5 DECOMMISSIONING OF NUCLEAR FACILITIES

The purpose of this section is to describe the status of and trends relative to nuclear facility decommissioning, where a nuclear facility is defined as [5.1]:

> *a facility and its associated land, buildings and equipment in which radioactive materials are produced, processed, used, handled, stored or disposed of on such a scale that consideration of safety is required*

and decommissioning is defined as [5.1]:

> *administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility (except for a repository which is closed and not decommissioned). The use of the term decommissioning implies that no further use of the facility (or part thereof) for its existing purpose is foreseen... ...For a repository, the corresponding term is closure.*

The following subsections are included to elaborate on the subject area:

- Factors Relevant to Selecting a Decommissioning Strategy
- Decommissioning Strategies Worldwide
- *in situ* Disposal
- Recent Decommissioning Experience
- Conclusions (for Power Plant Decommissioning)
- Topical Issue: Preliminary Scoping of the Decommissioning of Small Nuclear Facilities

As many nuclear reactors will reach the end of their design lifetime in the next few decades, it is expected that decommissioning will develop into an area of increasing interest. The decommissioning status of nuclear power reactors is available on the Internet at the following URL (at time of writing):

http://www.world-nuclear.org/wgs/decom/database/database.htm

5.1 Factors Relevant to Selecting a Decommissioning Strategy

The conceptual basis for the selection of a decommissioning strategy can be found in the IAEA's "*Principles of Radioactive Waste Management*" [2.2]. Principles 4 and 5 refer directly to protection of and burden on future generations (see Table 5-I) but they are not prescriptive in nature. The IAEA's Member States are given the flexibility of evaluating how to implement these principles as reflected in derived safety guides such as reference [5.2]. It can be generally assumed that "undue" delays in decommissioning of nuclear facilities should be prevented, but the interpretation of "undue" is left to national authorities.

Two of the basic decommissioning strategies for a nuclear facility are discussed in the current issue of this Status and Trends report. These two strategies are:

- immediate dismantling (known as **DECON** in the USA), and
- long-term storage followed by dismantling (known as **SAFSTOR** in the USA).

Currently, a third strategy is being considered, namely *in situ* disposal. This alternative involves encasement of the radioactive structures, systems and components in a structurally long lived substance, such as concrete. This option is known as **ENTOMB** in the USA**.** However, a US Nuclear Regulatory Commission (NRC) document states "*Currently, ENTOMB is not considered a viable option for reactor decommissioning because some of the long-lived radioisotopes present at the facility may not decay to acceptable levels within the sixty-year period.*" [5.3]

Table 5-I: Radioactive Waste Management Principles Relevant to Selecting a Decommissioning Strategy

PRINCIPLE 4:	PROTECTION OF FUTURE GENERATIONS Radioactive waste shall be managed in a way that the predicted impacts on the health of future generations do not exceed relevant levels that are acceptable today.
PRINCIPLE 5:	BURDEN OF FUTURE GENERATIONS Radioactive waste shall be managed in a way that will not impose undue burden on future generations.

The following discussion provides information on major factors affecting the selection of a decommissioning strategy, how these factors play a role in Member States' decision-making, and recent decommissioning examples.

The decision on how to proceed with the decommissioning of a nuclear facility is dependent on a number of factors, namely:

- legislative and regulatory requirements;
- waste arisings and national waste management strategy;
- spent fuel management strategies;
- physical conditions of the plant;
- owner's interest, including planned use of site;
- availability of technology and other resources;
- social considerations;
- decommissioning cost and funding; and
- radiological exposures.

Each factor must be examined for the conditions specific to the facility under consideration to arrive at a satisfactory decommissioning plan. Each of the factors is briefly discussed in the subsections that follow.

5.1.1 Legislative and Regulatory Requirements

Decommissioning strategies and their timing are regulated in different ways by Member States. Examples of different approaches to decommissioning nuclear power plants are:

a) Japan requires that facilities go to total dismantling within five to ten years of facility shutdown. In October 2001, Japan Atomic Power Co. announced the beginning of dismantling of Japan's first commercial nuclear reactor at Tokai.

The 166-MW gas-cooled reactor was operating until March 1998 after it came online in 1966.

b) Based on technical studies of different nuclear facilities, the US Nuclear Regulatory Commission (NRC) allows a possession-only licence only for nuclear power reactors and limits the surveillance period to up to 60 years. Technical studies showed that for US power reactors there is little benefit in delaying dismantling for longer time periods.

c) In Italy, the operator's decommissioning strategy for shutdown nuclear power plants was long-term safe enclosure. This was essentially based on the lack of a radioactive waste disposal site in the country. Recent developments towards early dismantling are driven by public opinion and strenuous efforts to achieve consensus on siting waste/spent fuel storage or disposal facilities.

It should be noted that other regulatory requirements are essential to safe and cost-effective planning/implementation of decommissioning. Clearance criteria (see subsection 3.1) are probably the most important of such requirements. Such criteria are now available in most countries, e.g. Germany, Spain and UK. In some cases they are part of the legislative framework, in others they were established for specific projects.

Large amounts of materials resulting from decommissioning contain very low levels of radioactivity or could be readily decontaminated to achieve such levels. Assuming that these materials should be all managed and disposed of as radioactive wastes would result in unnecessary penalties in terms of operational difficulties and significant extra costs. It is generally possible to establish radiological criteria and associated activity levels according to which materials can be released from regulatory control. Achieving clearance or authorized release is important to reduce the volumes of radioactive waste for storage/disposal.

Three general methods for removing solid materials/wastes from the facility can be identified as follows:

a) Clearance for unrestricted reuse or disposal
b) Authorized release/reuse within the nuclear industry or in the public domain; or
c) Storage/disposal under radiologically controlled and monitored conditions.

Criteria to be met for these methods vary between countries. Sometimes the criteria are based on nationally applicable regulations, while in other situations they are based on a case-by-case evaluation. Germany has a full set of clearance criteria, ranging from unrestricted or restricted release to nuclear re-use. However, such national limits have to be assessed in the context of recent international moves towards the harmonization of such criteria (see subsection 3.1).

5.1.2 Waste Arisings and National Waste Management Strategy

The generation of radioactive wastes in various classes (see Section 3) is a direct result of the dismantling of radioactive facilities. The extent of waste arisings in the various classes will be influenced by the timing of dismantling operations. Deferment may reduce the amounts of higher activity LILW and increase the amounts of low activity LILW. Additionally, decay and decontamination of some LILW may reduce activity enough to release the waste from regulatory control. This will influence disposal arrangements and costs.

If suitable disposal facilities for the amounts and classes of waste are not available, then the following options exist:

- maintain the facility in safe storage (i.e., minimize dismantling), and
- condition the waste from dismantling and store it.

Waste storage arrangements for large amounts of conditioned waste may also be costly or difficult to maintain. These considerations, therefore, will influence the timing of final dismantling and the period of safe storage.

Safe storage, however, is not considered to be an alternative strategy to the identification and qualification of a disposal site for decommissioning waste. It should be noted that disposal facilities now exist in many countries e.g. France, Spain, UK and the USA. However, other countries e.g. Canada do not have waste disposal sites and therefore have decided for long term safe storage of their shutdown facilities. Experience on disposing of large amounts of decommissioning waste at licensed disposal sites is still limited worldwide.

5.1.3 Spent Fuel Management Strategies

In some Member States, spent fuel management is not considered part of the decommissioning process, since it is assumed that the removal of fuel from the facility is a prerequisite for the implementation of major dismantling activities. However, experience shows that spent fuel management may strongly affect the selection of a decommissioning strategy. In several Member States, contracts were negotiated with other Member States to transfer spent fuel, but now, for various reasons, this has become difficult. It is encouraging that the policy of returning US origin fuel to the US has allowed prompt dismantling of several research reactors worldwide, while discussions are underway to allow such repatriation for Russian-design fuel. In general, it is desirable to remove spent fuel off-site or to a facility independent of the nuclear plant as soon as possible. This is the case at shutdown reactors in the UK (e.g. Berkeley, Trawsfynydd and Hunterston) where spent fuel was routinely transported to Sellafield for reprocessing as the first major step in decommissioning.

5.1.4 Physical Conditions of the Reactor

Design, construction and operational aspects of a given nuclear reactor may be more or less conducive to smooth decommissioning. In addition, the condition of a shutdown nuclear facility influences decisions concerning decommissioning from the viewpoint of integrity and maintainability of the facility and its systems. The importance of design features of a facility with a view to future decommissioning was also recognized in Article 14 (ii) of the Joint Convention [2.1] which prescribes:

> *"At the design stage, conceptual plans and, as necessary, technical provisions for the decommissioning of a radioactive waste management facility other than a disposal facility are taken into account;"*

5.1.5 Owner's Interest, Including Planned Use of the Site

The choice of a decommissioning strategy may also depend on the following considerations:

- The owner may have a shortage of sites for new reactor construction and may be forced to re-use a site for a new reactor. In that case, immediate dismantling may be chosen;
- If the reactor to be decommissioned is co-located with other operating facilities that will continue to be in service, deferred dismantling may be the preferred choice. The necessary security, surveillance and maintenance for

the shutdown facility could be provided by the remaining operating facilities. This is the case, for example, at the Dresden site in the USA;

- As a factor in a decision to proceed to safe storage, the owner may wish to consider the re-use of some of the reactor's facilities, for example the cooling water equipment, the infrastructure, and some of the process systems, for purposes other than those for which they were originally intended or as part of a new or modified reactor;
- If all decommissioning stages are available, the owner may wish to optimize expenditures, depending on the economic situation, in the choice of strategy.

5.1.6 Availability of Technology and Other Resources

Basic technologies for decommissioning are reasonably well known and tested. However, during the planning stages for dismantling, problems may be identified, for example, poor accessibility or specific operations to be undertaken during decommissioning. In such cases it may be necessary to develop special tools or means for remote operation or handling.

Long term storage followed by dismantling may take advantage of technological developments during the period of storage. Technological developments in decontamination procedures and techniques, robotics and remote cutting could facilitate future dismantling of a facility.

It should be noted that decommissioning technologies will be more accessible in countries (e.g., France, Germany, UK, USA etc.) that possess a significant nuclear programme. In such countries, a decommissioning "market" developed that should be financially beneficial to decommissioning budgets.

An advantage of immediate dismantling is the retention and utilization of plant expertise on the site during the actual dismantling. This expertise could lessen the potential for accidents and would avoid any radiation doses associated with retraining of personnel. This may be needed particularly in cases where there is a lack of records, where undocumented changes were made during construction or backfitting, and where experimental facilities are to be decommissioned.

As the storage period continues, expertise in the layout, maintenance and operation of the reactor lessens as personnel leave the facility so that at the time of dismantling there may be no one with personal experience of the facility. This expertise will have to be reacquired at the time of dismantling, with a possible corresponding penalty in costs, occupational exposure and other factors.

5.1.7 Social Considerations

The process of deciding between the different decommissioning strategies may take into consideration the possible effects on factors such as:

- environmental factors (e.g. the value of the neighbouring land);
- employment problems; and
- the public's perception of the hazards, whether the installation is maintained in a safe shutdown condition or is dismantled.

Public opinion about the proposed choice is usually taken into account in the procedure whereby the proposals are submitted for the approval of the relevant authorities; the way in which this is done varies from country to country. Social considerations are extremely important in countries having limited opportunities for re-location or re-training of the workforce. The need to reemploy operational staff was a key factor in the selection of the decommissioning strategy for the Greifswald reactor in Germany (Table 5-II). This issue is even more acute in countries resulting from the collapse of the former Soviet Union, where satellite cities were erected to support the operation of nuclear facilities [5.4]

Table 5-II: Specific Arguments for Greifswald to go to Immediate Dismantling

Need to reemploy large operational staff (thousands of workers) in an economically depressed region.
Prompt decision on decommissioning strategy allowing reemployment of key staff.
Availability of waste disposal facility at the beginning of the decommissioning project.
Funds made available by State.
Full set of clearance criteria
Difficulty of installing safe storage for WWER (no secondary containment).

5.1.8 Decommissioning Cost and Funding

Whatever choices and decisions are made, it is the responsibility of the owner of a nuclear power plant to make a financial provision sufficient to cover the costs of all stages of decommissioning up to final dismantling, in accordance with pertinent national legislation and funding requirements. If a long period of safe storage is envisaged, the forecasting of funding requirements may be uncertain because of the variations in costs of regulatory, social and industrial influences.

On the other hand, deferment of dismantling may improve the funding of the task by allowing time to accrue additional funds where these may not previously have existed or by discounted cash flow considerations over a reasonable period of time. This, together with radiological aspects, appears to be a major factor for the UK's Magnox operator to delay dismantling up to about 100 years.

The EC, the IAEA and the OECD/NEA developed a joint initiative to calculate decommissioning costs on the basis of an itemized list of cost factors. This has resulted in the publication of an interim Technical Document [5.5]. The US NRC has provided a simple algorithm to calculate decommissioning costs that would ensure that pertinent financial requirements are being met [5.6].

Next, two different examples of cost estimation are provided. The first is an example costing with the US NRC method (It should be borne in mind though, that the methodology is primarily intended as a compliance aid for US regulations and may not be universally applicable without adjustments.). The second example illustrates costing based upon actual costs incurred at existing facilities.

5.1.8.1 Example Costing with the US NRC Methodology

Licensees of operating nuclear power reactors must provide reasonable assurance that funds will be available to accomplish decommissioning within 60 years from the date of permanent cessation of operations, as required by 10 CFR 50.82(a). Reasonable assurance may be demonstrated by compliance with the requirements of 10 CFR 50.75(b), (c), (e), and (f). These requirements ensure that a licensee has financial assurance in effect for an amount that may be more but not less than the amount stated in the table in 10 CM 50.75(c). Specifically, this table says that if P equals the thermal power of a reactor in megawatts thermal (MWt), the minimum financial assurance (MFA) funding amount (in millions, January 1986 dollars) is:

For a pressurized water reactor (PWR): $MFA = (75 + 0.0088P)$

For a boiling water reactor (BWR): $MFA = (104 + 0.009P)$

For either a PWR or BWR**,** if the thermal power of the reactor is less than 1 200 MWt, the value of P to be used in these equations is 1 200, whereas if the thermal power is greater than 3 400 MWt, a value of 3 400 is used for P. That is, P is never less than 1 200 nor greater than 3 400.

The financial assurance amounts calculated in the above equations are based on January 1986 dollars. To account for inflation from 1986 to the current year, these amounts must be adjusted annually by multiplying by an escalation factor (ESC) described in 10 CFR 50.75(c), therefore,

MFA (in millions, current year dollars) = MFA * ESC (current year)

The ESC is:

$ESC\ (current\ year) = (0.\ 65L + 0.\ 13E + 0.\ 22B)$

where L and E are the ESC from 1986 to the current year for labour and energy, respectively, and are to be taken from regional data of the U.S. Department of Labor, Bureau of Labor Statistics, and B is an annual ESC from 1986 to the current year for waste disposal and is to be taken from the most recent revision of NUREG-1 307, "*Report on Waste Disposal Charges: Changes in Decommissioning Waste Disposal Costs at Low-Level Waste Burial Facilities*". NUREG-1307 is updated from time to time to account for disposal charge changes. In January 1986 (the base year), using disposal costs from the US Department of Energy's (DOE) Hanford Reservation waste disposal site, L, E, and B all equalled unity; thus the ESC itself equalled unity.

A licensee is required by 10 CFR 50.75(f) to report, on a calendar-year basis at least once every 2 years, the status of its decommissioning funding.

5.1.8.2 Example Costing Based on Costs Incurred at Existing Facilities

Another type of cost estimation is based upon costs actually incurred at similar facilities. This type of cost estimate would be appropriate if the licensee had access to the actual costs of decommissioning a facility that used the same decommissioning method and was of similar size (thermal power rating) and type (PWR/BWR) to the licensee's facility. For example, some utilities have built essentially identical nuclear power plants in the same geographical area. If one of these facilities has already been decommissioned, the cost data for that plant could serve as the basis for the cost estimate for another facility. However, site-specific factors such as changes in waste disposal costs and disposal facility availability, changes in radiological decontamination and dismantlement (D&D) techniques, and differences in operational history will cause the estimated cost to differ from the actual decommissioning cost of the reference facility. The estimate of expected radiological decommissioning costs based on actual decommissioning costs of a different but similar type of facility will generally be substantially less detailed than the site-specific cost estimate and can consist of just a few items:

- Thermal power rating, whether the facility is a PWR or BWR, name of the facility, license number (or former number if license is terminated), and reference documentation for the actual decommissioning costs of the facility.
- A list of cost factors and an assessment of how the factors impact the actual cost estimate.
- The major element of the cost estimate is the comparison of the actual decommissioning cost for a similar facility with the estimated decommissioning cost, in current year (estimate year) dollars. Adjustment factors between actual and estimated costs should be explained, as discussed in subsection 5.1.8.1.

For the immediate dismantling option, the total decommissioning costs should be separated into the following or a similar set of decommissioning cost categories:

- Major radioactive component removal -- reactor vessel and internals, steam generators, pressurizers, large-bore reactor coolant system piping, and other large components that are radioactive to a comparable degree
- Radiological D&D - removal of remaining radioactive facility systems, including radiological decontamination
- Management and support (undistributed costs) -- labour costs of support staff and decommissioning operations contractor staff, energy costs, regulatory costs, small tools, insurance, etc.
- LILW packaging
- LILW shipping from the decommissioning site to a waste management facility
- LILW disposal costs, including processing fees by the waste management operator
- Contingency - allowance for unexpected costs.

For the long-term storage followed by dismantling option, the decommissioning costs for the above cost categories should also be separated into the following or a similar set of decommissioning phases (time periods):

- Pre-decommissioning engineering and planning/plant deactivation - all activities from pre-decommissioning engineering and planning through defuelling, facility lay up, and placement of the reactor into a permanent shutdown condition
- Extended safe storage operations -- safe storage monitoring of the facility until dismantlement begins (if storage or monitoring of spent fuel is included in the cost estimate, it should be shown separately.)
- Final radiological D&D -- radiological D&D of radioactive systems and structures required for license termination, including demolition for the purposes of reducing residual radioactivity (if demolition of uncontaminated structures and site restoration activities are included in the cost estimate, they should be shown separately.)

5.1.9 Radiological Exposures

The removal of the reactor fuel or process materials from a facility and, if practicable, from the site removes the main radiological risk presented by that facility. However, a residual risk to workers, the public and the environment will remain during decommissioning based on the residual radioactivity. This risk will be most significant during the immediate post operational and initial and final decommissioning phases when physical work is being carried out on the facility.

One of the purposes in placing a facility in a prolonged period of safe enclosure between the initial and final phases of decommissioning is to achieve some radiological advantage for subsequent decommissioning. This will be primarily due to radioactive decay of radionuclides present and includes:

- the reduction in local dose rates and consequent reduction in operator doses;
- the reduction of the radiological consequences of any accidents during dismantling;
- the reclassification of some radioactive wastes (see subsection 5.1.1).

5.2 Decommissioning Strategies Worldwide

The choice between the two prevailing decommissioning strategies, deferred or direct dismantling, depends on a variety of factors, which are summarized in Table 5-III:

Table 5-III: Principal Decision Making Criteria for Decommissioning

Decision criteria for deferred dismantling

- Lack of availability of a repository
- Lack of funds for direct dismantling
- Radioactive decay of some radionuclides, and consequently:
  - Reduction of local dose rates
  - Reclassification of some radioactive wastes

Decision criteria for direct dismantling

- Availability of facility staff
  - Allows re-employment of staff
  - Use of specific expertise
- Use of existing infrastructure, including an available repository
- Experience with licensing procedures
- No long-term site commitment
- Unrestricted use of the grounds for other purposes
- Public and political acceptance

Decommissioning costs, waste disposal problems and political aspects are presently considered as major factors that influence decision making for decommissioning strategies.

The alternative of leaving a facility in long-term safe storage may cause a specific waste management problem in the future. With future disposal facilities so uncertain, a number of utilities have declared that they are unprepared to take the risk. The prospect of not having a disposal facility available at any cost may greatly overshadow the economics involved in the long-term build-up of decommissioning funds. It seems that immediate decommissioning will prevail in some countries that have limited waste disposal capacities. In fact, recent decisions appear to be driven by the desire to take advantage of existing disposal facilities while the option is still available and before disposal costs escalate to unbearable levels (e.g. in the USA).

The decision to delay the start of dismantling may also depend on other aspects than those mentioned above. To decommission its retired reactors, in the past Electricité de France (EDF) chose partial dismantling and deferral of final dismantling for 50 years. Although complete dismantling was technically possible, including availability of waste disposal facilities, the utility preferred the delay, which will result in a significant reduction in residual radioactivity, thus reducing radiation doses during the eventual dismantling. Improved techniques were also expected to be available at the dismantling stage, again reducing doses and also costs. A debate is underway in France to evaluate whether a shorter safe enclosure duration is viable. According to a recent development, it appears that the French nuclear operator has now selected early dismantling for first-generation reactors [5.7].

Germany, on the other hand, has chosen direct dismantling over safe enclosure for the closed Greifswald nuclear power station in the former East Germany, where five reactors had been operating, one was nearing operation and two were under construction. Among various reasons for this strategy, the socio-economic aspect of maximizing use of in-house resources played a major role. Other arguments are given in Table 5-II. In mid 1995, the site of the 100 MWe Niederaichbach nuclear power plant in Bavaria was declared fit for unrestricted agricultural use. Following removal of all nuclear systems, the radiation shield and some activated materials, the remainder of the facility was below accepted limits for radioactivity and the state government approved final demolition and clearance of the site.

Various factors influenced the decision about decommissioning of some shutdown US nuclear power plants. While some facilities have been or are being dismantled without putting the facility in a safe enclosure state (e.g. Trojan, Fort St. Vrain), the long safe enclosure periods for Dresden-1, San Onofre-1 or Indian Point-1 have origin in the utilities' considerations not to start dismantling unless other units located on site are also shut down.

Recently, the UK operator BNFL submitted its revised decommissioning strategy to national regulators in which it expects most shutdown reactor buildings to continue to stand for "around 100 years". This replaces the previous 135-year wait after shutdown to total dismantling. A lead Magnox station is scheduled to be dismantled 85 years after closure, although which one is still undecided. About halfway through its dismantling, BNFL will start on the second unit, and halfway through that, on the third. The schedule is devised so lessons learned can be applied as work progresses [5.8].

Independent from factors that are likely to prevail in the individual cases, it can be seen that the strategies eventually selected vary from country to country and even within one country. This is apparent from Table 5-IV, which shows a variety of strategies for shutdown reactor units in the USA [5.9].

Table 5-IV: Strategy for Decommissioning Reactors in the USA

Reactor unit	Type	Shutdown	Status
Indian Point 1	PWR	1974	SAFSTOR
Dresden 1	BWR	1978	SAFSTOR
Fermi 1	FBR	1972	SAFSTOR
GE VBWR	BWR	1963	SAFSTOR
Yankee Rowe	PWR	1991	DECON
CVTR	PHWR	1967	SAFSTOR
Big Rock Point	BWR	1997	DECON
Pathfinder	BWR	1967	SAFSTOR + DECON (Licence terminated)
Humboldt Bay 3	BWR	1976	SAFSTOR
Peach Bottom	HTGR	1974	SAFSTOR
San Onofre 1	PWR	1992	SAFSTOR
Fort St.Vrain	HTGR	1989	DECON (Licence terminated)
Rancho Seco	PWR	1989	SAFSTOR
TMI 2	PWR	1979	SAFSTOR
Shoreham	BWR	1989	DECON (Licence terminated)
Trojan	PWR	1992	DECON
La Crosse	BWR	1987	SAFSTOR

Legend: BWR=Boiling Water Reactor, DECON = Immediate Dismantling Decommissioning Option, HTGR = High Temperature Gas Cooled Reactor, PHWR=Pressurized Heavy Water Reactor, PWR=Pressurized Water Reactor, SAFSTOR = Long Term Storage Followed by Dismantling Decommissioning Option

5.3 in situ Disposal

Currently, the US NRC is seeking early public comment in developing changes to its regulations to permit *in situ* disposal (entombment) as an option in decommissioning nuclear power plants [5.10]. NRC regulations currently require that all decommissioning activities be completed within 60 years after a nuclear power plant permanently stops operating, unless exemptions are granted on a case-by-case basis. Entombment can reduce worker exposure to radioactivity because less handling is needed for contaminated materials left in place than for materials transported off-site. It also reduces the need for transporting radioactively contaminated materials from a nuclear power plant site to a disposal site.

Additional arguments encouraging the adoption of *in situ* disposal as a decommissioning strategy include:

- lack of available disposal sites;
- continued use of existing site support facilities;
- possible early releases of parts of the site for non-nuclear use.

It should be mentioned, however, that *in situ* disposal actually creates a new disposal site, perhaps at a location that was not considered earlier or is not optimal for this objective. An overview of studies, proposals and experience (see Figure 5-1) with *in situ* disposal as a decommissioning strategy is given in reference [5.11].

5.4 Recent Decommissioning Experience

In this subsection, a few descriptive examples are given of achievements and prospects at selected decommissioning projects. At Berkeley, UK, the preferred decommissioning strategy for the Magnox gas-cooled reactor is deferred dismantling, which essentially comprises three phases. The first phase involves removal of the fuel from the site. This takes place within a few years of shutdown. The second phase prepares the site for an extended period of Care and Maintenance. Preparations include retrieval and packaging of operational wastes, decontamination and dismantling of the fuel pond and construction of the safe storage structure. Most non-radioactive material, including the turbine hall, is removed during these preparations. The Care and Maintenance period is intended to take advantage of radioactive decay. At the end of the Care and Maintenance phase, the third phase, Site Clearance will take place. During Site Clearance, everything left on site, including the reactor, will be dismantled. Milestones completed to date include:

- spent fuel removed and consigned for reprocessing,
- fuel pond emptied and cleaned;
- majority of the conventional plant removed;
- boilers and main gas ducts extracted and stored;
- reactor sealed and reactor building structural alterations complete;
- turbine hall demolished and returned to green field;
- commissioning new facilities for retrieval, processing and storage of intermediate-level operational wastes.

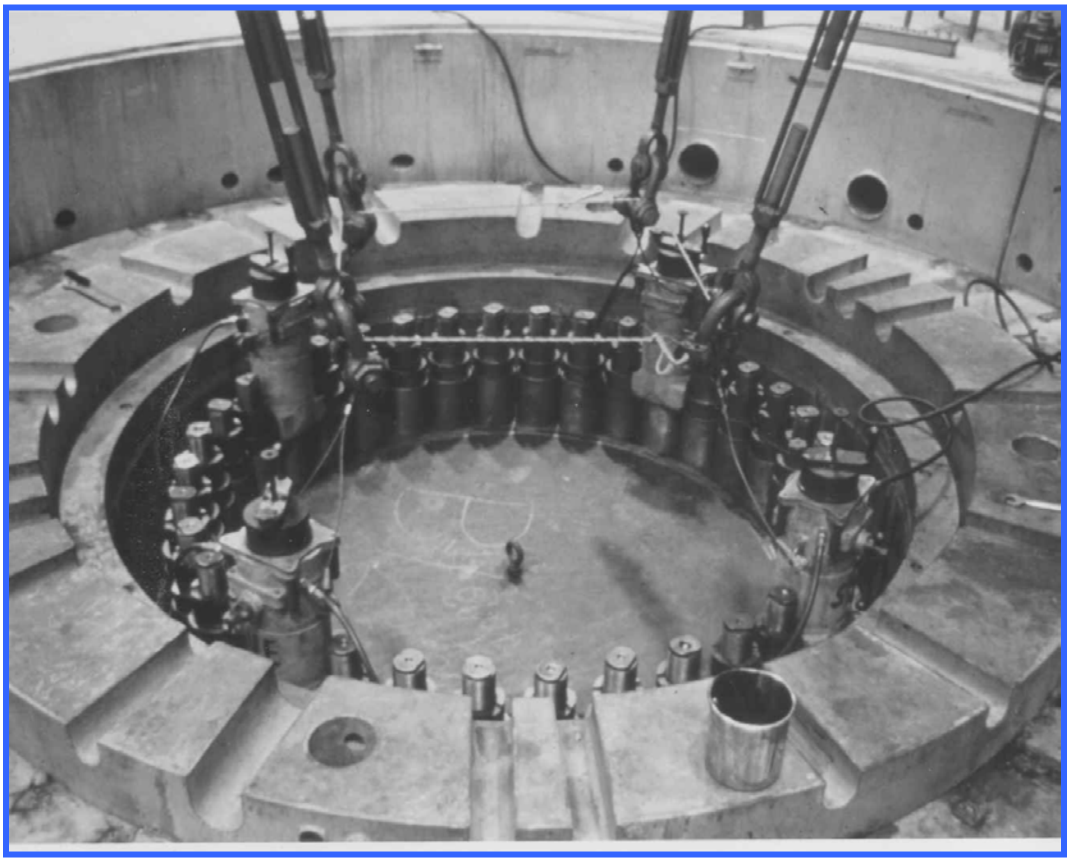

Figure 5-1: BONUS Reactor (an Old Entombment Project)
(this photo shows preparation of the reactor vessel for entombment)

The decommissioning project is expected to enter the Care and Maintenance phase by 2006.

A second UK project, the decommissioning of the Windscale Advanced Gas-Cooled Reactor (AGR) was meant to demonstrate the principles of reactor dismantling. Major achievements to date include:

- fuel removed and consigned for reprocessing;
- waste disposal route constructed;
- dismantling equipment and the decommissioning tools developed;
- items removed and disposed : majority of the conventional plant; boilers (see Figure 5-2) and main gas duct; and reactor shield floor and top dome.
- dismantling equipment and waste route commissioned;
- removal of operational waste complete;
- dismantling of the "hot box", a large cylindrical vessel used to distribute the hot coolant gas emerging from the reactor fuel channels to the four heat exchangers.

In the USA, the Trojan Nuclear Power Plant has started final radiation survey activities in accordance with its Licence Termination Plan, which was approved by the US NRC in early 2001. The final survey of the containment building marks the beginning of a long process that will ultimately result in termination of the Trojan licence and release of the site for unrestricted use. Final survey activities started in April 2001 with the containment dome. The final survey of the remainder of the containment building, which includes the vertical liner plate, floor liner plate, and reactor cavity was underway as of June 2002. Final surveys of other areas will begin upon completion of the containment building. The largest remaining project and the critical path to terminating Trojan's licence is the completion of the Independent Spent Fuel Storage Installation (ISFSI) Project, which includes the transfer of the spent fuel to the site-specific licensed ISFSI, which is scheduled for December 2002. The remaining major tasks associated with the ISFSI Project include oversight of the design, licensing, procurement and construction of spent fuel canisters, canister handling equipment, and loading of the canisters.

5.5 Conclusions (for Power Plant Decommissioning)

Radiological conditions, spent fuel and radioactive waste management, funding, economics and the development of suitable technology are important factors for selecting the decommissioning strategy. Although safe enclosure is the selected strategy for many shut down facilities, delay in dismantling may also have disadvantages such as loss of expertise and cost uncertainties. *In situ* disposal (entombment) is a decommissioning strategy worth consideration in special cases.

Currently, of the many large nuclear installations permanently shut down, only a fraction have been or will be in the near term totally dismantled and decommissioned to unrestricted release state. A trend towards immediate dismantling seems to emerge in some countries, but this is usually due to country-, site- or plant-specific conditions. In other countries, regulators seem to exert "moral suasion" to favour faster decommissioning strategies.

Figure 5-2: Removal of Heat Exchanger from the Windscale AGR

5.6 Topical Issue: Preliminary Scoping of the Decommissioning of Small Nuclear Facilities

The information in this subsection is based on a draft report that was prepared for the Waste Technology Section, Division of Nuclear Fuel Cycle and Waste Technology, Nuclear Energy Department, at the IAEA. The draft report describes an initial scoping study on the decommissioning of small nuclear facilities. The results and conclusions of the draft report should be considered as preliminary and have been described herein to illustrate the initial assessment conducted by the IAEA on the worldwide decommissioning of small nuclear facilities. For more information on this subject, please send an e-mail to DECOM@iaea.org.

Background

To date, decommissioning has focused on large facilities such as nuclear power plants, reprocessing plants and relatively large prototype, research and test reactors. There is, however, a much larger number of licensed nuclear facilities in the fields of medicine, industry and research. Most of these nuclear facilities are relatively small in size and complexity and, in general, present a lower radiological risk during decommissioning. Such facilities are located at medical treatment centres, biological and medical laboratories, industrial and manufacturing premises, service industries, research establishments and universities. These facilities are often operated by users who have not been fully trained or are unfamiliar with nuclear facility decommissioning and the associated safety aspects of facilities when they reach the end of their operating lives. In addition, for many small users of radioactive materials, such as sealed radioactive sources, nuclear applications are a small part of their overall business or process and, although the operating safety requirements may be adhered to, concern or responsibility may not go much beyond this. The minimum requirements for decommissioning could be overlooked resulting in avoidable delays, risks and safety implications (e.g. loss of radioactive materials and loss of all records). Incidents have occurred where innocent persons have been injured or put at risk.

In many cases, little consideration had been given to the problem of end-of-life management of small facilities with regard to regulations, responsibilities, decommissioning, waste management and finance. There is a tendency to do as little as possible in terms of planning and initiating decommissioning activities, which usually leads to longer term problems. The number of small facilities and users of radioactive materials and radioactive and radiation sources is very large and many exist in Member States without nuclear power and many have inadequate or no infrastructure for nuclear regulation, safety or waste management. In many instances, proper planning and implementation of decommissioning for small facilities is problematic for a variety of reasons.

Types of Facilities Considered

The main focus of the draft report was the decommissioning of medical, industrial and research facilities where radioactive materials and sources are produced, handled or used. The facilities covered in the draft document include, among others:

- medical facilities having small cyclotrons, particle accelerators, and radiotherapy units, as well as those using radioisotopes for diagnosis and treatment;
- industrial facilities such as those using irradiation and radiography; and
- research facilities such as those associated with the nuclear industry, pharmaceuticals and medicine, and universities.

Data Sources

The raw data used to prepare the draft document were gathered from several sources, compiled into several raw data tables, then used to develop an overall picture. The data sources included internal IAEA databases, extrapolations based on data such as GNP (Gross National Product), the results of various IAEA surveys, such as a survey of nuclear medical centres and gamma cameras in the developing countries, IAEA reports, and experts in the field.

Results of the Preliminary Scoping Study

The results of the preliminary scoping study were derived from a compilation of the raw data using the parametric framework of region-development status versus the number of countries, population, gross national product, land mass, and facilities, (medical, industrial, research).

- There are about 6 700 nuclear medicine centres worldwide with about 3 200 reported for developing countries. This number is likely to grow considerably as the countries develop and improve their medical infrastructure.

  The rate of facility decommissioning is very hard to determine since many factors are involved. If a facility has a useful life of about 40 years on average, perhaps 90 per year could be decommissioned in developed countries and 80 per year in developing countries.

- Of approximately 19 000 gamma cameras reported, about 3 000 are in developing countries. As medical infrastructures grow, so will the number of gamma cameras.

- In 2000, there were 246 particle accelerators (cyclotrons) for radionuclide production, of which 242 operating in 39 Member States were used for medical applications, particularly in relation to medical imaging technology (an increase of 19% since 1997). Most are in the USA, Germany and Japan but 40 are reported to be in developing countries. These facilities have a long lifetime, which could mean decommissioning for some could be up to 50 years from now.

  Since most are relatively new, there will be little demand for assistance in decommissioning them in the near future unless decommissioning is associated with shutting down or moving an entire nuclear medicine department. On the average, given a 50 year lifetime, about four per year could be decommissioned in developed countries and one per year in developing countries.

- The presence of gamma cameras and cyclotrons implies that a diagnostic radiology facility is in operation. The numbers generated in the estimates, however, are most likely related to x-ray facilities and not necessarily facilities using isotopes. It is safe to assume, however, that every nuclear medicine department has a diagnostic radiology facility. The decommissioning of these is generally tied to the overall nuclear medicine department. If the numbers given relate to isotope handling facilities then one can expect to decommission, on average, between 350 and 400 facilities per year in both developed and developing countries over the next several decades.

- Radiotherapy departments use both sealed and open sources. Sealed sources are mostly used for teletherapy and brachytherapy, as discussed below. The use of unsealed sources in medical radiotherapy was not specifically addressed in any of the data sources used for this document. Again, experience dictates that most nuclear medicine centres are also involved in open source radioisotope therapy (thyroid treatments, arthritic treatments, etc.). These facilities require some form of laboratory for source preparation. These are considered to be included with the nuclear medicine centres or with research labs.

- Of about 2 100 isotope teletherapy facilities reported, about 1 600 are in developing countries. This is not surprising since the per treatment costs associated with the use of accelerators is below that of isotope sources. Most developed countries are moving away from the use of isotope machines. In so doing, many of these are being donated to developing countries if the source is still useful since developing countries cannot afford the newest accelerators. The source life for a ^{60}Co facility is about 20 years, therefore, in developing countries an average of 80 per year either undergo a source replenishment or are removed from service. The current figure for developed countries is about 25 per year. Those removed from service should be under a decommissioning plan.

- About 2 600 brachytherapy facilities are in operation worldwide with a third of them in developing countries (about 900). Some countries are currently constructing additional brachytherapy units, especially in cardiology departments. In the USA and the UK, there is a vast expansion occurring in the field of vascular brachytherapy. The principal radionuclide is ^{90}Sr and a train of 16 small sources, each with an activity of about 185 MBq, is typical. If this trend continues it will eventually impact on developing countries.

Sources typically have service lifetimes varying from one to two years to 20 years or they have an undefined service time (^{192}Ir, ^{60}Co, ^{90}Sr). Since currently sources in developing countries are mainly ^{60}Co and ^{192}Ir, there probably will be a need to replenish about 50 sources per year. This does not necessarily mean that the facility is being decommissioned, only that the source is replaced. These spent sources, however do have to be tracked and eventually disposed of properly. In developed countries the number per year will be about the same, despite the larger number of sources. This reflects the different mix of isotopes used, including more ^{90}Sr, which has a useful lifetime of at least 50 years.

- There is a significant number of irradiators containing powerful sources (e.g. ^{60}Co) that have been used in research institutes but now need decommissioning. There are now estimated to be about 27 commercial large irradiators in the United States, compared with 54 a few years ago, at which time 9 had already been shut down in preparation for decommissioning. A recent survey, still underway, indicates that there are more than 130 worldwide, of which about 80 are reported in developing countries.

  So long as the sources have not leaked, the decommissioning of an irradiation facility is straightforward. If a leak has occurred, there is the potential for contamination of the facility and the environment with important consequences for decommissioning.

  In developing countries the use of industrial irradiators is expanding as techniques associated with plant growth, crop yields and food production expand. With more than 130 in existence one would expect a decommissioning rate of about 6 or 7 per year. More likely this figure will be slightly lower as the remaining facilities will undergo source replacement rather than full decommissioning. This would be proportioned about 3 to 2 for developed versus developing countries.

- About 30 000 sources are in use for industrial radiography worldwide with about 1/10 of these being in developing countries. This latter figure is considered to be low because of the nature of the use of these sources and the lack of regulatory oversight involved.

  Radiographic sources are usually contained in portable/mobile equipment and have been used extensively in many countries particularly for pipeline welding inspection. These sources, at least in developed countries, are mainly ^{192}Ir, which needs to be replaced about once per year. The potential decommissioning situations per year is about equal to the number of irradiators, about 20 000 for developed countries and about 2 000 for developing countries.

- About 130 000 industrial gauging application facilities were reported, less than 10 000 are in developing countries. This could be a significant underestimate as many resource-based industries have brought sources into these countries without any regulatory oversight. In fact, some of these countries do not register such sources, even if they know they exist.

The sources in most common use for gauging last for many years only become a problem when abandoned or lost. Assuming a lifetime more related to the equipment or process they are used in, one might suggest a lifetime of 50 years. This would require decommissioning about 2 000 per year in developed countries and about 150 per year in developing countries.

Research Facilities

No separate categorization of research facilities was possible from the data sources available. It is assumed that the data cover industrial research facilities, education and university research facilities, biomedical research facilities, etc. The lifetime of these facilities is hard to predict but probably spans 40 to 50 years, unless moved or taken out-of-service.

The data gathered indicate that there are about 320 000 such facilities worldwide, almost evenly split between the developed and developing countries. Assuming a facility lifetime of 40 years means that about 4 000 per year will undergo decommissioning in both developed and developing countries.

Summary and Preliminary Forecast

The data gathered and discussed above are summarized in Table 5-V. The table also forecasts, for developing countries, the total number of facilities to be decommissioned in the medium-term (5 to 10 years from now) and in the long-term (more than 10 years from now). These forecasts are based on the average number per year, combined with comments made earlier on the age and lifetime of facilities. Also, the development trends discussed play a role as facilities are either upgraded, expanded, or replaced.

Conclusions

There is an extensive array of small nuclear facilities in developing countries worldwide. To date, there has been little attention focused on the planning and implementing of decommissioning of these facilities except for a few problem areas that have caused concern.

The rate of facility decommissioning is very hard to determine since many factors are involved. Radioisotope laboratories or medical facilities may be replaced or upgraded as a Member State's development status improves. Some facilities may cease to function due to changes in government or regimes. Areas of strife may result in damaged or abandoned facilities. This is all independent of the normal useful lifetime of a facility since, in many cases the life is indefinite as the spent sources can be replaced. Thus attempting to determine need based on useful life of a source is not a very good measure but it may be the only one available.

The preliminary forecast for decommissioning the various types of facilities in developing countries is summarized in Table 5-V. The preliminary forecast is based on first order estimates of the future numbers of facilities being put into service versus those being taken out of service, as described in "Results of the Preliminary Scoping Study". The forecast indicates that the number of facilities that will require decommissioning in the future is growing as more countries develop their infrastructure in health care and industry.

The cost of having to deal with decommissioning problems after accidents occur is very high, especially when personnel exposure is involved. Also, the environmental cleanup is becoming more rigorous and extensive and therefore more costly unless forward planning is instituted.

Table 5-V: Decommissioning Forecasts for Small Nuclear Facilities Worldwide

FACILITIES		Estimated Worldwide			Average Number Decommissioning per year		Developing Country Forecasts	
		Developed Countries	Developing Countries	Total	Developed Countries	Developing Countries	Medium-Term (5-10 yr)	Long-Term (>10 yr)
MEDICAL	NUCLEAR MEDICINE CENTRES	3540	3167	6707	90	80	200	2800
	DIAGNOSTIC RADIOLOGY	13855	16413	30268	350	400	1000	14000
	GAMMA CAMERAS	15685	2685	18370	n/a	n/a	n/a	n/a
	CYCLOTRONS	202	40	242	4	1	5	35
	TELE-THERAPY (Co-60, Cs-137)	491	1602	2093	25	80	600	1000
	BRACHY-THERAPY	1662	888	2550	50	50	200	600
INDUSTRIAL	INDUSTRIAL IRRADIATORS	50	81	131	3	2	8	70
	INDUSTRIAL RADIOGRAPHY	24309	2757	27066	20000	2000	10000	?
	LUMINIZING APPLICATIONS	558	0	558	n/a	n/a	n/a	n/a
	GAUGES, ETC.	120621	8108	128729	2000	150	800	7000
RESEARCH	RESEARCH FACILITIES	162810	156499	319310	4100	3900	10000	140000

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