry;
   — Determination of conversion coefficients from unit lost beam power to induced specific activity at saturation.
(b) Distributed beam losses: Simulations.
(c) Synchrotron radiation: Monte Carlo calculations have shown that for E < 105 GeV, the activation due to synchrotron radiation is negligible.
(d) High energy X rays emitted by the superconducting radiofrequency cavities: Measurements.

I–5.4. Gamma spectrometry measurements during dismantling

In addition to the dose rate measurements performed on all equipment in the LEP underground areas, random samples were taken from various materials (e.g. cables, cable trays, dipoles, yokes, nuts and bolts, concrete of the tunnel floor and walls) and analysed by gamma spectrometry. These measurements were carried out on four classes of material:

(1) Material classified as conventional according to the zoning study and confirmed to be conventional by the radiation check (i.e. non-radioactive material);
(2) Material classified as conventional according to the zoning study but measured as very low activity material (i.e. anomalies);
(3) Material classified as very low activity according to the zoning study but measured as conventional;
(4) Material classified as very low activity according to the zoning study and confirmed as such by the measurement.

All measurements were carried out with a high sensitivity, low background Canberra hyper-pure germanium detector (245 cm^3 of sensitive volume; efficiency of 60% at 1.33 MeV). Figure I–10 shows the superconducting accelerator modules that were stored after dismantling; each module was about 12 m long. Figure I–11 shows the very low level waste that resulted from the LEP dismantling.

The entire system of superconducting accelerator modules (72 modules, about 2000 m^3 and 440 t) was examined in 2017 for residual activity. On the basis of thorough measurements, supported by computational studies performed via Monte Carlo, 95% of the material could be released from regulatory control. The remaining 5% of the material was just above the Swiss regulatory limit for release as conventional waste and was stored at CERN in view of further disposal as low level waste. The radiological characterization was based on the definition of activity ratios, allowing the activity of the no gamma emitting radionuclides to be linked to the activity of a 'leading nuclide' gamma emitter (e.g. ^{22}Na or ^{60}Co) for each region and for each type of material.

A very detailed sampling procedure was presented to the Swiss authorities in order to validate the calculations. It was based on samples from the most activated parts, according to the calculations and to the measurements performed during the operation of the machine; the samples were selected to be representative of each part of the modules and each type of material.

Before and during the dismantling of the accelerator, experiments were carried out to assess the radioactivity induced in the most abundant LEP materials, namely aluminium (e.g. vacuum chambers, dipole excitation bars), copper (e.g. radiofrequency cavities, magnet coils, vacuum joints, collimators), lead (e.g. shielding around the

FIG. I–10. Seventy-two superconducting accelerator cavities were stored after dismantling. Each module was about 12 m long. (Courtesy of CERN.)

FIG. I–11. Very low level waste from the LEP dismantling (courtesy of CERN).

vacuum chamber), stainless steel (e.g. vacuum chambers, vacuum valves, bellows) and iron-laminated concrete (dipoles). The composition and the principal trace elements of the various materials, important for both the Monte Carlo calculations and the gamma spectrometry analyses, are discussed in the following and are given in Table I–1.

All vehicles transporting conventional material to scrap facilities underwent a final radiation check by a highly sensitive gate monitor. The gate monitor was very reliable and was capable of detecting even exetrmely weak emissions from radioactive materials.

TABLE I–1. COMPOSITION AND PRINCIPAL TRACE ELEMENTS OF THE LEP MATERIALS

LEP material	Principal trace elements	Weight (%)
Al type 6060[a]	Si	0.3–0.6
	Fe	0.10–0.30
	Cu	0.10
	Mn	0.10
	Mg	0.35–0.6
	Cr	0.05
	Zn	0.15
	Ti	0.10
	Other	0.15
Pb (99.94%)	Ag	0.0015 max.
	Cu	0.0015 max.
	Ag+Cu	0.0025 max.
	As+Sb+Sn	0.002 max.
	Zn	0.001 max.
	Fe	0.002 max.
	Bi	0.050 max.
Stainless steel 316L[b]	Cr	16–18.5
	Ni	11–14
	C	0.03 max.
	Si	1 max.
	Mn	2 max.
	Mo	2.5 max.
	N	0.05 max.
	P	0.03 max.
	S	0.01 max.
	Co	0.22 max.

TABLE I–1. COMPOSITION AND PRINCIPAL TRACE ELEMENTS OF THE LEP MATERIALS (cont.)

LEP material	Principal trace elements	Weight (%)
Oxygen-free high conductivity copper (OFHC) (99.99% Cu)[c]	Ca	1×10^{-4}
	P	3×10^{-4}
	S	1.8×10^{-3}
	Zn	1×10^{-4}
	Hg	1×10^{-4}
	Pb	1×10^{-3}
	Bi	1×10^{-3}
	O	1×10^{-3}
Fe of the LEP dipoles[d,e]	C	$1–2 \times 10^{-3}$
	P	$7–14 \times 10^{-3}$
	Mn	$165–218 \times 10^{-3}$
	Ni	$18–21 \times 10^{-3}$
	Cr	$10–16 \times 10^{-3}$
	Cu	$8–25 \times 10^{-3}$

[a] The remainder is aluminium.
[b] The remainder is iron.
[c] The total concentration of the seven elements As, Sb, Bi, Se, Te, Sn and Mn does not exceed 40 ppm.
[d] The remainder is iron.
[e] The ranges in the percentages refer to different castings.

I–5.5. Lessons learned

At the end of the dismantling project, some lessons could be drawn.

I–5.5.1. Induced radioactivity estimate

Some estimates of the expected amount of induced radioactivity in the LEP were made during the design phase of the collider [I–11, I–12]. The factors considered in arriving at these estimates were limited and were based on assumptions of beam loss distributions that were not necessarily confirmed by the operational experience and, therefore, were of limited use when planning the decommissioning.

Owing to a lack of understanding or poor knowledge of the components installed in the tunnel and, in particular, of their detailed chemical composition and irradiation conditions, systematic radiochemical analyses were necessary at the start of the project to assess the influence of trace elements on the global material activation (e.g. the quantity of cobalt in stainless steel that gives rise to ^{60}Co).

I-5.5.2. Radiation protection

From a radiation protection point of view, the dose rate measurements performed in the underground areas were very accurate. In fact, only a few vehicles set off alarms at the gate monitor (the final control on material leaving the CERN site), indicating that slightly activated items had escaped the first measurement. The final measure of the success achieved was that none of the approximately 1600 vehicles that left CERN with metal for recycling returned to CERN owing to detection of radioactivity at the monitoring station in the reception area of the scrap dealer.

The individual doses of the workers involved were very low, with a collective dose for the almost 250 workers involved over 15 months totalling less than 7 mSv. The maximum individual dose received did not exceed 0.55 mSv.

I–5.5.3. Management

Good results were achieved in coordinating so many activities under rigorous time constraints: work days were set at eight hours per day. A contingency measure was the possibility of working shifts.

A challenge throughout the dismantling process was the limited storage space available at CERN. In fact, during the dismantling of the LEP, other projects — and especially a major revision of the injector chain — concomitantly requested the use of the available storage space.

I–5.5.4. Traceability

A thorough inventory of equipment to be removed was performed by applying barcodes to components and subcomponents. This ensured detailed knowledge of the total amount of material and components to be dismantled (67 000 items in the LEP) but required consistent investment and very precise procedures (e.g. databases, follow-up).

I–5.5.5. Waste and recycling

More than half of the equipment (by weight) was removed from the tunnel as complete units that could be suitable for recycling or reuse (valuable material). CERN donated these items to other research institutes or accelerator centres.

I–5.5.6. Technical problems

Prior to the start of decommissioning, preventive maintenance was scheduled on all transport equipment, which ensured a low rate of failure during the decommissioning project and therefore a low rate of work site shutdown.

I–5.5.7. Incidents/accidents

No major accident or incident occurred during the dismantling, though a high rate of small incidents and accidents were attributable to the lack of training of the contractor’s personnel.

I–6. DECOMMISSIONING OF A LINEAR ACCELERATOR IN GERMANY (CLASS 1)

I–6.1. Introduction

One of the most common fields of use for linacs is the treatment of cancer in radiotherapy. These machines usually have a high workload because of the ever increasing need for cancer treatment. The normal lifetime of a device of this kind is between 10 and 20 years. There are different reasons for shutting down and decommissioning linacs. These include:

(a) New technologies or methods of cancer treatment have become available, and the existing machine cannot be adapted to incorporate them.
(b) Components of the machine, such as bearings, have failed or been damaged.
(c) The supplier (manufacturer) of the machines in use within groups of hospitals has changed, and it is necessary to ensure that all the machines are the same for ease of staff rotation and maintenance.

Decommissioning of the accelerator in this case study occurred owing to the last factor referred to above. The hospital in the study is related to one of the biggest hospital groups in Germany. The group renews its equipment on a regular basis. In this example, the total number of accelerators was to be increased and the department was to be uniformly supplied with machines from a single manufacturer over a three year period. Therefore, four old machines had to be decommissioned. The first linac was decommissioned by the hospital, but the remaining three machines were decommissioned by a commercial decommissioning company, namely Gamma-Service Recycling GmbH. The contractor was asked to submit a quote for the decommissioning of each remaining machine, and all three quotes were accepted. This case study describes the decommissioning of the last linac.

The device was an SLi (SLi is the type of accelerator and stands for ‘sliding window’). The machine had the serial number 5552 and was manufactured in 1998, the year it was installed in the hospital. The accelerator was in regular use for cancer treatment until 18 April 2012, with just minor periods when it was not operational owing to shutdown and planned maintenance, upgrading or repairs.

The SLi type of accelerator shown in Fig. I–12 is a travelling wave accelerator and was augmented with a multileaf collimator. The common photon energies used for cancer treatments with this machine were 4 and 10 MeV, although the machine was capable of producing higher energies. Higher energies would only be used for special applications, but their use would be likely to result in activation in parts of the machine.

I–6.2. Decommissioning project

Before submitting a quote for the decommissioning of the machine, a checklist was sent for completion by the hospital. Although the decommissioning contractor could acquire information on the new accelerator to be installed, the checklist was a useful means of collecting other information essential for decommissioning that the new installer would not be able to provide (e.g. details of ease of access to the equipment for dismantling and ease of movement of materials into and out of the area under consideration). In this example, a site inspection was

FIG. I–12. SLi accelerator (courtesy of Ion Beam Applications).

also performed. With reference to the information obtained, a quote for decommissioning was prepared. Once the quote was accepted, the decommissioning contractor coordinated the decommissioning of the machine with the responsible authorities, the manufacturer and the hospital. The decommissioning contractor had permission to carry out decommissioning that was not site specific (i.e. not just limited to its own site). This meant that the decommissioning contractor was allowed to handle radioactive material on the site of the linac by extension of the permission it held to cover other facilities, by agreement with the responsible authority. For this project, the responsible authority was the regulator for the linac.

The dismantling of this small accelerator started on 24 April 2012 and was finished on 25 April 2012. The decommissioning contractor worked alongside a qualified subcontractor, who had permission granted under the German radiation protection ordinance (Ref. [I–13]) to work in foreign facilities. The subcontractor carried out the heavy duty dismantling and the disposal of inactive waste. The subcontractor's areas of specialization were non-common logistics (e.g. the installation and decommissioning of medical devices), and the subcontractor was experienced in dismantling linacs as well as other machines.

The decommissioning contractor offered complete service for the decommissioning of the accelerator, including writing the decommissioning plan and applying for any regulatory permissions. As well as doing all the necessary paperwork, the decommissioning contractor undertook the dismantling in liaison with subcontractors, put in place radiation protection and general safety arrangements, undertook transport of materials off the site with due regard for the European Agreement concerning the International Carriage of Dangerous Goods by Road and the recycling of inactive components in accordance with the Waste Electrical and Electronic Equipment Directive.

Prior to commencing dismantling operations, the responsible radiation protection officer of the decommissioning contractor signed an agreement between the hospital and the decommissioning contractor that allowed the contractor to use its own non-stationary permission related to §7 of the radiation protection ordinance (Ref. [I–13]) in the hospital, limited to the working areas of the irradiation bunker. Such an action was necessary because prior permission for the decommissioning of the accelerator was needed and the hospital did not have such permission included as part of its operating licence. The next stage was to instruct all personnel working within the area on the radiation protection measures and work safety procedures, as confirmed in the documented protocol for the project. Once the paperwork formalities were completed, the dismantling process started. Some of the technical data for dismantling the machine shown in Fig. I–13 are presented in Table I–2.

While dismantling the machine, the responsible radiation protection officer of the decommissioning contractor separated the activated parts of the machine using different kinds of measurement equipment (e.g. a dose rate meter and a contamination monitor). The activated parts were packaged in compliance with the regulations for the shipment of radioactive goods stipulated in the European Agreement concerning the International Carriage of Dangerous Goods by Road. While carrying out this work, the highest dose rate measured on the target was 35 μSv/h. After sealing the transport boxes, the maximum dose rate on the surface of the entire package was 1 μSv/h.

FIG. I–13. Isochron cyclotron Philips 140/IV (reproduced from Ref. [I–14] with permission courtesty of K. Peschel).

TABLE I–2. TECHNICAL DATA OF THE MACHINE REQUIRING DECOMMISSIONING
(reproduced from Ref. [I–14] with permission)

Type	Isochron cyclotron Philips 140/IV specifications	
Magnet	Middle field	15 kg
	Mass iron	80 t
	Mass copper coils	8 t
	Diameter of pole shoe	140 cm
	Distance of pole shoes min.	16 cm
	Distance of pole shoes max.	32 cm
Sender	Frequency	5–23 MHz
	HF-output	Max. 100 kW
	Acceleration potential	Max. 50 kV
Particle energy	Protons	30 MeV
	Deuterons	15 MeV
	Helium-3	40 MeV
	Helium-4	30 MeV
Target sites	Internal	2
	External	6

The activated parts that were identified included the multileaf collimator, the collimator bends with driving engines, the target, the hardening filters, the bending section and the shielding material (lead, tungsten). In addition, a complete collimator section that the hospital had stored on the site, which was also activated, was removed from the site for future reuse as spare parts. At the termination of dismantling activities on 25 April 2012, the accumulated dose to the subcontractor workers was confirmed to be consistent with the working protocol and was entered in their radiation passports. The disassembled linac was taken over completely by the decommissioning contractor as confirmed in the written procedure. The identified inactive parts were passed to the subcontractor for recycling. The subcontractor confirmed that the parts passed to them for immediate recycling were in compliance with clearance criteria.

The decommissioning contractor accepted ownership of the activated material removed from the hospital. The responsibility of the hospital for the decommissioning project ended with the settlement of the bill to the decommissioning contractor. Further dismantling and characterization of the activity in the material removed from the accelerator site took place in the storage facility of the decommissioning contractor in Leipzig. This work is still in process as some of the material remains in decay storage. The longest storage time is foreseen for some of the components removed from the linac.

The cost for decommissioning linacs depends on the photon energy used for radiotherapy, the working life of the machine and installed equipment, the adjacent facilities, and the characteristics of the site. The cost to decommission the machine described above was €21 000, including the dismantling, the generation of records, the characterization of radionuclides and the storage of the materials until final clearance. The policy of this decommissioning contractor was to route as much of the material as possible for recycling: this required clearance for release after an appropriate storage time. Recycling such material is essential to minimize the amounts of low activity waste to be stored in national facilities.

I–6.3. Lessons learned

The following lessons can be learned from this project:

(a) Hospitals have a licence to operate the accelerator but often fail to consider that they might need to apply for a different licence for decommissioning. This can result in delays in the decommissioning of accelerators, depending on the regulatory regime of the State. In rare cases, specialist decommissioning contractors may have a licence that allows for them to decommission the accelerator utilizing their own regulatory permission, hence allowing the project to progress.
(b) All the materials from the dismantled machine and any spare parts already stored on the site need to be segregated at source in preparation for further management off the site. This permits the contractor to have full flexibility to decide when the time is appropriate to recycle or clear material from their own facility. A maximum decay period of approximately six years is anticipated for some of the parts removed from this machine to reach clearance levels, although many parts will be disposed of earlier than this.
(c) Leaks from the cooling water system or the cessation of maintenance once the accelerator is no longer in use can result in the corrosion of screws and bolts, making dismantling operations more difficult and reinforcing the need for an appropriate maintenance programme to be in place through decommissioning.

I–7. DECOMMISSIONING OF AN ISOCHRONCYCLOTRON IN GERMANY (CLASS 2)

I–7.1. Introduction

Between 1966 and 1968 on the site of the Deutsches Elektronen-Synchrotron in Hamburg–Bahrenfeld, an isochron cyclotron was installed. It was used by the first Institute of Experimental Physics of the University of Hamburg and started its working life on 26 December 1968. It was manufactured by the Philips Company in Eindhoven (Netherlands) and was called the Hamburger Isochron-Zyklotron. Before installation, the basic functions were tested at the factory. After installation at the site with the help of the Deutsche Bahn (German railway company), it was tested for several years for the main functions of the machine itself and the corresponding systems such as the beam guides and the so-called splitter magnets. After the testing phase, the experimental sites were installed. For around two decades the experimental sites were in use for different purposes in experimental physics and for the production of radionuclides and for experiments relating to the activation of materials and medical research. Only very sparse information on the actual experiments and radionuclide production that had been carried out over the years of operation was available at the time of decommissioning, so if such records had ever existed, they clearly had been lost. Some information on past activities could be found by searching through dissertations and research reports, but there were no comprehensive data available to assist with facility characterization in preparation for decommissioning.

After switching their focus to the high energy physics of the Deutsches Elektronen-Synchrotron, the institute had no further need for the Hamburger Isochron-Zyklotron. With the support of the city of Hamburg, a laboratory for radiochemistry and plant physiology was built, and a positron–electron project camera and connected devices were also installed. The Hamburger Isochron-Zyklotron was transferred to the newly founded accelerator and tomography centre, which had a special focus on the use of positron emission tomography (PET).

In 1994, the cyclotron and the centre were incorporated into the radiotherapy and nuclear medicine department of the university hospital of Hamburg–Eppendorf. There the cyclotron was used primarily for the production of radionuclides for PET to meet the requirements of some hospitals in the north of Germany. Later, the department of cyclotron and radiochemistry was organized as an independent section called Norddeutsche Zyklotron GmbH. This section continued to produce radionuclides until its closure in October 2007. A tender process was initiated for the decommissioning of the machine, and the work started at the end of September 2008. Table I–2 provides technical data of the machine that required decommissioning, which is shown in Fig. I–13. A detailed description of the isochron cyclotron is given in Ref. [I–14].

I–7.2. Radiological survey of the Hamburger Isochron-Zyklotron

As mentioned previously, the radiation history of use of the isochron cyclotron was not fully documented. Less information was available in relation to the research projects carried out in the early years of use of the machine. The original staff were gone too, so the knowledge had been lost to time. From the data available at the time the tender process started, it was not possible to submit a quote for the decommissioning of the machine. Gamma-Service Recycling GmbH was asked to submit a quote for the decommissioning but was unable to comply at that time. Basic data referring to contamination and activation would be needed to calculate the requirements for the decommissioning of the Hamburger Isochron-Zyklotron and related installations and to clear the building for further use. Gamma-Service Recycling submitted a quote, in cooperation with the Verein für Kernverfahrenstechnik und Analytik (VKTA), to conduct a radiological survey of the machine, related installations, mobile shielding and the structure of the building.

The quote was accepted, and the survey completed in 2008. Samples were taken from the wall structure, the magnet, the beamline, the target site and different side installations, such as the indoor crane. The types of sample collected included wipe tests, cuttings and removal of smaller parts of the machine, including screws. While measuring the samples by different methods (gamma spectrometry, liquid scintillation counter for ^{3}He, etc.), it was discovered that only activation products were present in the concrete of the accelerator wall, target bunker and mobile shielding, as well as in the metal structure of the cyclotron, related installations and the target sites, as given in Table I–3.

As shown in Table I–3, the spectrum of nuclides present in the samples of metal and concrete was similar. There were only differences in the concentrations of the nuclides. Samples from metal structures contained primarily ^{60}Co, ^{54}Mn, ^{55}Fe and ^{63}Ni, whereas concrete samples contained primarily ^{152}Eu, ^{154}Eu and ^{155}Eu. In each sample, all the mentioned radionuclides were detected. The measurements were made with an in situ gamma spectrometry system called Genie 2000 V3.1 (detector and software). Regarding the survey, two guiding nuclides were chosen. For metal samples the guiding nuclide was ^{60}Co; for concrete samples and the wall structure, it was ^{154}Eu. On the basis of the results for the mentioned radionuclides, correction factors were established to calculate the total activity.

During the survey, contamination was discovered at the target site and in the beamline. This meant that decontamination would be required for these sections.

After securing a sufficient database, a final quote was established for the decommissioning project. Gamma-Service Recycling won the tender and started the decommissioning of the Hamburger Isochron-Zyklotron on 24 September 2008.

I–7.3. Arrangement before starting the project

The main contractor for the decommissioning project was Gamma-Service Recycling; the main subcontractors were the previously mentioned VKTA and the Gerdts Spedition GmbH, a transport company well experienced in the decommissioning of devices. There were also other subcontractors engaged in this project.

VKTA developed a concept based on the data from the radiological survey of the Hamburger Isochron-Zyklotron for the clearance of dismantled materials, mobile shielding and the wall structures. The concept included measurement methods to be used in the project and methods for conditioning the material in a form fitting to

TABLE I–3. RADIONUCLIDES IDENTIFIED DURING THE SURVEY

Sample type	Radionuclides
Metal, different samples	Co-60, Ag-108m, Cs-137, Eu-152, Eu-154, Eu-155, Mn-54, Fe-55, Ni-63
Concrete, different samples	Co-60, Ag-108m, Cs-137, Eu-152, Eu-154, Eu-155, Mn-54, Fe-55, Ni-63

the measurement requirements; it also defined how to measure surfaces and included clearance criteria for the materials being dismantled. The concept was discussed with the responsible person in the regulatory authority and adapted to the further requirements of the authorities.

The relevant authorities checked that Gamma-Service Recycling and the subcontractors had all of the necessary licences, were skilled enough to be able to decommission the cyclotron and were well trained in radiation protection and safety at work requirements. After each requirement had been fulfilled, the decommissioning was accepted. The final steps were signing a contract for the project and assigning responsibilities for radiation protection, safety at work, recycling of the material, measurement plans and organization of any work related to the decommissioning (security service patrolling of the site at night, contract to subcontractors for special tasks, etc.).

I–7.4. Dismantling of the cyclotron and related installations

The areas of the building, including the machine, the target bunker and related installations, were marked, and the work commenced with the opening up of the modular wall of the cyclotron hall.

Meanwhile, installations in the periphery of the machine were removed and packed into barcoded boxes as defined in the measurement programme, ready for gamma spectrometry.

Under the coordination of Gamma-Service Recycling staff, devices such as the beamline and the electronic parts of the cyclotron were dismantled.

The radiological evaluation of the dismantled parts and conditioned parts of the machine started two weeks after commencement of the project. Up to this point, a great amount of material had been collected that had to be cleared or stored for decay. The segregation was carried out by Gamma-Service Recycling staff; the evaluation by VKTA followed. During the dismantling of the cyclotron, different problems occurred. There were some very heavy and bulky parts that needed to be brought into compliance with the requirements for measurement by VKTA. VKTA utilized computer programs to calculate the activity contained in the machine parts on the basis of measurements carried out with a gamma spectrometer.

A resonance chamber that was 4 m long and 1.5 m in diameter was part of the machine. The chamber was a double walled copper tube with a smaller tube inside (same length and diameter: 0.5 m). Both were cut into pieces for handling and measuring purposes. It was found that the copper was not activated and could be scrapped.

The magnet core, as well as the lower pole shoe and aluminium coil, had to be transported out. The work was carried out as follows. First, double T girders were installed and were coated with Teflon. The magnet was then lifted with hydraulic stamps and set on sliding blocks also coated with Teflon. To minimize the friction, a soap solution was applied on the double T girder. Then the magnet was pulled to the wall with hydraulic hoists. When reaching the wall, the magnet was lifted again with the stamps and set on the double T girders. Finally, it was moved out of the building.

Once outside the building, the magnet was set down on parts of the concrete shielding to facilitate cutting the magnet and removing the pole shoe as well as the coil. It was planned to use four safes to set down the magnet. The safes could not withstand the weight and cracked open, so mobile shielding had to be used. The pole shoe consisted of three sections, each weighing 2 t. The aluminium coil also weighed in at that range.

The mentioned parts were activated as well as contaminated. It was discovered during dismantling that in the coil, some flax sliver had been used that contained large amounts of ^{152}Eu, ^{154}Eu and ^{155}Eu. The activity was high enough that the VKTA staff thought about using a box filled with the flax sliver as a calibration source for their measuring devices. Finally, the magnet was cut into square blocks weighing in around 1 t each to be measured with a gamma spectrometer.

The fire department of the Deutsches Elektronen-Synchrotron was notified in advance of the work. During the cutting process, huge clouds of yellow smoke were produced. This was reported to the local fire department by a resident who lived nearby, and a full fire brigade unit showed up to extinguish the fire. The situation was quickly resolved between the two fire departments.

In parallel, the target bunker was dismantled by Gamma-Service Recycling staff with due regard to contamination and activation. The bunker devices were decontaminated until no further removable activity remained. Then the target site was completely dismantled. It contained the six target stands, the cooling system and the air-conditioning system. The bunker itself consisted of mobile shielding, which was removed and measured. Activated material was stored in locked 6 m containers to be moved later to the Gamma-Service Recycling site in Radeberg. Some activated material had to be stored outside of the building; also, the containers containing waste materials were placed in the parking lot. To ensure that no activated material could be stolen during the night, a security patrol was assigned.

Throughout the entire dismantling process, activated material was separated and stored and inactive material was cleared and scrapped once a week after permission was received from the responsible authority. After removing the cyclotron and the whole technical part of the machine, the building was examined for clearance. It was discovered that there was no relevant activation in the wall structure of the cyclotron hall. At the target site, only hot spots could be measured. The hot spots contained metal markers made from a copper alloy in the ground and could be removed easily. The radionuclides identified during the measurement process are listed in Table I–3. Small amounts of other nuclides were found but are not mentioned because they were found only in trace quantities that had no relevance to clearance requirements.

I–7.5. Conclusions

It took three months to dismantle the Hamburger Isochron-Zyklotron, including segregating activated and non-activated materials, as well as clearing non-activated material, and conducting the radiological survey of the machine, the building and the mobile shielding. Around 70% of the dismantled mass could be cleared, including the building.

The activated material was taken over completely by Gamma-Service Recycling and is still being treated in its storage depot in Radeberg. Some, meanwhile, could be scrapped or deposited. The residual is still subject to further investigation.

To measure activation and contamination, dose rate meters, contamination monitors, gamma spectrometers and wipe test devices were used. Dose rates of activated materials ranged between 1 µSv/h and 22 mSv/h. Waste with dose rates above 1 mSv/h amounted to just a minor volume of around 300 kg. The rest of the material had modest dose rates ranging from 1 to 200 µSv/h. Around 250 t of the activated material, mainly mobile concrete shielding, was taken over. There were no reliable data of the contained activity. It was defined in the decommissioning plan that activated material would be stored and then examined at a later time. There was no time left on the site for completion of this task.

The bid budget for the project was estimated to be at least €1 000 000. After finishing the work on the site and taking into account further work requirements for waste management and handling, including additional decontamination, measurements and probe taking, this amount appeared to be insufficient owing to the additional costs encountered. The job was, however, successfully finished by Gamma-Service Recycling, but more costs were incurred for labour, waste handling measurements, probes and free release than originally planned.

I–7.6. Lessons learned from Phase 1 of the project

The following lessons were learned during the project's first phase:

(a) Significant amounts of low activation materials were produced during the working life of the machine; these materials could not be cleared easily and required storage for decay or waste deposition.
(b) Each machine was different and had special features that had to be considered carefully, especially for decommissioning (amount of work, costs, etc.).
(c) A large amount of measurement equipment, as well as sufficient staff on the site, was needed to produce a reliable database suitable for decommissioning.
(d) There had to be a decommissioning plan, and it needed to be updated weekly (time and resource management, tasks, etc.).

I–7.7. Handling of waste materials

As a result of this decommissioning project, the remaining waste materials were handed over to another party for treatment and storage, hereafter referred to as Phase 2 of this project. The information that follows identifies how this waste was handled, especially the concrete shielding material.

As mentioned in the case study above, the activated materials were handed over with transfer of responsibility, having been placed into five 6 m sea containers and stored by an external storage company under their licence conditions. The whole mass was calculated to be about 250 t, including about 160 t of concrete (shielding) materials, such as bricks, walls and roof bars. Ninety tonnes consisted of a wide range of parts and different materials [I–14].

Because the materials were poorly segregated during the decommissioning project, the waste had to be properly segregated and assessed, resulting in additional doses and further work for the employees. Furthermore, at the time that the waste was produced, no thought was given to the possibility of segregating materials that met free release criteria. During reworking of the accumulated waste, it was noted that to demonstrate which waste was suitable for free release, measurements would have to be made in a low activity measurement unit, which required the use of special volumes, masses of waste, surfaces, filling levels and material mixes. This resulted in the need for substantial handling and reworking of the waste and segregating it into special boxes. Sometimes only a single item of waste could be placed into one box for free release measurements. This resulted again in the need for a greater level of logistical processes and staffing.

The costs for the decommissioning project were calculated to be at least €1 000 000. In retrospect, no additional costs had been considered in the financial provision for decommissioning to cover all the additional handling, segregation, logistics and pre-measurement works that were subsequently required to properly deal with the waste. There were also additional costs incurred for storage rental and to extend the storage arrangement permitted as part of the licence conditions for the storage facility to provide for mid-term storage of some parts of the accelerator with a higher level of activity that required decay storage.

Because of the high volume and masses of materials that were transported at one time to the external storage facility, the training and preparation of the employees required to carry out the additional unforeseen work requirements was insufficient, as was the infrastructure (e.g. storage place, measurement equipment, handling equipment, equipment for further dismantling of larger parts).

All these problems occurred because no adequate waste treatment plan was established prior to commencement of the decommissioning project. Some of the materials remained in storage waiting to be treated five years after completion of the decommissioning project.

In the intervening five years, after decommissioning wastes were transferred for further management, much of the material was declared suitable for free or restricted release. Some material went to recycling or scrapping after release. Other material (mostly activated materials containing ^{60}Co) is still being stored for decay in a mid-term storage facility, awaiting release once it is adequately decayed. Some waste was finally declared as radioactive waste and sent to the state radioactive waste collection facility. Some problematic waste — such as asbestos, PCB- or oil-containing materials — was found. These materials are waiting for a treatment solution to be identified so that they can be finally disposed of.

Another challenge was the treatment and examination of the materials made of concrete used as shielding around the accelerator. As shown in Fig. I–14, 128 concrete bricks of different shapes and 12 roof bars were considered to be activated and had to be analysed with surface contamination monitors, low level dose rate meters and in situ gamma spectroscopy, as well as with samples that were subject to analysis at an external laboratory.

To transport the concrete shielding materials to the external storage facility, special vehicles with heavy duty trailers had to be used. This was also a special logistical issue to be considered in combination with the dangerous goods regulations (European Agreement concerning the International Carriage of Dangerous Goods by Road, Class 7, radioactive materials).

All the materials were situated around the target room in which the radionuclides for medical treatment were produced. After the concrete materials were transported to the external storage facility, the radiological examination for free release measurements was carried out. Each brick was clearly numbered, and additional probes or samples were taken from the highest count rate measurement found on the surface of the bricks (Figs I–15 and I–16).

To differentiate between possible surface contamination of the bricks through produced radionuclides or activation through particle beams of the irradiator, two samples were taken from the bricks. One scraping sample off the surface and one borehole sample divided into several depth profiles were also collected. The samples were analysed for radionuclide content in a specialized laboratory. The single depth profiles of the borehole sample were examined separately to get a depth profile of the activation.

Figure I–17 illustrates the results of the radiological analysis of the bricks. The specific activity in becquerels per gram is shown over the depth in centimetres of the concrete material.

The maximum level of activation from the 18 MeV proton beam and its secondary reactions (p/n), (n/γ) was located between 6 and 13 cm in depth; the produced secondary neutrons must therefore have had energies of less than 3 MeV.

FIG. I–14. Roof bars, shielding bricks and pieces of wall (reproduced from Ref. [I–14] with permission courtesty of K. Peschel).

FIG. I–15. Concrete block with identification number (reproduced from Ref. [I–14] with permission courtesty of K. Peschel).

FIG. I–16. Probe/sample taking from point of highest count rate measurement (reproduced from Ref. [I–14] with permission courtesty of K. Peschel).

Furthermore, a nuclide vector could be determined to simplify the measurements for free release. This vector was discovered with 89.5% ^{60}Co and 10.5% ^{54}Mn; the γ-emitting ^{60}Co with its specific γ lines could thus easily be measured and identified.

After all the samples were measured and activities were determined as specific activities in becquerels per gram, the results could be compared with the threshold values for free and restricted release from the German radiation protection act for threshold values for free and restricted release of the material. Table I–4 gives an overview of some threshold values of selected nuclides that had to be considered for the release procedures [I–13].

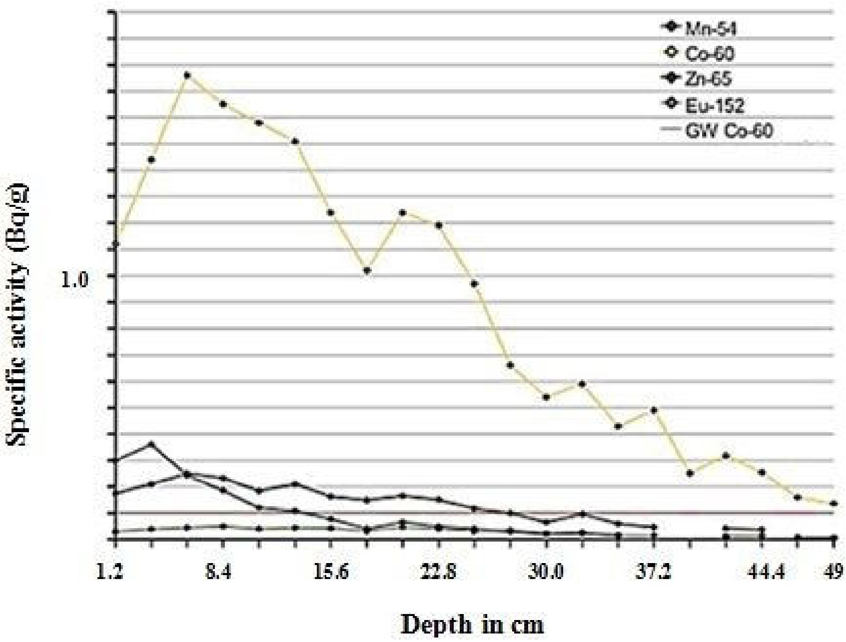

FIG. I–17. Specific activity of material of one brick versus depth (reproduced from Ref. [I–14] with permission courtesy of K. Peschel).

TABLE I–4. THRESHOLD VALUES FOR FREE AND RESTRICTED RELEASE OF MATERIALS AND FOR SURFACE CONTAMINATION

Nuclide	Half-life	Free release (Bq/g)	Restricted release (Bq/g)	Surface contamination (Bq/cm^2)
Mn-54	312.2 d	4E–01	1E+01	1E+00
Fe-55	2.7 y	2E+02	1E+04	1E+02
Fe-59	45.1 d	1E+00	7E+00	1E+00
Co-60	5.3 y	1E–01	4E+00	1E+00
Ni-63	100.0 y	3E+02	3E+03	1E+02
Ni-59	7.5E+04 y	8E+02	5E+03	1E+02
Zn-65	244 d	5E–01	1E+01	1E+00
Eu-152	13.3 y	2E–01	8E+00	1E+00
Eu-154	8.8 y	2E–01	7E+00	1E+00

As can be seen in Table I–4, the value for free release of ^{60}Co is 0.1 Bq/g. The value of the sample shown in the graph has a maximum specific activity of 1.8 Bq/g. Thus, for this example, there were only two ways to further manage the waste:

(a) Restricted release;
(b) Decay storage for about four to five half-lives of ^{60}Co (equates to 20 to 25 years).

Because the storage time of about 25 years was not an acceptable solution, the route of restricted release was utilized. Most of the roof bars and shielding bricks were subsequently reused for other construction projects as additional stabilization in the infrastructure of a new building, which is used as a storage facility for sealed radioactive sources in a water pool and as an irradiation facility for sterilization.

I–7.8. Problems and solutions arising from Phase 1 of the project

The following problems were encountered during the project's first phase:

(a) Additional handling, logistics and workforce were necessary at the external storage facility to manage the materials accepted from the decommissioning project.
(b) Costs for decommissioning exceeded the planned budget owing to inadequate planning for waste management in the final decommissioning plan.
(c) External storage was not properly prepared for the receipt of such large amounts of inappropriately segregated waste, and more workforce, staff training, infrastructure and storage space were required.

The related solutions and analysis were as follows:

(1) Segregation of activated and contaminated materials during the decommissioning project was poor, and further extensive reworking was required.
(2) No additional costs were provisioned for extra handling, segregation, logistics and pre-measurement works for the waste, nor for the initial and extended storage of some parts of the waste.
(3) Owing to time pressures during the decommissioning project, all potential waste and materials for release were put into 6 m sea containers at the time of generation and were transferred to the external storage for further management.

I–7.9. Lessons learned

The following lessons were learned during this project:

(a) The final decommissioning plan did not include a comprehensive waste management plan that identified the possible routes for release of the generated wastes and the measurement techniques to be used for waste segregation at source into the various waste categories. This oversight resulted in the budget for the project being substantially exceeded when a second contractor had to rework the waste.
(b) The failure of the operators to perform any segregation of waste at the time of production (it was all placed directly into a shipping container with no attempt at measurement or segregation) demonstrated the lack of knowledge of the workers in acceptable standards for waste management, especially in relation to clearance levels and waste minimization principles. A comprehensive waste management plan appropriate to the project, supported with written procedures and staff training in their implementation, could have avoided such errors.
(c) The financial planning of this project was inadequate and did not properly consider the likely costs for waste management and disposal. Factors such as logistics, storage, analytical work, post-treatment of materials and waste treatment needed consideration at the financial planning stage of the decommissioning project. Waste management and disposal costs are a fixed and essential component of any decommissioning plan.
(d) Procedures did not exist to ensure that all the post-treatment requirements, such as equipment, logistical routes and staffing, to deal with the activated and contaminated material and wastes were in place before the material was shipped to the waste storage facility. Again, this highlighted the inadequacy of planning for decommissioning, especially for waste and materials management.

I–8. CURRENT STATUS OF ACCELERATOR DECOMMISSIONING IN JAPAN

I–8.1. Introduction

In Japan, the clearance system, which contains (a) the clearance level of radioactive substances for release to the environment and (b) the control procedures of the Nuclear Regulation Authority, has been introduced in radioisotope handling facilities and accelerator facilities. In this regulation, the definition and the handling rules for activated materials were stated. This annex introduces several related topics of Japanese regulation and some examples of accelerator decommissioning.

I–8.2. Accelerators in Japan

Table I–5 shows the accelerators in Japan divided into the types of accelerator and facility. To make rules for handling activated materials, it is very important to pay due regard to the medical uses that account for 73% of the accelerators in Japan (about 70% of the linacs are 10 MeV and 20% are 6 MeV). The lifetime of linacs for medical use is about 10 years owing to the continuing progress in medical and computer science. Therefore, about one hundred accelerators are decommissioned every year. The numbers of small cyclotrons for radioisotope production for PET diagnosis in hospitals have recently been increasing.

TABLE I–5. NUMBER OF RADIATION GENERATORS IN USE IN JAPAN AS OF 31 MARCH 2016

Type	Number of units	Hospitals and clinics[a]	Educational organizations	Research institutions	Industrial firms	Other organizations
Cyclotrons	233	155	4	22	50	2
Synchrotrons	44	11	3	26	4	—
Linear accelerators	1292	1107	26	65	63	31
Betatrons	2	—	1	1	—	—
Van de Graaff accelerators	35	—	13	21	1	—
Cockcroft–Walton accelerators	80	—	17	29	34	—
Transformer type accelerators	14	—	—	6	8	—
Microtrons	6	1	3	2	—	—
Plasma generators	2	—	—	2	—	—
Total number	1708	1274	67	174	160	33
Ratio (%)	100	74.6	3.9	10.2	9.4	1.9

Note: —: no accelerators of this type.

[a] Numbers are based on data from Ref. [I–15].

I–8.3. Classification of non-activated parts of accelerators

Non-activated parts of accelerators can be classified according to the three categories stated below:

(a) Energy limit:
- — Particle accelerators lower than 2.5 MeV/nucleon (except for neutron generators);
- — Electron accelerators for medical use at 6 MeV or less.

(b) Zoning:
- — Outside the self-shield of cyclotron for PET isotope production;
- — Electron accelerator for medical use at 10 MeV or less (except for target and collimators);
- — Electron accelerators for medical use of 15 MeV or less (except for target, collimators and shielding materials).

(c) Others: Non-activated accelerators that are recommended by the academic society based on the evidence of radioactivity measurement and the result of Monte Carlo calculation. Electron synchrotrons for light source and tandem accelerators for analytical purposes would be included in this group of non-activated accelerators.

I–8.4. Rules for the handling of activated materials

Accelerator components in use are not treated as activated materials. When activated materials are removed from accelerators, they should be divided into radioactive waste materials and material for reuse. Many accelerator components (e.g. magnets, vacuum system, power supply, control system) may be reused at another accelerator facility. Therefore, storage arrangements for components intended for reuse are provided for in the new regulation to distinguish such storage arrangements from the radioactive waste storage facility. To handle activated materials for repairing or cutting, workers are obliged to protect themselves from radioactive contamination by using ventilators, masks, gloves, and so on. Activated material should be properly characterized by recording relevant data, such as the major nuclides and their activities, for each facility. The major nuclide composition and activity will vary depending on the incident particle and its energy, the activated material, the irradiation time and the cooling time. Therefore, the procedure of radioactivity estimation based on the measurement of surface dose rate was proposed by the regulatory authority for radiation protection in the case of electron accelerators for medical use.

I–8.5. Clearance system for decommissioning

As a case study, the total amount of activated and contaminated materials arising from accelerator or radioisotope handling facilities in one year was estimated. A 10 μSv dose limit for workers and the public as an annual effective dose received through the various possible exposure scenarios was calculated as the activity level permissible for the release of materials by the clearance system. Finally, the government adopted IAEA Safety Standards Series No. RS-G-1.7, Application of the Concepts of Exclusion, Exemption and Clearance [I–16]. Activated materials from accelerator facilities for clearance are principally metals and concrete. Additionally, paper, glass, plastic and soil are included as contaminated materials from radioisotope handling facilities. The clearance levels for 37 and 53 nuclides are set for activated materials from accelerator facilities and radioactive waste from radioisotope handling facilities, respectively.

To apply the clearance system, each institution has to propose to the Nuclear Regulation Authority a decommissioning plan that includes details of the evaluation methods for the clearance level and the quality control method to be used. After segregation of the materials intended for clearance, the Nuclear Regulation Authority checks the validity of the activity evaluation of the segregated materials prior to giving permission to release them.

I–8.6. Decommissioning method for a small accelerator facility

Adoption of the clearance system is currently time consuming and too costly for small facilities. Hospitals generally have no storage areas suitable for the accumulation of decommissioning materials and often must maintain continuity of patient treatments. In such circumstances, the Nuclear Regulation Authority accepts that hospitals can utilize a decommissioning procedure without using clearance levels. In the case of low energy accelerators, observed nuclides are generally gamma emitters. The adopted methodology is based on the use of scintillation survey meters to make a measurement to segregate activated materials from non-activated materials. In this case, the detection limit is affected by the setting of the time constant and the scanning speed of the survey meter. This procedure was effective at checking for the non-activated levels on the basis of the detection limits [I–17].

In the case of PET cyclotron facilities, the wall, floor, ceiling and surrounding materials might be activated by secondary neutrons during operation. Additional data should be obtained in each facility to confirm the above procedure: (a) the radioactivity of several materials sampled in the accelerator room should be measured with a germanium detector, and (b) after collecting the data concerning the operational history, the elemental compositions of each material, the spatial distribution of neutrons under typical operation conditions and the induced activity of several typical materials, including concrete, should be estimated. Both datasets are useful for the decommissioning procedure. Typical neutron flux in a vault of a PET cyclotron is 10^5–10^6 n·cm^{-2}·s^{-1} during the production of ^{18}F from ^{18}O. Therefore, total production amounts of ^{18}F become good indicators of neutron fluence. Neutron fluence of ten years of operation in a typical hospital is estimated to be 10^{12}–10^{13} n/cm^2. The specific activity of ^{60}Co and ^{152}Eu in surface concrete is almost the same as the clearance levels. Therefore, it is also important to reduce the neutron activation by effective neutron shielding of the target.

I–8.7. Case study of the decommissioning of the Institute for Nuclear Study at the University of Tokyo

The decommissioning of the Institute for Nuclear Study (renamed as the Tanashi branch of Kō Enerugī Kasokuki Kenkyū Kikō (KEK) after 1997) was carried out in 1999. This project was the first time that decommissioning of a large accelerator complex including electron charged particles and heavy ion accelerators was carried out in Japan [I–17].

I–8.7.1. Evaluation of background dose rate

To define the activation materials, natural background dose rates were measured on the campus. The results are shown in Fig. I–18. The background dose rates were 0.03–0.09 µSv/h. This result is consistent with the statistical calculation of three standard deviations of 0.06 µSv/h in the case of a 1 in. NaI (Tl) scintillation survey meter (time constant: 10 s). Therefore, activated material was defined as material with a dose rate higher than 0.1 µSv/h.

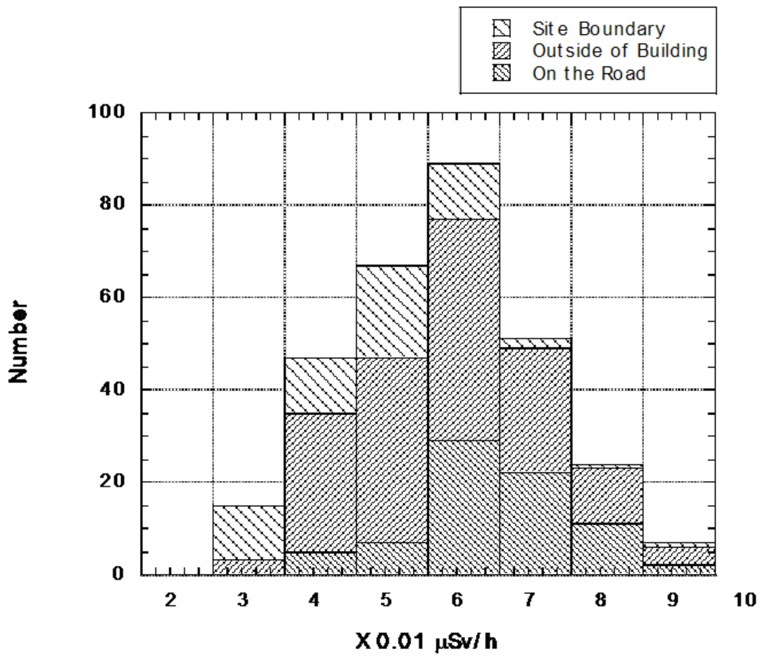

FIG. I–18. Histogram of dose rates at the Institute for Nuclear Study site obtained by survey meter (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

I–8.7.2. Survey scheme

At first, the surface dose rate was measured using a NaI (Tl) survey meter. Then, a smear method was used to detect surface contamination (>4 Bq/cm^2) to prevent radioactive cross-contamination. If the dose rate was below 0.1 μSv/h, a Geiger-Mueller survey meter was used directly. The detection limit for this instrument was 0.35 Bq/cm^2. If the count rate of a material was below the threshold of the detection limit, this material could be released. If the count rate was higher than the detection limit, the material could not be released.

I–8.7.3. Example of shield blocks

Figure I–19 shows the survey results of concrete blocks from the accelerator shielding. About 1000 blocks were divided into non-activated and activated groups. All the activated concrete blocks were transferred to KEK and used to shield another accelerator.

I–8.7.4. Evaluation of structure activation

About 70 concrete samples obtained from the floor, walls and ceiling were analysed. Results are shown in Table I–6. The total natural activity was 0.47 ± 0.22 Bq/g. The surface dose rate estimated from the activity was 0.05 ± 0.02 μSv/h. The activity contribution of ^{40}K was large, but the dose contribution from thorium was higher than from ^{40}K. This analysis is important for decision making about activated materials when the clearance system is not used. Reference [I–19] provides useful information for the evaluation of induced activation.

The relationship between surface dose rate and ^{60}Co specific activity was obtained, as shown in Fig. I–20. This figure shows a good linear relationship. To assess the activation level, a dose rate of 0.1 μSv/h, which includes the contribution of natural background, was adopted in this project. Inside the accelerator room, the surface dose rates of the walls, floor and ceiling were surveyed and mapped by 1, 2 and 4 m^2, respectively. If the dose rate was higher than the detection limit, a core sample was obtained. The core sample was used to determine the cutting depth needed to remove activated material from the area. For background dose rate levels, surface samples were cut out to be analysed by gamma spectrometry. The concrete core sample for which the depth profile of nuclides was obtained from the wall near the deflector of the cyclotron is shown in Fig. I–21. A buildup phenomenon of

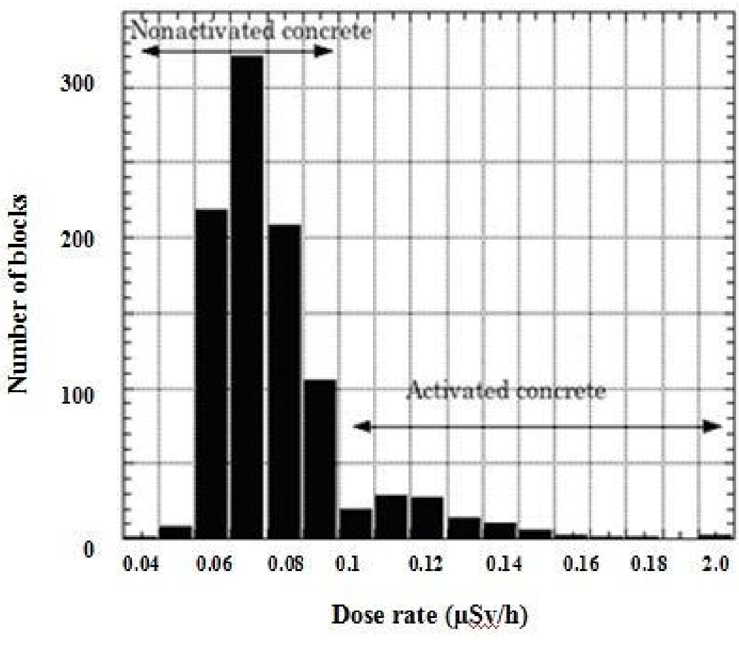

FIG. I–19. Survey results of about 1000 concrete shielding blocks (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

TABLE I–6. ACTIVITY OF ^{40}K, URANIUM AND THORIUM IN CONCRETE SAMPLES OBTAINED FROM FLOOR, WALLS AND CEILING OF SATURATION FACTOR–CYCLOTRON FACILITY
(reproduced from Ref. [I–18] with permission courtesy of K. Masumoto)

Nuclide	Activity (Bq/g)	Variation (Bq/g)	Surface dose rate (μSv/h)	Variation (μSv/h)
^{40}K	0.428	0.217	0.018	0.009
U series	0.015	0.008	0.006	0.003
Th series	0.022	0.012	0.022	0.012
Total	0.465	0.217	0.046	0.015

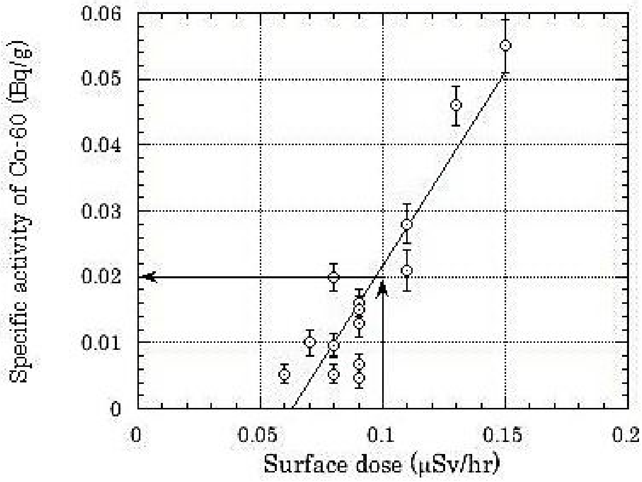

FIG. I–20. The relationship between surface dose rate and 60Co specific activity of concrete obtained from the cyclotron room (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

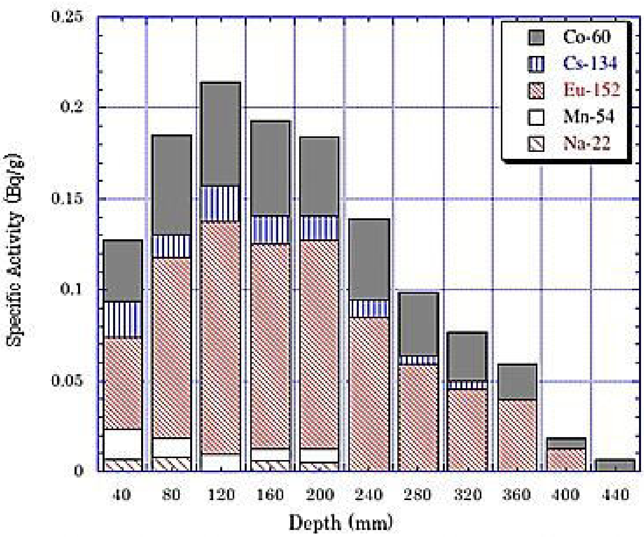

FIG. I–21. Depth profiles of radionuclides obtained from the wall near the deflector of the cyclotron (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

thermal neutrons was observed in this area. The higher region of the clearance level was within the depth of about 25 cm. Dose mapping data results after removal of the cyclotron were very similar to the results of neutron fluence obtained by activation methods using gold foils.

I–8.7.5. 1.3 GeV electron synchrotron

The electron synchrotron (750 MeV) was constructed in 1961, and its power was increased to 1.3 GeV, 0.4 mA in 1966. In 1971, the SOR-RING (500 MeV, 500 mA), an electron storage ring used as a synchrotron radiation source, was also constructed. The major part of the total activity was from ^{60}Co and ^{54}Mn in the synchrotron magnets. The dose contribution from these two nuclides was 80%. Other nuclides were ^{22}Na (from aluminium), ^{65}Zn (from brass), ^{56}Co and ^{58}Co. No activity was observed in the SOR-RING. The concrete base of the synchrotron magnet was cut by a wire saw to make the shield block. As the synchrotron was covered with about one thousand shield blocks, no activity was observed in the buildings. Figures I–22 to I–24 show the various stages of the decommissioning of the 1.3 GeV electron synchrotron. Figure I–22 shows removal of the shielding blocks, and Fig. I–23 shows removal of the synchrotron magnets. Figure I–24 shows the type of vehicle used to transport the magnets to KEK.

I–8.7.6. 40 MeV SF-cyclotron

In 1971, the saturation factor (SF)–cyclotron (proton energy: 50 MeV; beam current: 10 μA) was commissioned as the first azimuthally varying field type cyclotron constructed in Japan. After 1996, the proton energy was reduced to 40 MeV and various heavy ions were also accelerated to supply the beam to the storage ring TARN-II. The cyclotron was transferred to KEK, Tsukuba, and a large spectrometer and many magnets were transferred to Japan's largest comprehensive research institute, RIKEN, Wako. About 100 t of concrete became radioactive waste. Figure I–25 illustrates the yoke of the SF–cyclotron that required decommissioning. Figures I–26 and I–27 show separation of the upper and lower yoke, respectively, and Fig. I–28 shows the magnets ready for transport to KEK.

Figures I–29 to I–31 show the various stages of decontamination work that was carried out in the vault, which included marking up the wall for drilling depths to be used and cutting and drilling the wall. Figures I–32(a) and I–32(b) show the interior of the building that was used to store activated materials.

FIG. I–22. Removal of shielding blocks (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

FIG. I–23. Removal of synchrotron magnets (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

FIG. I–24. Transportation of magnets to KEK (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

FIG. I–25. Decommissioning of SF-cyclotron (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

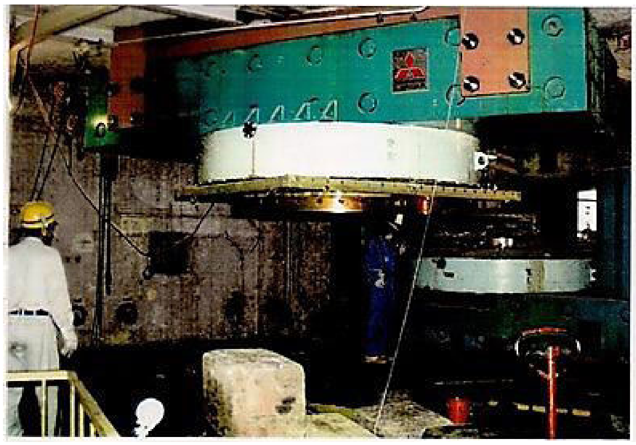

FIG. I–26. Separation of upper yoke (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

FIG. I–27. Separation of lower yoke (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

FIG. I–28. Transportation of magnets to KEK (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

FIG. I–29. Marking the decontamination depth of the wall (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

FIG. I–30. Cutting concrete wall (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

FIG. I–31. Drilling concrete wall (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

(a) (b)

FIG. I–32. Inside the storage building for activated materials (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

I–8.7.7. Quantities of decommissioning materials

Table I–7 shows the quantities of segregated materials arising from this decommissioning work. In the case of the SF–cyclotron, most of the 120 t of radioactive waste was concrete removed from the wall, floor and ceiling in the cyclotron vault. In the case of the synchrotron, concrete blocks were used for shielding. Therefore, radioactive concrete could be reused for shielding in KEK.

To perform the decommissioning work safely and properly, various radiation and radioactivity measurements were performed. Several methods of decontamination were also planned and tried. Careful evaluation of residual radioactivity in various materials was very important for reducing the radioactive waste. Many kinds of accelerator components and shielding materials were reused at the various accelerator facilities of universities and research institutes. All accelerators were completely decommissioned within a year. After removal of all buildings, the vacant land was carefully checked for radioactive and chemical contamination, and the land was subsequently converted to a public park.

To store all the quantities of non-radioactive materials and radioactive magnets quantified in Table I–7, a storage facility of 800 m^2 was constructed in KEK. Within a few years, many accelerator components were given to other accelerator facilities for reuse. In the case of decommissioning, it is important to make a recycling for reuse plan, because many parts of the accelerator are very expensive to purchase.

I–8.8. Case study of KEKB electron synchrotron facility of KEK

After the shutdown of TRISTAN (the Transposable Ring Intersecting Storage Accelerator in Nippon), KEKB (the electron synchrotron facility of KEK) was constructed for the study of particle physics by electron–positron colliding; it was composed of two electron synchrotrons, the low energy ring (5.0 GeV) and the high energy ring (10 GeV), in one accelerator tunnel. The circumference of the two accelerators was about 3 km. To upgrade to Super KEKB, the activated amount for decommissioning was estimated by radiation measurement. The results are shown in Tables I–8 to I–12. In the case of the vacuum chamber, the total weight was about 300 t, and 5% of it was activated. A categorization of the grey component (the materials close to clearance level) indicated that the materials were close to the clearance level and hence that any material compliant with the clearance level should be extracted from the grey part after further careful analysis. The weight of the magnets used was about 6000 t in the high energy ring and 1700 t in the low energy ring. The bending magnets were very heavy. Therefore, the assessment of the activated part was important for the estimation of the requirements for a storage facility. Since a small percentage of the magnets were activated, the grey part of the component was important. Major nuclides observed were ^{54}Mn and ^{60}Co.

TABLE I–7. QUANTITIES OF MATERIALS (t) DURING THE DECOMMISSIONING

	Instruments					Surroundings			
Type of accelerator	Non-radioactive			Radioactive		Radioactive		Non-radioactive	
	Recycle and waste	Reuse	Storage	Waste	Storage	Reuse	Waste	Recycle	Reuse
SF-cyclotron	40	30	10	3	400	30	120	5 000	0
Synchrotron	60	10	5	2	70	350	2	5 200	700
TARN-II	30	200	15	0	20	0	6	2 500	0
Heavy ion linac	5	70	0	0	20	10	2	1 000	0
Total	135	310	30	5	510	390	130	13 700	700

TABLE I–8. SURVEY RESULTS OF VACUUM CHAMBER

Location	Non-activated part (%)	Grey part (%)	Activated part (%)
HER-arc	42.4	52.7	5.0
HER-straight	44.6	52.6	2.8
LER-arc	51.1	42.8	6.2
LER-arc	37.5	56.7	5.7

Note: HER — high energy ring; LER — low energy ring.

TABLE I–9. SURVEY RESULTS OF HIGH ENERGY RING–ARC SECTION MAGNET

Location	Number	Non-activated	Grey	Activated
B	341	144	189	8
Q	360	258	95	7
S	116	92	18	6

Note: B — bending magnet; Q — quadrapole; S — sextupole.

TABLE I–10. SURVEY RESULTS OF HIGH ENERGY RING–STRAIGHT SECTION MAGNET

Location	Number	Non-activated	Grey	Activated
B	41	20	18	3
Q	97	59	33	5
S	88	45	39	4

Note: B — bending magnet; Q — quadrapole; S — sextupole.

TABLE I–11. SURVEY RESULTS OF LOW ENERGY RING–ARC SECTION MAGNET

Location	Number	Non-activated	Grey	Activated
B	122	101	15	6
Q	343	258	76	9
S	113	80	31	2

Note: B — bending magnet; Q — quadrapole; S — sextupole.

TABLE I–12. SURVEY RESULTS OF LOW ENERGY RING–STRAIGHT SECTION MAGNET

Location	Number	Non-activated	Grey	Activated
B	201	113	88	0
Q	114	53	57	4

Note: B — bending magnet; Q — quadrapole.

In the case of the storage type of electron synchrotron, residual activity was very low. Cooling time of several years to several tens of years is very effective to reduce radioactive waste. In KEKB, building structures were not activated during operation. In the construction of Super KEKB, most of the magnets were reused.

Figure I–33 illustrates how analysis of the nuclides and activity induced in the magnets was made using a germanium detector. Figure I–34 shows workers making dose rate measurements.

I–8.9. Case study of 12 GeV proton synchrotron of KEK

The facility of the 12 GeV proton synchrotron was composed of a Cockcroft–Walton 40 MeV linac, a 500 MeV booster synchrotron and a 12 GeV proton synchrotron. Several experimental laboratories and beamlines

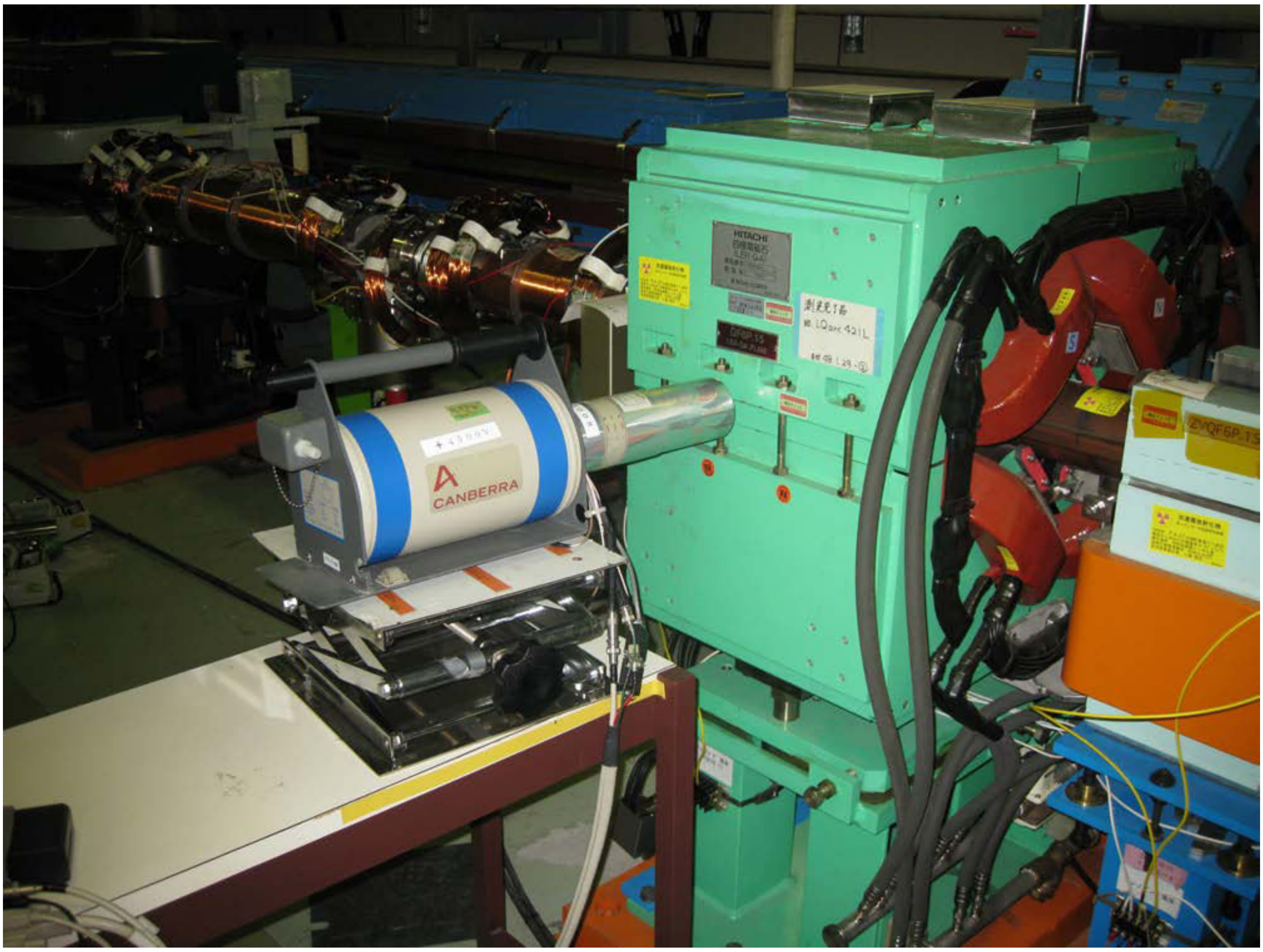

FIG. I–33. Analysis of nuclides and activity induced in the magnets by a germanium detector (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

for neutron, muon, nuclear, particle and neutrino science were also attached. Most of this facility was closed in 2005. Several instruments and shields were transferred to the high intensity proton accelerator facility, J-PARC, for reuse, as shown in Table I–13.

After subtracting the amount of reused materials given in Table I–13, the total quantities of materials from decommissioning that required further management are given in Table I–14. It was found that very large amounts of radioactive waste and clearance level materials were released in the case of the high energy proton synchrotrons.

FIG. I–34. Dose rate measurements (reproduced from Ref. [I–18] with permission courtesy of K. Masumoto).

TABLE I–13. REUSED AMOUNT (t) UTILIZED IN THE CONSTRUCTION OF J-PARC

Activity level	Magnet	Iron shield	Concrete shield
Low level	450	150	1000
Clearance level	n.a.	300	3000
Non-radioactive	n.a.	1000	5000
Sum	450	1450	9000

Note: n.a. — not applicable.

TABLE I–14. QUANTITIES (t) FROM THE DECOMMISSIONING OF THE 12 GeV PROTON SYNCHROTRON

Level	Iron	Copper	Concrete
Low level	6 350	825	36 230
Clearance level	3 840	225	36 380
Non-radioactive	300	n.a.	73 850
Total	10 490	1 050	146 460

Note: n.a. — not applicable.

Especially important to this project was the method of evaluating the induced radioactivity of concrete for decommissioning, as reported in Ref. [I–20]. Major parts of the 12 GeV proton synchrotron were retained as activated materials. The decommissioning project has not started yet.

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Annex II

DEVELOPMENT OF ACCELERATORS

II–1. INTRODUCTION

In November 1895, Wilhelm Conrad Röntgen was the first to accelerate a beam of electrons by a static potential difference to acquire energy in the order of 20 000 eV. By the beginning of the twentieth century, several laboratories had mastered the technique [II–1] and many hospitals had developed interest in its application. The history of early particle accelerator development has been described in Ref. [II–2].

The science leading to the construction of modern particle accelerators began in 1911, when Ernest Rutherford discovered the nucleus by scattering alpha particles off a gold foil [II–3]. However, the interest in using proton accelerators started in about the 1920s, when Rutherford disintegrated the nucleus of nitrogen using alpha particles from a natural radioactive source [II–1]. The physics and technology of accelerators and storage rings involves many branches of science. These include electromagnetism, solid state properties of materials, atomic physics, superconductivity, non-linear mechanics, spin dynamics, plasma physics and quantum physics. The first high voltage particle accelerator had a potential drop in the order of 100 kV; it was conceived by Cockcroft and Walton in 1920 and named the Cockcroft–Walton Accelerator. Cockcroft and Walton used an alternating current supply to charge several capacitors to a high voltage. These were then discharged so that the potential differences added together. In 1932, Cockcroft and Walton produced the first nuclear reaction using artificially accelerated particles, bombarding and disintegrating lithium nuclei with protons accelerated to 700 kV [II–4]. This was the first time that a particle accelerator had been used to trigger a nuclear reaction. Cockroft and Walton were awarded the Nobel Prize in Physics for this work in 1951.

In 1929, Robert Jemison van de Graaff constructed the first working model of an electrostatic accelerator, which achieved 80 kV. This accelerating machine was developed further for use in ‘atom smashing’ experiments; in November 1931 at the inaugural dinner of the American Institute of Physics, a demonstration model was exhibited that produced over 1 MV. Figure II–1 is drawn to illustrate the simple well known van de Graaff accelerator concept. Van de Graaff generators are still used today, particularly in the initial stages of modern accelerators, and are ultimately capable of potential differences of around 10 MV [II–5].

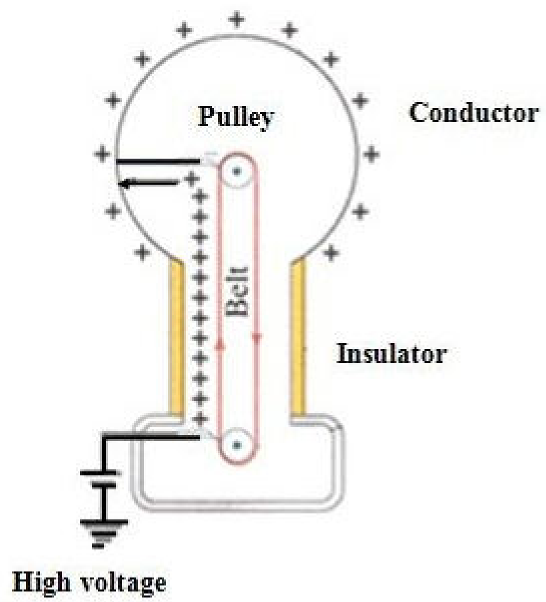

FIG. II–1. A simple sketch of a van de Graaff generator.

In the early 1930s, Raymond G. Herb, along with his students and colleagues at the University of Wisconsin, developed the van de Graaff electrostatic generator for practical use as a mega-electronvolt ion beam accelerator.

In 1931, Ernest Lawrence designed the ‘cyclotron’, a circular device made of two electrodes placed in a magnetic field, in which particles followed a circular trajectory. By reversing the electric field of the electrodes between two gap crossings, it was possible to accelerate the particles. With an alternating current potential of only 2000 V, Lawrence accelerated protons to 80 kV and this success inspired him to accelerate protons to roughly 1.2 MeV in a magnetic field of about 0.5 Tesla across 30 cm in 1932. He received the Nobel Prize in Physics in 1939 for this work [II–2, II–6].

James A. Ferry invented the basic Pelletron inductive charging system in 1965 and later founded the National Electrostatics Corporation, together with Herb, to produce Pelletron accelerators [II–7].

Although Lawrence and Livingston designed the first small cyclotron in 1930, Rolf Wideröe had already published a paper in 1928 on his results from a radiofrequency powered linear accelerator (linac) for ions. This device followed a 1925 proposal by Ernst Ising. It consisted of a series of cylindrical tubes placed along the longitudinal axis of an evacuated glass cylinder. Alternate tubes were connected to opposite terminals of a radiofrequency generator [II–3]. By selecting the frequency and applied radiofrequency voltage, a variety of heavy ions could be accelerated across the gaps and bunched simultaneously. In 1931, David H. Sloan and Lawrence used such an array of 30 electrodes, and accelerated Hg^+ ions to 1.26 MeV with a voltage of 42 kV at a radiofrequency of 10 MHz [II–3].

In the late 1940s, after World War II, Lawrence initiated a programme at the University of California Radiation Laboratory (now known as the Lawrence Berkeley National Laboratory) with the US Atomic Energy Commission to investigate electronuclear breeding of ^{239}Pu, ^{232}U and ^{3}H (tritium) by bombarding depleted uranium with accelerator produced neutrons [II–3, II–8]. A series of high power radiofrequency linacs for protons and deuterons was built and tested starting in 1950 at the site which is now known as the Lawrence Livermore National Laboratory. When the first linac was built, the only other proton linac that had been operated was the 32 MeV linac built by Luis Alvarez, although a 68 MeV p^+ linac was under construction at the University of Minnesota [II–3, II–8].

The large linacs in the Materials Testing Accelerator programme (12–48 MHz) were disassembled in the mid-1950s, but the scientists who worked on these systems went on to build many successful proton linacs at research facilities such as Brookhaven National Laboratory, Argonne National Laboratory, Fermi National Accelerator Laboratory and Los Alamos National Laboratory [II–3]. Most of these modern linacs, which are used for physics research, were based on Alvarez’s original 200 MHz design [II–3]. Typical linear gradients achieved in these Alvarez linac structures are 1–2.5 MeV/m, with the gradients in the gaps ranging from 6 to 10 MeV/m. By taking advantage of the development in 1938 of strong focusing magnets (quadrupole magnets), these structures also employed quadrupole magnets within the cylindrical drift tubes [II–3]. Usually, magnets are made of steel or iron. However, special alloys of iron, nickel, copper, cobalt and aluminium can also be made into powerful magnets.

A betatron is a cyclic particle accelerator developed by Donald Kerst at the University of Illinois in 1940 to accelerate electrons [II–10 to II–12]. The concept for the betatron originated, however, with Wideröe [II–13], whose development of an induction accelerator failed owing to the lack of transverse focusing [II–14]. Max Steenbeck, in Germany, also worked on developing a betatron in the 1940s [II–15]. Unlike other particle accelerators, the name of the betatron does not tell us anything about how it works. In the betatron, an alternating current induced by the varying magnetic field is responsible for accelerating electrons (beta particles) to high energy in a circular orbit. The betatron was the first important machine for producing high energy electrons.

The first betatron at the University of Illinois was invented by Kerst [II–16] and is shown in Fig. II–2. The first private medical centre to treat cancer patients using a betatron was opened in the late the 1950s by Dr. O. Arthur Stiennon in a suburb of Madison, Wisconsin, United States of America (USA).

Betatrons are still used in industry and medicine as they are very compact accelerators for electrons. However, the maximum energy that a betatron can impart is limited by the size of the magnet core and the strength of the magnetic field due to the saturation of iron. The synchrotrons, the next generation of accelerators, overcame these limitations.

Edwin Mattison McMillan was an American physicist and Nobel laureate who shared the Nobel Prize in Chemistry with Glenn Seaborg in 1951. He joined Lawrence’s group at the University of California, Berkeley,

FIG. II–2. The first betatron with the inventor in 1940 at the University of Illinois (courtesy of the University of Illinois Archives).

upon receiving his doctorate and moved to the Berkeley Radiation Laboratory when it was founded in 1934 [II–3]. His experimental skills led to the discovery of ^{15}O with Livingston and ^{10}Be with Samuel Ruben.

In 1937, Hans Albrecht Bethe demonstrated the limitation of the energies that could be produced in a cyclotron [II–16]. Based on Albert Einstein's theory of relativity, which demonstrates the increase in the mass of a particle as it moves with a velocity approaching the speed of light, Bethe showed this increase in mass would eventually reduce the rotation of each particle. Thus, particle velocity will decrease as the rotation of each particle slows and the frequency of the alternating electric field remains constant, eventually setting an upper limit on the particle energy produced in the cyclotron [II–2].

To overcome this limitation, Vladimir Iosifovich Veksler independently proposed that the frequency of the alternating electric field be slowed to meet the decreasing rotational frequencies of the accelerating particles. This meant synchronizing the electric field with the moving particles, a concept that later resulted in the development of the synchrocyclotron. The synchrotron was used at the Berkeley Radiation Laboratory to create new elements, extending the periodic table of elements beyond the atomic number 92. Early studies on attaining energetic particles are available in Refs [II–19 to II–21].

In 1957, the Berkeley Radiation Laboratory redesigned its apparatus to achieve particle energies up to 720 million eV, the highest record for cyclotrons at that time. This success led to the construction of other synchrocyclotrons in the USA and Europe.

In February 1949, US physicist Robert Andrews McMillan announced the first synthetically produced mesons using the synchrocyclotron. Later, his theoretical works led to the development of the electron synchrotron, proton synchrotron, microtron and the linac. The increased use of the accelerator especially with large accelerators has ushered in a new era in physics research. In the 1960s, it was recognized that the synchrocyclotron could be used as a powerful source of radiation (X rays) and some accelerators started to make this radiation available to users.

The first electron–positron collider, Anello di Accumulazione, was built in 1961 in Italy at the Instituto Nazionale di Fisica Nucleare in Frascati by the Austro-Italian physicist Bruno Touschek [II–22]. Around the same time, Gersh Budker independently developed the VEP-1 electron–electron collider at the Soviet Institute of Nuclear Physics.

In 1966, work began on the Intersecting Storage Rings at the European Organization for Nuclear Research (CERN), which was the first facility ever built for colliding hadron beams. This collider was operational from 1971 to 1983 [II–23]. This was the first hadron collider, as all of the earlier colliders had worked with electrons or with electrons and positrons.

Between 1989 and 2000, the Large Electron–Positron collider (LEP) at CERN produced electron beams of 105 GeV using a tunnel 27 km in circumference. Between 2000 and 2006, the LEP was replaced by the Large Hadron Collider (LHC).

The LHC has pushed the boundaries of science and technology to new heights. It uses 1232 large dipole magnets to steer the beam; each dipole magnet is 14.3 m long and weighs 35 tons. The LHC operates at about 300 degrees Celsius below room temperature. This system produced a proton beam of 7 TeV per proton. Based on the success of the LHC, CERN has ambitious plans for future research.

II–2. THE FUTURE OF ACCELERATORS

The LHC is one of the most complex machines ever created, taking 24 years to come to fruition, at a cost of approximately €10 billion. In less than a century, accelerator designs have raised the particle energy from Rutherford's 10 MeV alpha particles to the LHC's 7 TeV proton beams, a factor of nearly a million. In the past ten years, the LHC has contributed to developing new scientific horizons. This includes producing two counter–rotating beams of protons to an energy of 7 TeV and forcing them to collide. Its role in the detection of the Higgs boson particle on 4 July 2012 was significant, providing the mechanism that contributes to the origin of mass of subatomic particles.

Based on the research and technological development, lessons learned, and success, CERN is hosting an international collaboration of more than 150 research institutes, including universities and industrial partners, and is planning the construction of the Future Circular Collider (FCC). This collider is expected to achieve a particle smashing energy of up to 100 TeV through a tunnel with a 100 km circumference. This will be built next to the existing LHC tunnel and it is expected to be the world's largest collider with more than ten times the power of the LHC. Detailed information is given in Ref. [II–24]. Developing an advanced design for the FCC will expand on the research currently being conducted at the LHC after it reaches the end of its lifespan. The FCC is also expected to unravel the unforeseen complexities that may be uncovered by the ongoing research at the LHC.

The possibilities held by the FCC raise many exciting questions. Its ability to study galaxies and other inter-scalar structures in the universe may help decipher the mystery of dark matter: Is dark matter made of unknown particles? How does it interact? Why was a small fraction of matter left out after the big bang led to matter and antimatter asymmetry? How did that imbalance create the world full of matter in which we live? What is dark energy? What holds rotating galaxies together where deep space gravity force is too weak? Physicists hope that some of these questions can be answered by LHC and FCC experiments, leading to future amazing discoveries.

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Annex III

DECOMMISSIONING OF FUSION MACHINES

III–1. INTRODUCTION TO FUSION

According to the US Energy Information Administration report published in International Energy Outlook 2016, world net electricity generation in 2012 was 21.6 trillion kW·h and expected to increase to 25.8 trillion kW·h by 2020, and further to 36.5 trillion kW·h by 2040 [III–1]. An important factor in electricity demand is economic growth in modern society. A commercially sustainable, safe, inexpensive source of energy is needed to bridge the growing demand. Various prospective sources are being investigated, and nuclear fusion is one of the most important.

Since the beginning of the 20th century, it has been clear that the energy of the sun and other stars is created by thermonuclear fusion. The simple version of nuclear fusion is the basic hydrogen fusion cycle: four hydrogen nuclei (protons) forming a helium nucleus. It takes extreme pressure and heat, which occur naturally under strong gravitational force at the core of the sun; these conditions cannot be created in a laboratory.

For decades, the scientific community has been pursuing nuclear fusion. In fusion reactions, light atomic nuclei are compressed under intense pressure and heat to form heavier nuclei and release energy in the process. The main fuels used in nuclear fusion are deuterium and tritium, both heavy isotopes of hydrogen. Deuterium constitutes a fraction of natural hydrogen and can be extracted inexpensively from sea water. Tritium can be produced from lithium, which is abundant in nature. Therefore, fusion fuel is inexpensive and abundant in nature. At present, research has reached a critical stage, as scientists are building an experimental reactor that is expected to demonstrate that nuclear fusion energy is indeed viable and can be used commercially to generate electrical power. The process needs to be optimized to generate more energy than it consumes.

Building a fusion power plant that can withstand the immense temperature and pressure needed is one of the greatest engineering challenges ever tackled. The mixture of isotopes of deuterium and tritium must be heated to about 100 million degrees Celsius. At that temperature, a fully ionized plasma must be kept dense enough and confined for a duration long enough to allow the nuclei to fuse. The aim of the controlled nuclear fusion research programme is to achieve ‘ignition’, which occurs when enough fusion reactions take place for the process to become self-sustaining. At present, scientists are pursuing two methods for achieving nuclear fusion: magnetic confinement and inertial confinement, explained in brief below. The resulting heat is then used to generate steam that powers electricity-generating turbines.

The potential advantages of nuclear fusion energy are numerous: it represents a long term, sustainable, economic and safe energy source, with short lived nuclear waste.

While research on nuclear fusion continues, many spin-offs relating to plasma physics and fusion technology are already benefitting society. These include improvements in materials research, space science, the environment, medical science, communication and waste removal. There are several types of spin-off associated with fusion research, including the knowledge gained through the experiments [III–2].

Two important schemes to achieve the high temperatures and intense pressures necessary for nuclear fusion reactions using isotopes of hydrogen are discussed below. Success will provide the world with a safe, sustainable, environmentally responsible and abundant source of energy.

III–2. NUCLEAR FUSION TECHNOLOGIES

Today, nuclear fusion programmes are vigorously in progress either under international collaboration or with strong national support in several States, including Brazil, Canada, China, India, Japan, the Republic of Korea, the Russian Federation and the United States of America (USA), as well as in the European Union. Soon after World War II, fusion research in the USA and the former USSR was linked to atomic weapons development, and it remained classified until the Atoms for Peace conference in 1958 in Geneva. In the late 1960s, fusion research was adopted as a pragmatic approach to energy provision. Following a breakthrough at the Soviet tokamak, fusion research became ‘big science’ in the 1970s. Owing to the complexity in the development of technology and the high cost of the devices, international cooperation was initiated as the only way forwards.

The difficulty has been to develop a device that can heat the deuterium–tritium fuel to a high temperature and confine it for long enough that the energy released through fusion reactions is higher than the energy used to get the reaction going.

At present, two main experimental approaches are being studied:

(a) Magnetic confinement, which uses magnetic and electric fields to heat and squeeze the mixture of deuterium and tritium. The International Thermonuclear Experimental Reactor (ITER) project in France is such an experimental approach.
(b) Inertial confinement, which uses intense laser beams or ion beams to squeeze and heat the mixture of deuterium and tritium. An experimental approach in realizing the scheme is under way at the National Ignition Facility, Lawrence Livermore National Laboratory, USA.

III–2.1. Magnetic confinement

A brief historical overview of magnetic confinement fusion is described in Fifty Years of Magnetic Fusion Research (1958–2008) [III–3].

Seven magnetic concepts have been developed to date for fusion science and technology. These include tokamak, stellarator, reversed-field pinch, tandem mirror, spherical torus, field-reversed configuration and spheromak. Currently, over 90% of the worldwide magnetic fusion research is using tokamak, and the scheme is regarded as the most promising design; research is continuing on various tokamaks around the world to demonstrate fusion energy generation.

The tokamak (a Russian acronym for ‘torus shaped magnetic chamber’) was designed in 1951 by Soviet physicists Andrei Sakharov and Igor Tamm. The first tokamak experiment began at the Kurchatov Institute (then the Laboratory of Measuring Instruments of the USSR Academy of Sciences) in Moscow in 1954.

Magnetic fields are ideal for confining plasma because the electrical charges on the separated ions and electrons mean that they follow the magnetic field lines. The aim is to prevent the particles from coming into contact with the reactor walls, as this will dissipate their heat and slow them down. The most effective magnetic configuration is toroidal, shaped like a doughnut, in which the magnetic field is curved around to form a closed loop. In a magnetic confinement fusion scheme, hundreds of cubic metres of deuterium–tritium plasma at a density of less than a milligram per cubic metre are confined by a magnetic field and heated to fusion temperature up to 50 million degrees Celsius. For proper confinement, this toroidal field must have superimposed upon it a perpendicular field component (a poloidal field). In a tokamak, the toroidal field is created by a series of coils evenly spaced around the torus shaped reactor, and the poloidal field is created by a system of horizontal coils outside the toroidal magnet structure. A strong electric current is induced in the plasma using a central solenoid, and this induced current also contributes to the poloidal field [III–4].

Research is also being carried out on several types of stellarator, with the intention of supplementing the understanding of plasma behaviour in order to scale up to large size tokamaks. Lyman Spitzer devised and began work on the first fusion device — a stellarator — at the Princeton Plasma Physics Laboratory in 1951. Confining plasmas is difficult in a stellarator, but the burning plasma can be easily monitored and controlled.

III–2.2. Inertial confinement

Inertial confinement fusion, which is a newer line of research, was initiated in the 1970s, although the initial computer simulations on the inertial confinement fusion concept were performed by John Nuckolls and collaborators at the Lawrence Livermore National Laboratory in the late 1950s. Here, laser or ion beams are focused very precisely onto the surface of a target, which is about a 10 mm diameter pellet containing a mixture of deuterium–tritium fuel. The interaction of intense beams on the pellet surface heats the outer layer of the material, which expands outwards, generating an inward-moving shock front or implosion that compresses and heats the inner layers of material. The core of the fuel may be compressed to one thousand times its liquid density, resulting in ignition conditions in which fusion can occur. The energy released then would heat the surrounding fuel, which may also undergo fusion, leading to a chain reaction as the reaction spreads outwards through the fuel. The time required for these fusion reactions is limited by the inertia of the fuel and is less than a microsecond. So far, inertial confinement work involving lasers is in an advanced stage compared with light or heavy ion beams.

Several designs have been proposed for the inertial fusion energy concept, including direct drive, indirect drive, fast ignition and shock ignition. However, no final target design and drivers have been accepted to date, and research continues in optimizing the target and driver parameters. The concept of inertial fusion energy is advantageous as reactor design is completely independent of drivers, allowing driver and reactor design to progress concurrently.

III–3. FUSION MACHINES

At the first International Conference on the Peaceful Uses of Atomic Energy held in Geneva, Switzerland, in 1955, the presiding Chair, Homi J. Bhabha, predicted that nuclear fusion would be in commercial use within two decades. At the second conference in 1958, also in Geneva, nuclear energy experts, especially American, British and Soviet scientists, began to share previously classified controlled fusion research. Regarding nuclear fusion for commercial deployment, breakthroughs have been made in recent years and there are a number of promising projects that may lead to the commercial realization of nuclear fusion power.

Several tokamaks have been built, including the Joint European Torus (JET) and the Mega Amp Spherical Tokamak (MASK) in the United Kingdom and the Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory in the United States of America (USA). A considerable amount of research has also been carried out on stellarators; the biggest of these, the Large Helical Device at Japan's National Institute for Fusion Science, became operational in 1998. It is being used to study the best magnetic configuration for plasma confinement. The ITER, in Cadarache, France, will be the world's largest tokamak to date as well as the largest magnetic confinement plasma physics experimental project.

At the Max Planck Institute for Plasma Physics, Garching, Germany, research was carried out at the Wendelstein 7-AS between 1988 and 2002. This work progressed at the Wendelstein 7-X device at the Max Planck Institute's Greifswald site. Wendelstein 7-X is the largest stellarator type of fusion device. Operating since December 2015, it produced its first hydrogen plasma on 3 February 2016. This device is intended to investigate the suitability of this configuration in a power plant.

Figure III–1 shows the interior of a Wendelstein 7-X stellarator containing a plasma vessel, stellarator coils, planar coil, cryostat and cooling pipes. Another stellarator, TJII, is in operation in Madrid, Spain.

The JET project in the United Kingdom is involved in testing materials for ITER walls and understanding plasma behaviour for ITER using deuterium-tritium fuel. Figure III–2 shows an image of the interior of the JET facility. JET produced its first plasma in 1983 and it was also the first tokamak to produce experimentally controlled fusion power in November 1991. Although fusion power up to 16 MW for one second was achieved in 1997 using deuterium–tritium plasmas (although input was 25 MW) it is still less efficient. Many experiments are being conducted to study different heating schemes and other techniques. JET has been very successful in operating remote handling techniques to modify the interior of the device in the radioactive environment. JET is a vital device in the preparations for ITER. It has been significantly upgraded in recent years to study and test plasma physics research and engineering systems relevant to ITER. In 2006, JET was converted to ITER-like magnetic configurations and an ITER-like wall was installed between 2009 and 2011.

The TFTR was operated from 1982 to 1997 at the Princeton Plasma Physics Laboratory, USA. In December 1993, it was the first magnetic fusion device to perform extensive experiments using deuterium–tritium plasmas; the following year it produced 10.7 MW of power — a record at that time. It did not achieve its goal of break-even fusion energy (where the output energy is greater than the input energy) but did achieve all its hardware design goals, thus making substantial contributions to the development of ITER. TFTR had set the record of achieving a plasma temperature of 510 million degrees Celsius in 1995.

In November 2006, six Member States — China, India, Japan, Republic of Korea, Russian Federation and USA — and the European Union signed the ITER implementing agreement. Site preparation works at Cadarache, France, commenced in January 2007. Experiments are due to begin around 2020, when hydrogen will be used to avoid activating the magnets. The first deuterium–tritium plasma is not expected until 2026. The vacuum vessel will be 19.4 m across and 11.4 m high and will weigh 5200 t. ITER is large because confinement time increases with the cube of the machine size. ITER is designed to produce 500 MW over 1000 seconds, with just 50 MW of

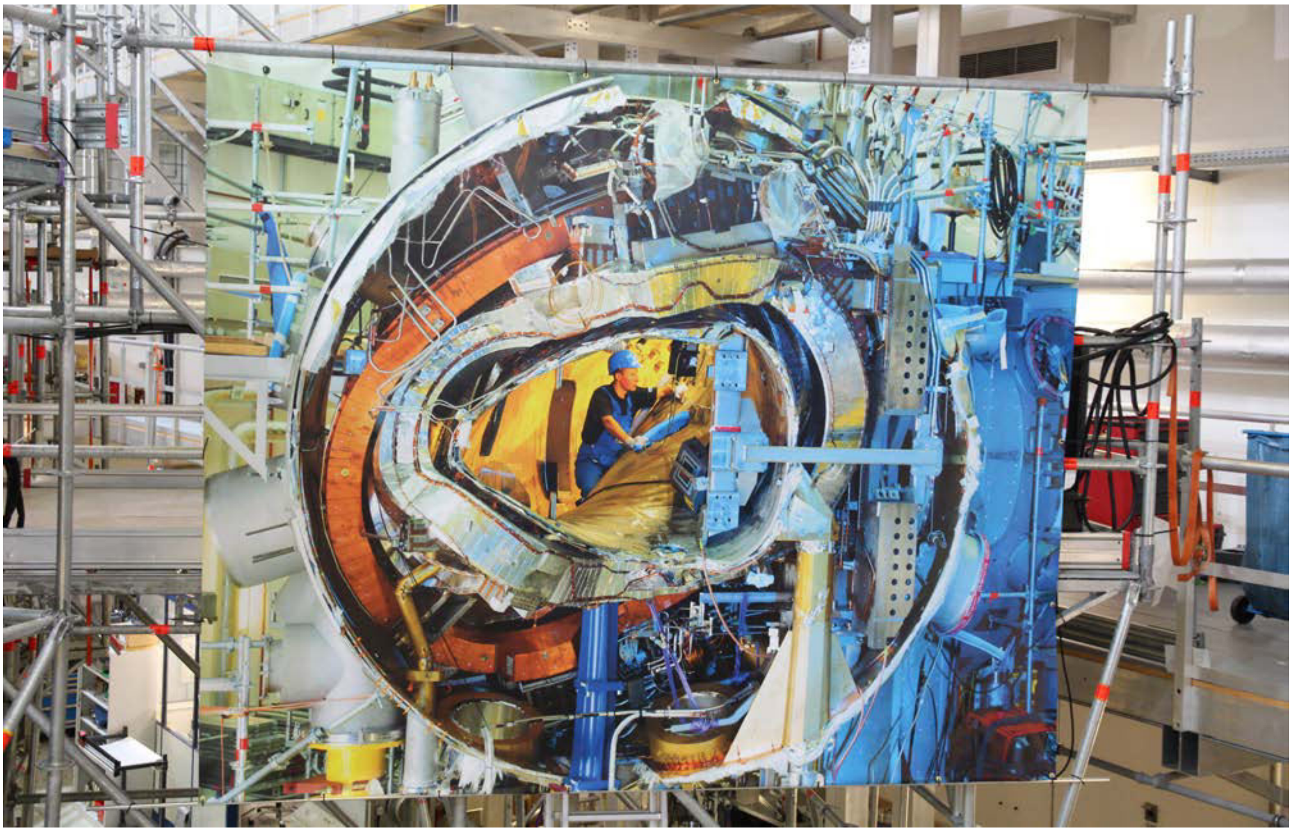

FIG. III–1. Wendelstein 7-X stellarator at the Max Planck Institute at Greifswald (courtesy of the Max Planck Institute).

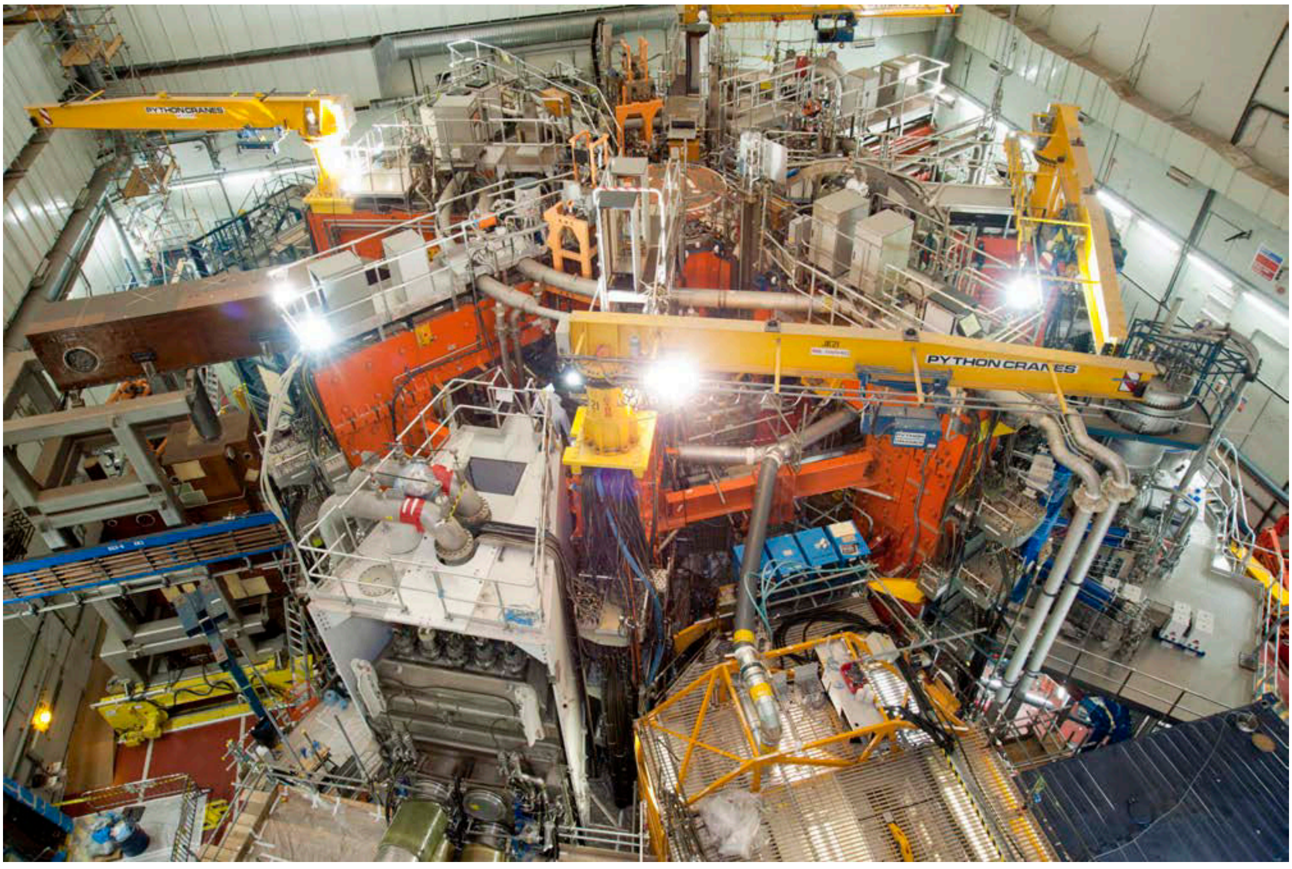

FIG. III–2. Interior of JET facility (courtesy of EUROfusion).

input power. This success will facilitate an actual fusion power plant, and the demonstration plant is expected to be ready by 2040.

The ITER (Fig. III–3) is based on the tokamak concept of magnetic confinement, in which the plasma is contained in a doughnut shaped vacuum vessel. The fuel, a mixture of deuterium and tritium, is heated to temperatures in excess of 150 million degrees Celsius, forming hot plasma. Strong magnetic fields are used to keep the plasma away from the walls produced by superconducting coils surrounding the vessel, and by an electrical current driven through the plasma.

The Naka Fusion Institute, Japan, has planned another advanced contribution to the nuclear fusion programme. A schematic of the JT-60SA (Super Advanced) tokamak is shown in Fig. III–4, and it is one of the three projects being undertaken jointly by Japan and the European Union. Construction started in January 2013, and it is expected to produce its first plasma in September 2020.

As a satellite tokamak of the ITER, JT-60SA plays an essential role in addressing the key physics and engineering issues of the ITER [III–5] and its successor, DEMO [III–6], which is the final step to commercial fusion reaction energy production.

There has been a significant development in research into inertial fusion energy, based on the concept of the inertial confinement of the plasma. Important facilities worldwide working towards realizing inertial fusion energy are the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and the Laboratory for Laser Energetics at the University of Rochester in the USA; the Megajoule Laser Project in France; Vulcan in the United Kingdom; HiPER, the European High Power Laser Energy Research

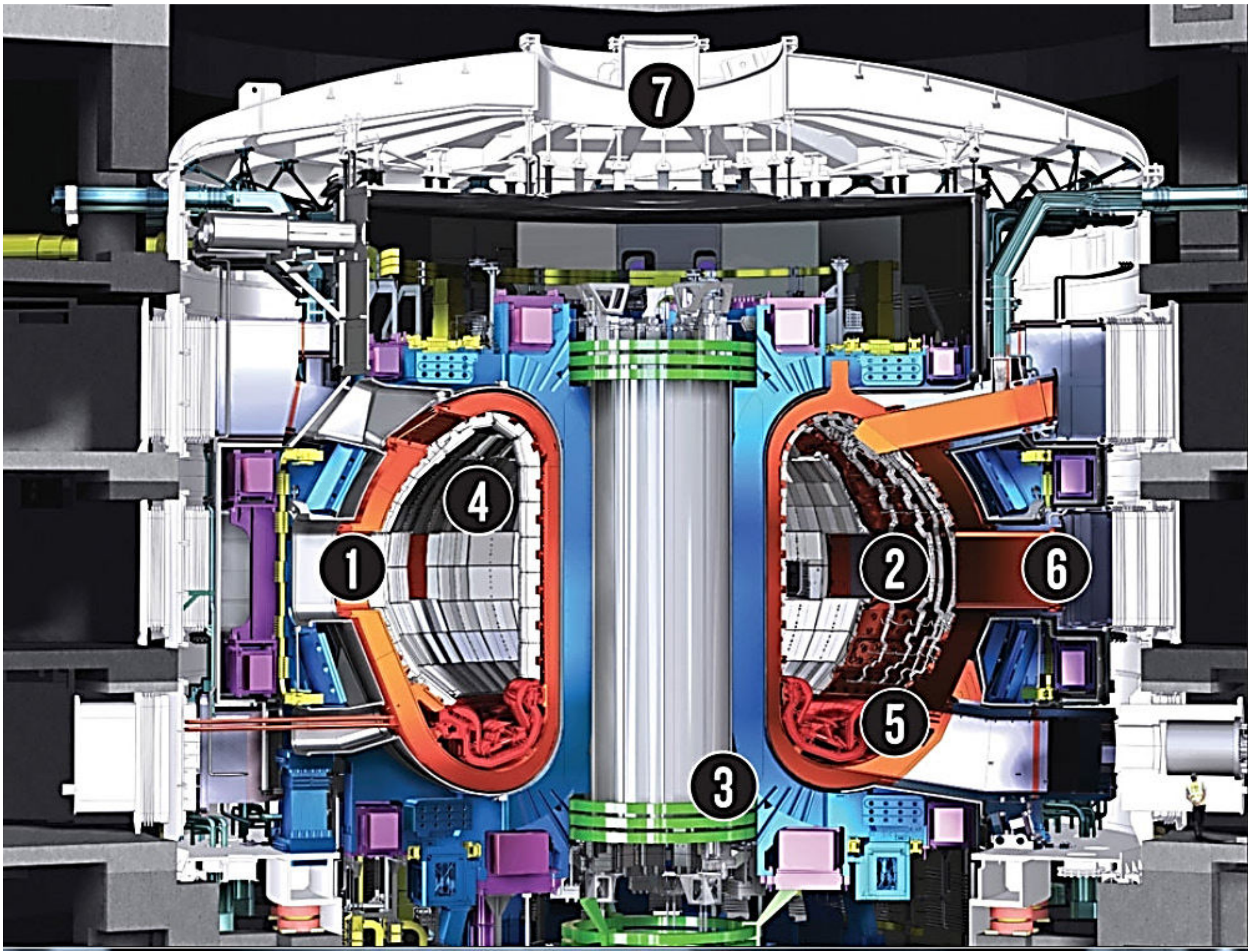

FIG. III–3. ITER design: 1 — vacuum vessel, 2 — plasma heating, 3 — superconducting magnets, 4 — blanket, 5 — divertor, 6 — diagnostics, 7 — cryostat (courtesy of ITER).

facility; Gekko XII in Japan; and ISKRA 5 in the Russian Federation. Of these, NIF is the leading research laboratory to date [III–7].

The construction of NIF at Lawrence Livermore National Laboratory was funded by the National Nuclear Security Administration and completed in March 2009; the first attempts at ignition were made in 2010. Figure III–5 shows the inside of the NIF preamplifier support structure for NIF's ignition experiment.

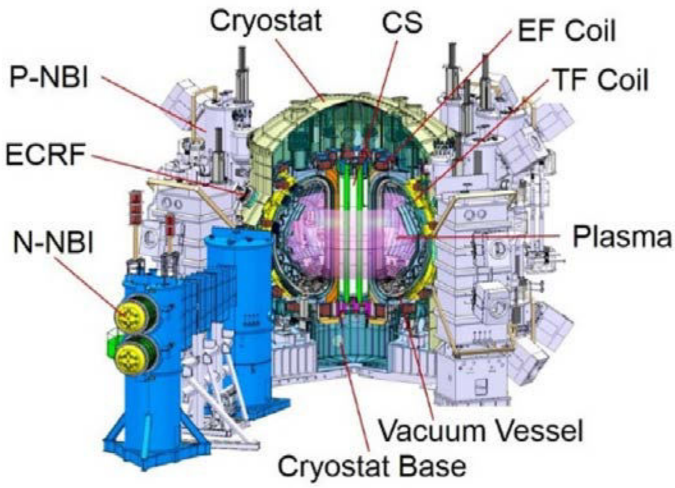

FIG. III–4. Schematic view of JT-60SA tokamak (reproduced from Ref. [III–5]).

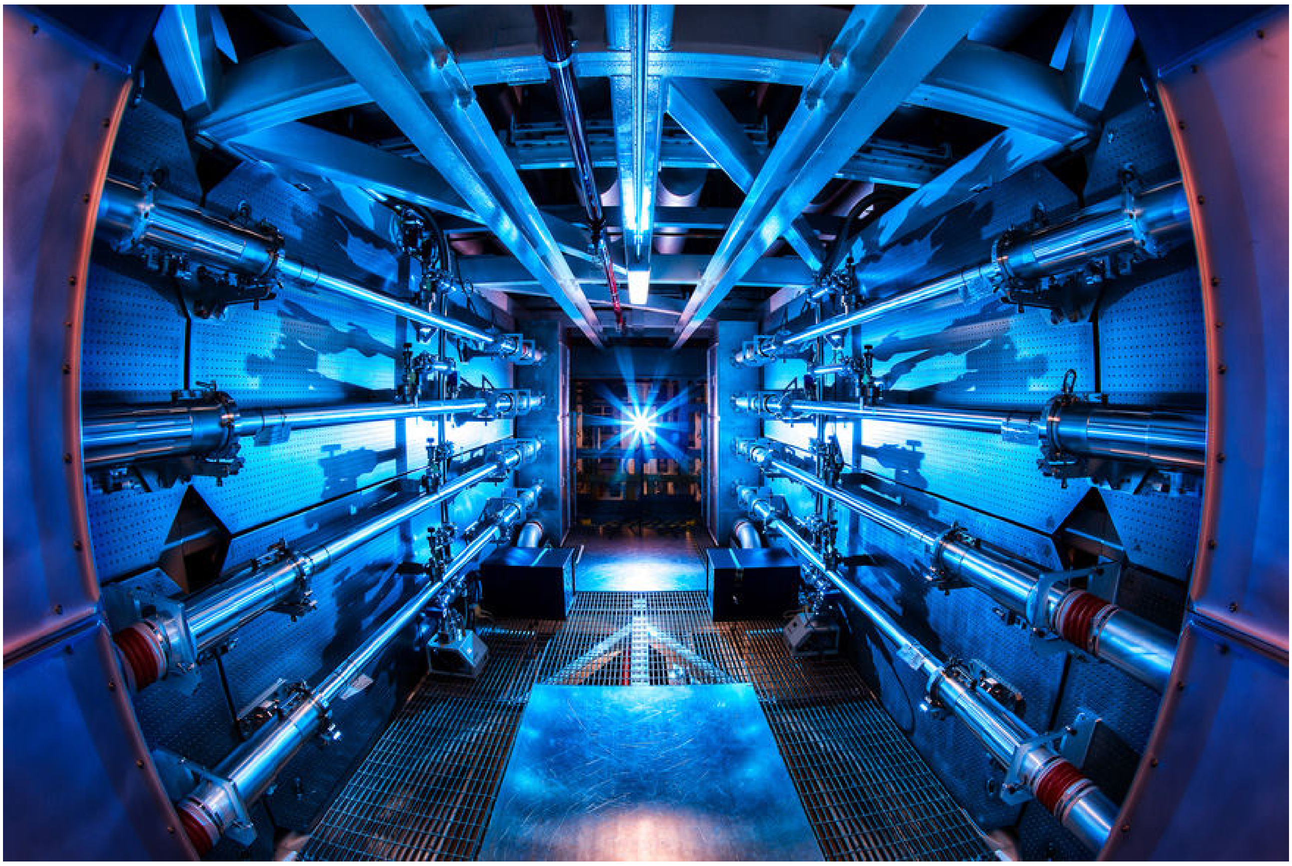

FIG. III–5. A colour enhanced image of the inside of the NIF preamplifier support structure (courtesy of the Lawrence Livermore National Laboratory).

At present, NIF is the only experimental facility in the world capable of creating temperatures and pressures like those found in the cores of stars and giant planets. It consists of 192 neodymium glass laser beams in 24 bundles of eight and a 10 m diameter target chamber for ignition experiments in which nuclear fusion reactions take place [III–8].

According to the recent Lawrence Livermore National Laboratory report published in August 2017 [III–9], using the indirect drive approach, the experiments are the first thermonuclear measurements of nuclear reaction cross-sections, a quantity that describes the probability that reactants will undergo a fusion reaction that is equivalent to the burning cores of giant stars, ten to 40 times more massive than the sun. These results boast that under extreme plasma conditions, hydrogen isotope densities are compressed by a factor of a thousand and temperatures are heated to about 50 million degrees Celsius. NIF's mission is to achieve fusion ignition with high energy gain and to support nuclear weapon design and maintenance by studying the behaviour of matter under the conditions found within nuclear weapons [III–7].

Construction on NIF began in 1997, but owing to management problems and technical delays, NIF was completed five years behind schedule and at almost four times the cost originally budgeted. Construction was completed on 31 March 2009 by the US Department of Energy [III–11]. The first large scale laser target experiments were performed in June 2009 using a Hohlraum target (see Fig. III–6), and the first 'integrated ignition experiments' (which tested the laser's power) were declared completed in October 2009 [III–11].

The Lawrence Livermore National Laboratory announced in July 2012 that the NIF laser system of 192 beams delivered more than 500 TW of peak power and 1.85 Megajoules (MJ) of ultraviolet laser light into a 2 mm diameter hohlraum for a few trillionths of a second [III–8]. The NIF reported that in September 2013, for the first time, the amount of energy released through the fusion reaction exceeded the amount of energy being absorbed by the fuel, but not the amount supplied by the giant lasers. Reference [III–12] reported that 17 kJ of energy was released.

Recent work at Osaka University's Institute of Laser Engineering in Japan suggests that ignition may be achieved at a lower temperature using an intense second laser pulse guided through a few-millimetres-long gold cone into the compressed fuel and timed to coincide with the peak compression. This technique, known as 'fast ignition', means that fuel compression is separated from hot spot generation with ignition, making the process more practical. Figure III–7 shows the conceptual design of the Laboratory Inertial Fusion Test facility for power generation. This is based on the ongoing research at the Fast Ignition Realization Experiment (FIREX-II) facility, and fusion power generation is expected to be in 2035.

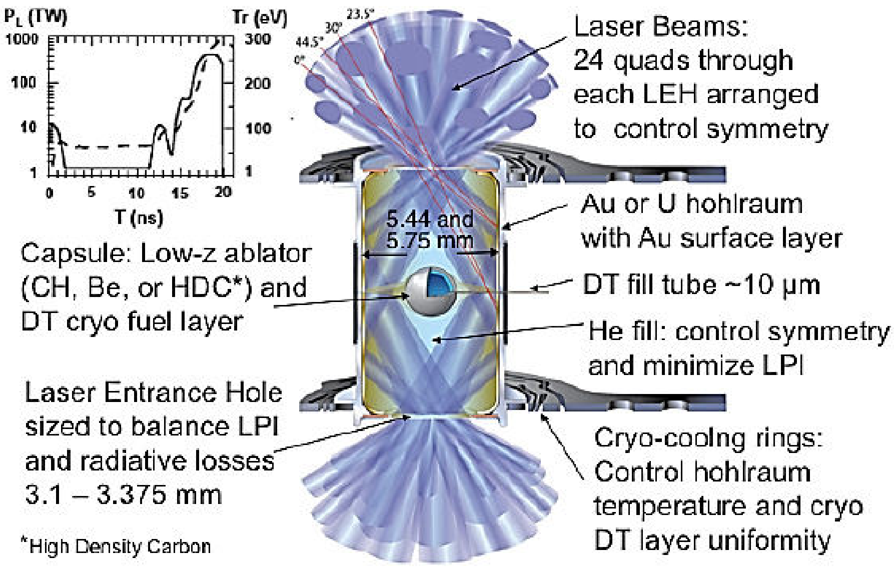

FIG. III–6. Hohlraum target structure (reproduced from Ref. [III–10]).

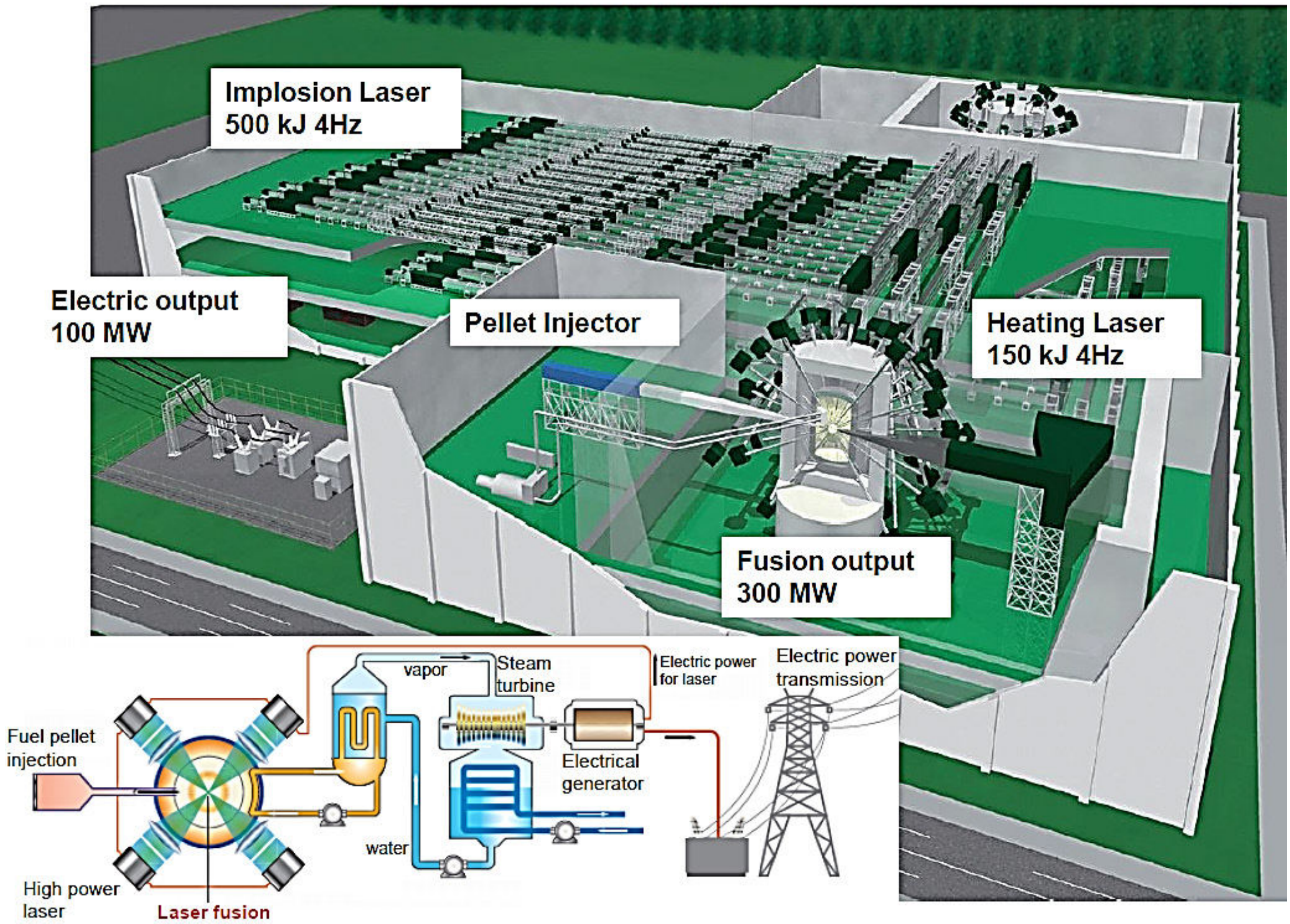

FIG. III–7. Conceptual design of the Laboratory Inertial Fusion Test facility, Japan (reproduced from Ref. [III–13]).

III–4. DECOMMISSIONING EXPERIENCE AND STUDIES

The TFTR was shut down in 1997 after 15 years of operation. Work on the removal of the TFTR began in October 1999 and was completed in September 2002 on schedule and under budget. The TFTR contained an 80 t doughnut shaped vacuum chamber, 587 t of magnetic field coils, a 15 t titanium central column and a massive stainless steel support structure. Figure III–8 shows the TFTR.

The deployment of tritium presented several challenges for the successful decommissioning project. In addition to the 260 TBq of tritium remaining in the vacuum vessel, predominately in the co-deposited layer within the graphite tiles, a relatively high concentration of surface tritium contamination existed (160 000–640 000 Bq/cm^2 for surface smears). The vacuum vessel and support structures were activated to levels ranging from approximately 0.5 mSv/h on contact with the vessel to approximately 0.02 mSv/h on ancillary equipment. At the end of the three year TFTR decommissioning project, approximately 1470 m^3 of radioactive and tritium contaminated waste had ultimately to be disposed of. The deployment of novel technologies during decommissioning led to an approximately 63% reduction in the amount of radioactive and contaminated waste materials that was initially estimated to be generated using conventional tooling and procedures. The project was completed at a cost of US $36.8 million, approximately 9.5% under the original estimated cost [III–14].

The most challenging aspect of the TFTR disassembly was the segmentation of the 76 m^3 vacuum vessel. The use of conventional technologies, such as abrasive sawing and flame cutting, could not satisfy health and safety concerns. Princeton Plasma Physics Laboratory’s engineering team effectively addressed all challenges by developing an innovative system that reduced workers’ radiation exposure, airborne emissions and waste generation. The vacuum vessel was first filled with lightweight concrete and then cut into ten segments using diamond wire cutting for transportation and radioactive waste burial at the Hanford site. The feasibility of diamond wire cutting

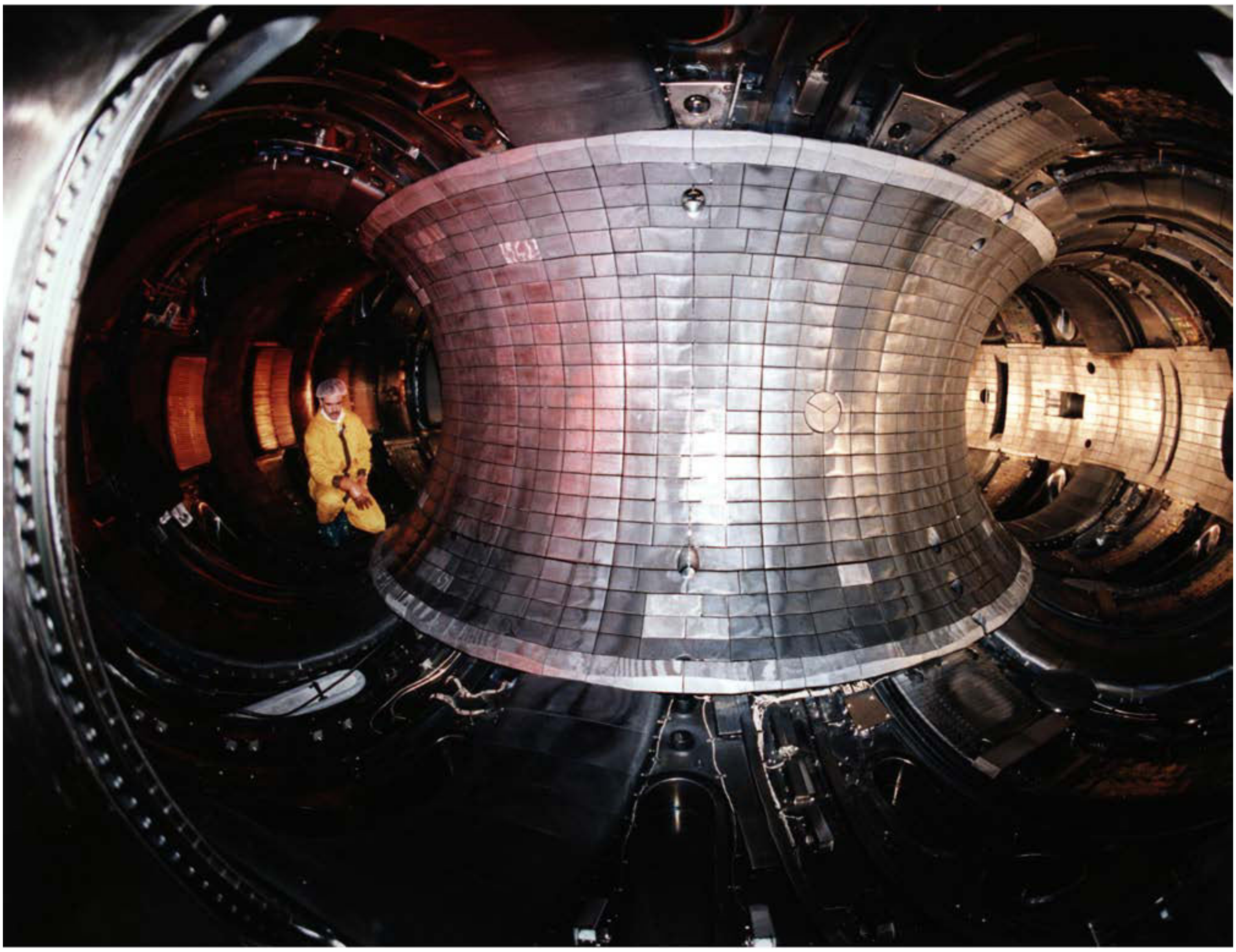

FIG. III–8. Tokamak Fusion Test Reactor.

a concrete filled stainless steel vessel was demonstrated at the Princeton Plasma Physics Laboratory during the summer of 1999. This demonstration was funded by the US Department of Energy's EM-50 Decommissioning Focus Area [III–15, III–16].

The use of industrial crimpers provided a method for isolating tritium contaminated surfaces in a manner that protected the workers and mitigated tritium off-gassing. In addition, pieces of pipes and lines could be crimped and cut in a way that reduced dismantling labour costs while optimizing the size of the component that could fit into the waste disposal package. The deployment of crimpers significantly reduced the quantity of removable tritium contamination at the work site, which led to a reduction in the quantity of radiological waste that needed to be disposed of.

Large industrial power saws were an efficient means of cutting large metal components such as the toroidal field coils. Saw technology has advanced significantly over the past several years and provided an effective cutting platform for large, irregular pieces of hard metals (e.g. stainless steel, Inconel) that needed to be reduced in size to fit into the appropriate waste packages. In several saw cutting configurations, workers would set up the saw cutting geometry and lock the pieces in place; the saw would perform the cut while the worker was observing at a location outside of the radiological area. This also led to worker exposure being kept 'as low as reasonably achievable'. During the entire TFTR decommissioning project, the radiological exposure for all workers was determined (by dosimetry) to be 110 person-mSv. Stack releases to the environment during the course of decommissioning were determined to be 16.5 TBq of tritium, as measured by passive stack monitors [III–14].

Tritium was first introduced into the JET in 1991, and it is estimated that at the end of operations and following a period of tritium recovery there will be 2 g of tritium in the vacuum circuit. All in-vessel items are also contaminated with beryllium, and the structure of the machine is neutron activated.

Decommissioning of the facility will commence immediately after JET operations cease, and the plan is to remove all the facilities and to landscape the site within ten years. The decommissioning plan has been through a number of revisions since 1995 that have refined the detail, timescales and costs [III–17].

Preliminary plans for the decommissioning of ITER are given in Ref. [III–18]. Three decommissioning stages are foreseen: Phase 1 (five years), a radioactive decay period (23 years), and Phase 2 (six years). The aim of Phase 1 is to bring the machine into a safe state soon after the end of operation, utilizing the facilities and personnel still available on the site from the previous operation phase. The responsibility for Phase 1 belongs to the ITER organization and will terminate with the handing over of the facility to a new organization inside the ITER host country in ready-for-decommissioning status. Phase 1 will consist mainly of the removal of mobilizable tritium from the in-vessel components and of any recoverable activated dust (e.g. beryllium, tungsten, carbon). The in-vessel components will also be removed. During the radioactivity decay period, radioactivity inside the vacuum vessel will continue to decay to a target contact dose rate for hands-on operations below 10 μSv/h, on average [III–18]. Phase 2 will complete the dismantling of all remaining components.

The JT-60 tokamak was constructed for fusion plasma research and development in 1985 in Japan. The duration time of plasma was increased from five to 65 seconds, and the world record was achieved for the Q value, the ion temperature and the fusion triple product. Figure III–9 shows an image of the JT-60 [III–19].

Disassembly of the JT-60 U torus began in 2009, after 18 years of deuterium–deuterium operations, and was completed in October 2012 so that the JT-60SA torus could be assembled in the same position. The JT-60 U torus had a complicated and welded structure against the strong electromagnetic force and by the radioactivation due to deuterium–deuterium reactions. Since this work was the first experience of disassembling a large radioactivated fusion device in Japan, careful preparations of disassembly activities, including treatment of the radioactivated

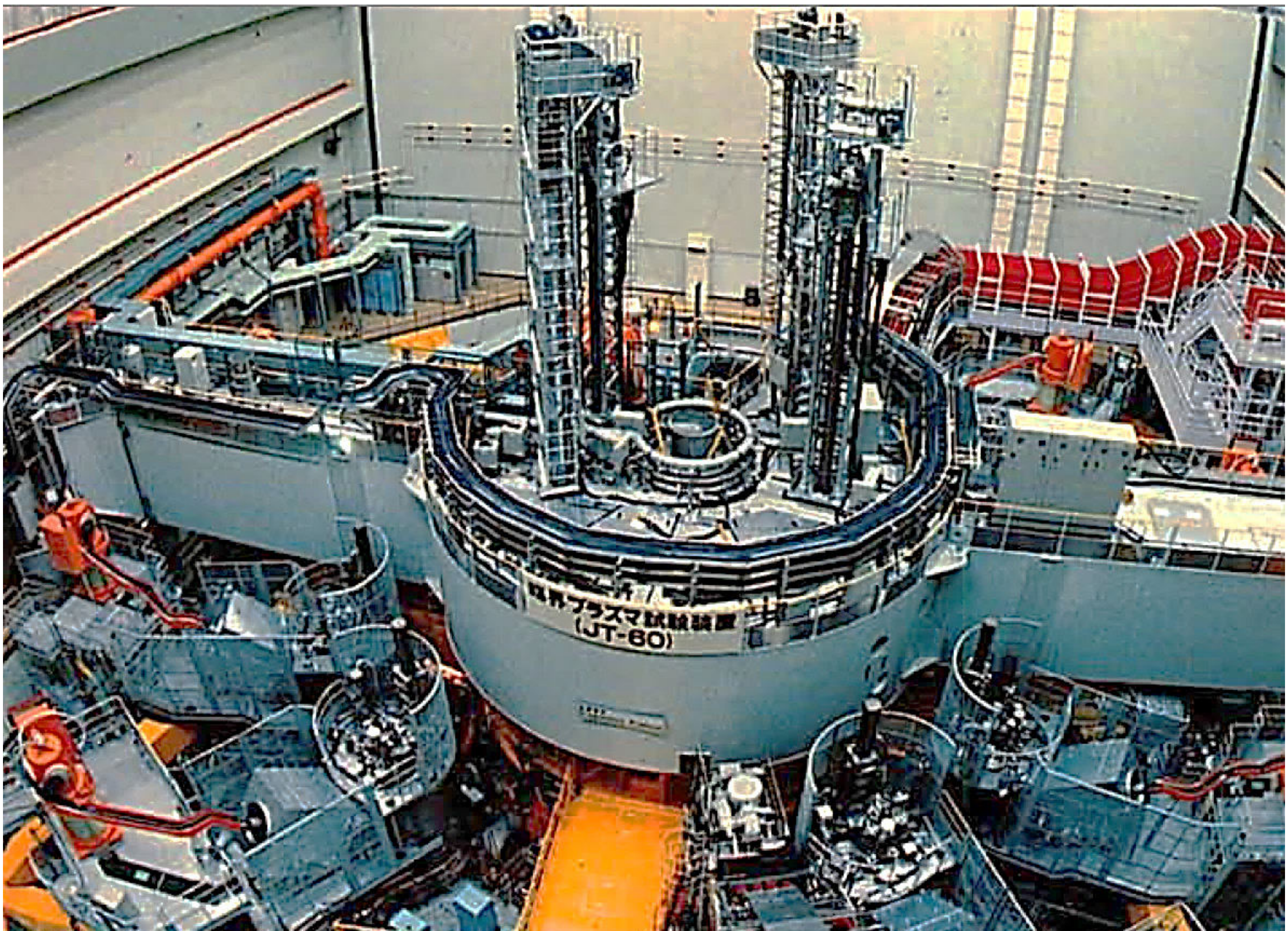

FIG. III–9. Aspects of JT-60 and its parameters (reproduced from Ref. [III–19]).

materials and safety work, were made. During the disassembly period over three years, careful measures against exposure were taken and stringent control of exposure dose was implemented; as a result, the accumulated collective effective dose of 41 000 person-days to workers was only 22 mSv in total, and no internal exposure was observed. About 13 000 components, cut into pieces when measuring the contact dose, were removed from the torus hall and stored safely in storage facilities. The total weight of the disassembly components reached up to 5400 t. Most of the disassembly components will be treated as non-radioactive after the clearance level inspection under the Japanese regulations. The assembly of JT-60SA started in January 2013, after the disassembly of the JT-60 U torus [III–20].

III–5. DECOMMISSIONING ASPECTS OF FUSION MACHINES

It is not the purpose of this annex to provide comprehensive guidance on the decommissioning of fusion machines. The decommissioning experience for these facilities is limited to a few prototypes. However, an important factor for plasma stability and energy balance is the plasma size (and thus the machine size); therefore, large plasma chambers and large machines are needed. The main factors affecting the decommissioning of fusion reactors are [III–21]:

(a) The presence of rather large quantities of tritium, hence the potential of getting contaminated (tritiated) materials and the need for de-tritiation;
(b) The emission (by fusion reaction) of high energy (14 MeV) neutrons with rather high flux (exceeding 10^{13} $n \cdot cm^{-2} \cdot s^{-1}$), leading to activation in the materials facing the plasma;
(c) The fusion reaction not producing residues (such as fission products and actinides in nuclear fission) as the product of the reaction is ^{4}He, a stable atom.

The dominating waste mass stream is generated in the decommissioning stage. Radioactive nuclides in fusion waste are mainly solid metallic activation products (from the main machine components), activated concrete from the biological shield, and tritium.

Therefore, fusion waste is quite different from fission waste, both in type of material and isotopic composition. A number of approaches are currently being pursued to minimize the radioactive inventory, and therefore the decommissioning waste, from a fusion power plant, mostly limited to the deuterium–tritium fuel cycle. The common element of all approaches is the use of low activation materials. Vanadium based alloys are an example of such materials. Low activation materials allowing, firstly, a significant reduction in the risk of exposure of personnel and, secondly, partially solving the problem of long life wastes are a widely studied solution for the close-to-plasma components in a commercial reactor. A comprehensive discussion on fusion versus fission reactors and waste with a focus on decommissioning is provided in Refs [III–22 to III–24]. Approaches intended to facilitate decommissioning became more technically feasible in recent years with the development of radiation resistant remote handling tools and the introduction of the clearance category for slightly radioactive materials by the IAEA and other national nuclear agencies. A great deal of the decommissioning materials (up to 80%) have a very low activity concentration and can be cleared from regulatory control, especially when a period of interim storage (up to 100 years) is anticipated. The remaining 20% of the active materials could be disposed of as low level waste or, preferably, recycled. The clearance and recycling approaches to the management of fusion waste are described extensively in Ref. [III–25].

The experience gained from the existing tokamaks indicates that in-vessel tritium retention could represent a burden for ITER operation and decommissioning. Therefore, erosion–deposition studies were performed to better understand the layer co-deposition and tritium retention processes in tokamaks. Moreover, the testing of in situ de-tritiation processes, in particular laser and flash lamp treatments, need to assess de-tritiation techniques for in-vessel components in the ITER relevant JET configuration. To reduce the constraints on waste disposal, dedicated procedures were investigated for the de-tritiation of metals, graphite, carbon-fibre composites, process and housekeeping wastes [III–26]. Figure III–10 shows the decommissioned research tokamak located in the Canada Science and Technology Museum in Ottawa.

During the operational and decommissioning phases of a fusion reactor, many processes will produce tritiated water. Key components for an ITER relevant water de-tritiation facility were studied experimentally, with the aim

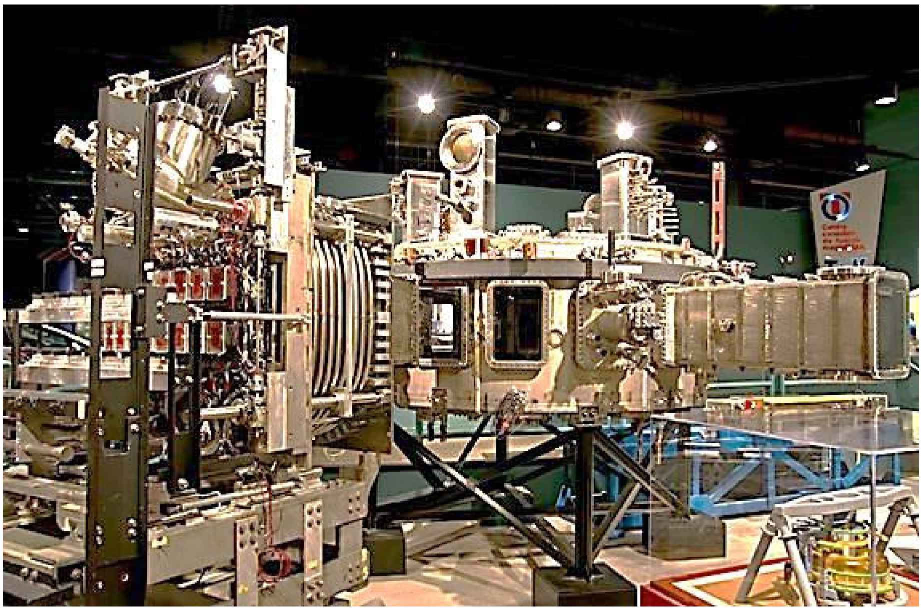

FIG. III–10. Decommissioned research tokamak at the Canada Science and Technology Museum, Ottawa (courtesy of the Canada Science and Technology Museum).

of producing a complete design that could be implemented and tested at JET [III–26]. In future, it will be important to select materials that have low affinity to tritium or that allow low tritium diffusion.

Another aspect that can play a very important role is the possibility of recycling fusion materials. For very low radioactive materials, material clearance can drastically reduce the amount of radioactive waste. Regarding the rather short half-life of the activation isotopes (provided the material was adequately chosen), less radioactive waste can be expected after a decay storage period (release after decay). This has even led to the concept of (almost) zero waste if highly activated materials are able to be recycled. This is in fact an objective towards which the designers of future fusion power plants are striving. Even if this goal cannot be met, future fusion plants will only lead to the production of radioactive waste, not to a request for geological disposal [III–21].

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GLOSSARY

accelerator. A scientific apparatus used to accelerate charged particles (electrons, protons or ions) so that they reach a high energy.

activation. The process of inducing radioactivity. Most commonly used to refer to the induction of radioactivity in moderators, coolants, and structural and shielding materials, caused by irradiation with neutrons or other nuclear particles.

beam. A slender unidirectional stream of particles or radiation.

beam loss. Loss of particles or radiation from the beam chamber.

cavity. The main part of any accelerator.

chicane. A beamline bump made with bend magnets. Chicanes are used as energy filters to transmit only the part of the spectrum wanted or to eliminate particles of the wrong charge. The strengths of the bends are calculated to transmit beams of a specific energy.

clearance. Removal of radioactive material or radioactive objects within authorized practices from any further regulatory control by the regulatory body.

collider. A particle accelerator that allows beams of particles to collide.

contamination. Radioactive substances on surfaces or within solids, liquids or gases (including the human body), where their presence is unintended or undesirable, or the process giving rise to their presence in such places.

cyclotron. A particle accelerator in which the particles move in a constant magnetic field in a spiral orbit, the energy of the particles being increased by the application of an alternating electric field at constant frequency.

decommissioning. Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility (except for a repository or for certain nuclear facilities used for the disposal of residues from the mining and processing of radioactive material, which are ‘closed’ and not ‘decommissioned’).

dismantling. The disassembly and removal of any structure, system or component during decommissioning; dismantling may be performed immediately after the permanent retirement of a nuclear facility or it may be deferred.

disposal. Emplacement of waste in an appropriate facility without the intention of retrieval.

graded approach. For a system of control, such as a regulatory system or a safety system, a process or method in which the stringency of the control measures and conditions to be applied is commensurate, to the extent practicable, with the likelihood and possible consequences of, and the level of risk associated with, a loss of control.

licence. A legal document issued by the regulatory body granting authorization to perform specified activities related to a facility or activity. The holder of a current licence is termed a ‘licensee’.

light source. An accelerator that produces exceptionally intense beams of X rays and ultraviolet and infrared light, used in both basic and applied research.

linac. A contraction of 'linear accelerator', a machine designed to accelerate charged particles in a single pass along a straight trajectory through a linear accelerating structure.

magnet. A device that produces magnetic fields that are applied to charged particles to bend, focus or correct the trajectory.

mixed waste. Radioactive waste that also contains non-radioactive toxic or hazardous substances.

off-site / on-site. Outside the site area / within the site area.

operator (operating organization). Any organization or person applying for authorization or authorized and/or responsible for nuclear, radiation, radioactive waste or transport safety when undertaking activities or in relation to any nuclear facilities or sources of ionizing radiation. This includes, inter alia, private individuals, governmental bodies, consignors or carriers, licensees, hospitals and self-employed persons.

potential drop. The difference in electric charge (in volts) between two points in a circuit.

regulatory body. An authority or a system of authorities designated by the government of a State as having legal authority for conducting the regulatory process, including issuing authorizations, and thereby regulating nuclear, radiation, radioactive waste and transport safety.

restricted use (release). The use of an area or of materials subject to restrictions imposed for reasons of radiation protection and safety. Restrictions would typically be expressed in the form of prohibition of particular activities (e.g. house building, growing or harvesting particular foods) or prescription of particular procedures (e.g. materials may only be recycled or reused within a facility).

spallation. A nuclear reaction in which many particles are ejected from an atomic nucleus by incident particles of sufficiently high energy.

stakeholder. Interested party; concerned party.

storage ring. A ring of magnets having the capability of storing particles from an accelerator for defined periods.

structures, systems and components (SSCs). A general term encompassing all of the elements (items) of a facility or activity which contribute to protection and safety, except human factors. Structures are the passive elements: buildings, vessels, shielding, etc. A system comprises several components, assembled in such a way as to perform a specific (active) function. A component is a discrete element of a system. Examples of components are wires, transistors, integrated circuits, motors, relays, solenoids, pipes, fittings, pumps, tanks and valves.

synchrotron. A cyclotron in which the magnetic field strength increases with the energy of the particles to keep their orbital radius constant.

tandem accelerator. An electrostatic accelerator in which negative hydrogen ions generated in a special ion source are accelerated as they pass from ground potential up to a high voltage terminal; both electrons are then stripped from the negative ion by passage through a very thin foil or gas cell, and the proton is again accelerated as it passes to ground potential.

target. A body, surface or material bombarded with nuclear particles in accelerators.

transport. The deliberate physical movement of radioactive material (other than that forming part of the means of propulsion) from one place to another.

unrestricted use or release. The use of an area or of material without any radiologically based restrictions.

Van de Graaff accelerator. An electrostatic generator in which an electric charge is either removed from or transferred to a large hollow spherical electrode by a rapidly moving belt, accelerating particles to energies of about 10 MeV.

ABBREVIATIONS

ALARA	as low as reasonably achievable
CD	critical decision
CERN	European Organization for Nuclear Research
CLIC	Compact Linear Collider
CLS	Canadian Light Source
DOE	Department of Energy (United States of America)
EIA	environmental impact assessment
FLUKA	fluctuating cascade (a Monte Carlo code for simulation of radiation transport)
HPGe	hyper-pure germanium
IPNS	Intense Pulsed Neutron Source
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
KEK	Kō Energī Kasokuki Kenkyū Kikō
LBNL	Lawrence Berkeley National Laboratory
LEP	Large Electron–Positron collider
LHC	Large Hadron Collider
linac	linear accelerator
MCNP	Monte Carlo N-Particle
MCNPX	Monte Carlo N-Particle X
NIF	National Ignition Facility
PCB	polychlorinated biphenyl
PEP	Positron–Electron Project
PET	positron emission tomography
PPE	personal protective equipment
SSCs	structures, systems and components
TFTR	Tokamak Fusion Test Reactor
VKTA	Verein für Kernverfahrenstechnik und Analytik

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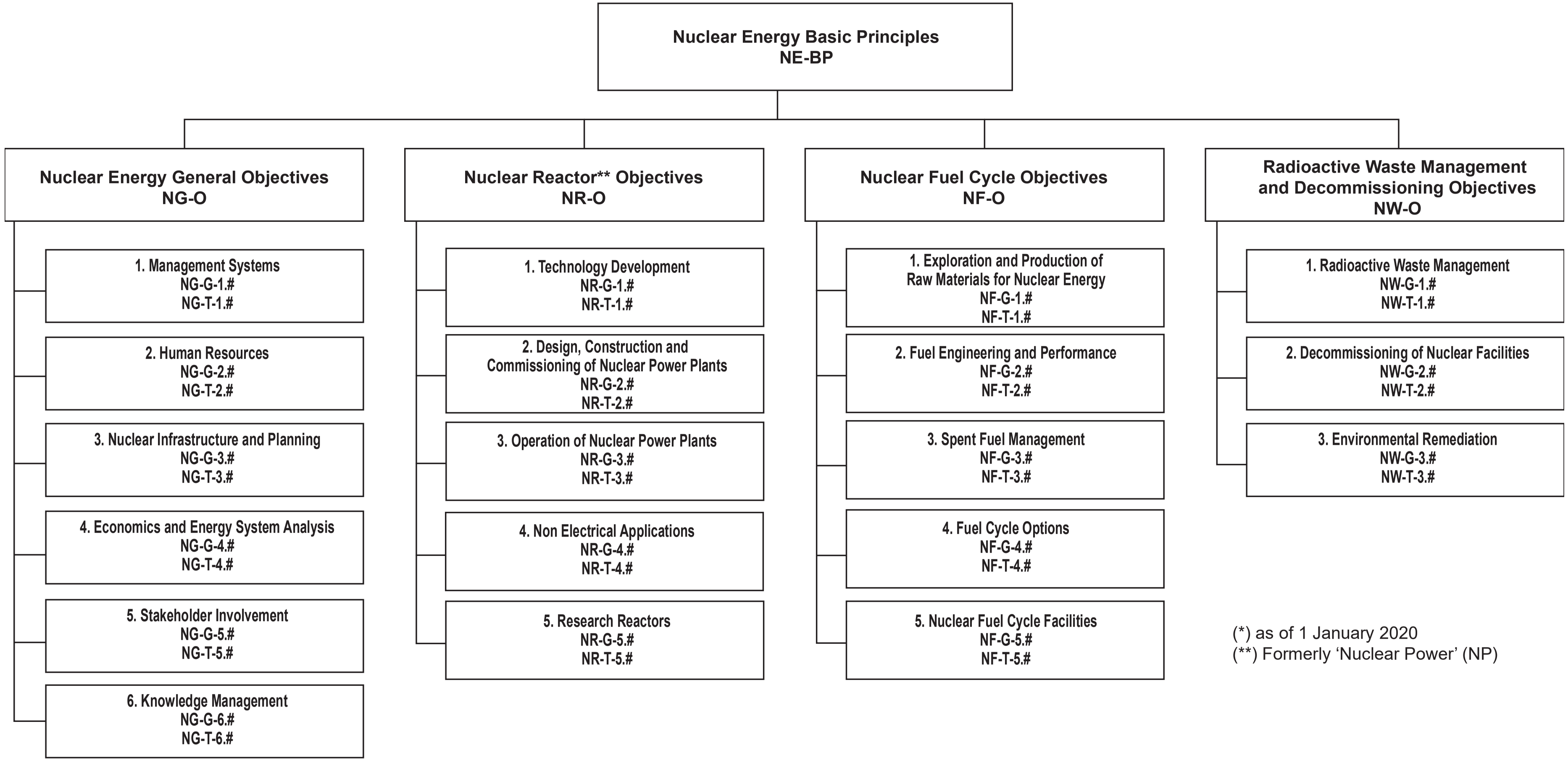

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