Studies on Future Decommissioning of the Swiss Nuclear Power Plants

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The financing of future decommissioning of the Swiss nuclear power plants and the permanent, safe disposal of the wastes arising therefrom is secured by payments into a legally established decommissioning fund. In order to update the required level of payments into the fund, which have been ongoing since 1984, 20 years after the first study the costs of decommissioning have been re-calculated from scratch using complete decommissioning studies for each plant. Following the specification of boundary conditions which take into account the specific situation in Switzerland, decommissioning concepts are drawn up for the individual plants. The measures outlined in these concepts are integrated into a cost structuring plan and the decommissioning costs are then calculated using standard models (e.g. STILLKO). The radiological inventory, which is re-calculated for each plant, has a significant influence on costs. Furthermore, the disposal costs which can be allocated to decommissioning waste have to be determined; these are based on a concept in which only two types of containers are considered for disposal. The studies have resulted in decommissioning costs which, with a range between 200 and 390 million €, are comparable with costs in other countries.

1 Introduction

The obligation of the owner-operator of a nuclear facility to dispose of all hazardous sources following decommissioning of the facility is embodied in the Swiss Atomic Act of 1959 [1]. In 1978, this obligation was made more specific in a Federal Government Ruling on the Atomic Act [2], which states that the owners of nuclear facilities are required to make financial contributions to a joint decommissioning fund which is under the supervision of the Federal Council. The level of these contributions should be sufficient to cover the costs of decommissioning and possible dismantling of plants which are no longer operational. The fund presently contains around 600 Mio. € and assumes an operational lifetime of 40 years for the power plants. Decommissioning costs are subject to revision every three years (see [3]). With a view to updating the model used for planning financial reserves, the costs will be recalculated from scratch by the end of 2001.

Completely new decommissioning studies are necessary for this purpose. As was the case for the studies completed in 1980, the aim of these studies is complete removal of the plants down to a depth of 2 m below the earth's surface ("green field" condition). The key requirements to be met are transparency and the possibility to make full cross-comparisons between the individual power plants. A recent study (from the year 1998) already exists for the Beznau NPP (KKB, 2 PWR Westinghouse; each 380 MW_{el}, in operation since 1969 and 1971 respectively) and similar studies for the NPP's Mühleberg (KKM; SWR GE; 355 MW_{el}, in operation since 1972), Gösgen (KKG; PWR Siemens; 1'020 MW_{el}, in operation since 1979) and Leibstadt (KKL; SWR GE; 1’145 MW_{el}, in operation since 1984) are currently being prepared by the company NIS Ingenieurgesellschaft mbH. Information required on activity inventories and disposal costs is provided by the National Cooperative for the Disposal of Radioactive Waste (Nagra).

2 Defining Boundary Conditions and Assumptions

Since actual decommissioning of the nuclear power plants still lies relatively far in the future, it is important, at the beginning of the investigations, to accurately define the boundary conditions, assumptions and input data used to calculating the decommissioning costs for the individual plants. The results of these investigations then serve as a basis for the studies.

The following key boundary conditions and assumptions apply:

1. Final shut-down of the plants is followed by a so-called post-operational phase, which is still covered by the operating licence. Key activities at the plant during this phase are management of the fuel elements and all existing operational wastes and media, as well as drainage, rinsing and drying of the different systems. The costs of this work are determined separately by the individual plants and are not defined as decommissioning costs. Decontamination of the systems is, however, part of decommissioning.
2. Decommissioning (dismantling of the reactor, conditioning, (waste)management and removal of structures) begins 5 years (duration of post-operational phase) after final shut-down, i.e. there is immediate dismantling without a phase of safe containment.
3. In terms of current legislation and regulations, decommissioning requires a licence from the relevant authority. The documentation supporting the licence application requires to present the whole concept (including an environmental impact statement). Once the licence has been granted, individual stages proceed according to the "step-by-step" method with clearance by the authority.
4. The effects (in terms of costs and deadlines) of public participation in the licensing procedure are not taken into consideration.
5. It is implicit in the procedure that the supervisory authority and their experts will monitor and review the progress of work over the entire dismantling period.
6. Transport activities are carried out in compliance with current national provisions [4] and the new IAEA regulations, which are valid from 2001 [5].
7. Dismantling of installations and demolition of structures of the buildings shown in Table 1 are included in the cost calculations.
8. The radioactivity inventory is made up of two components:
   - activated components (in the area of the neutron field),
   - contaminated components.

   The activity inventory has been re-calculated by Nagra for the new decommissioning studies (see section 4.3). For contamination, values have been taken over from the existing study of 1980 and supplemented by empirical values calculated in the meantime. Natural radioactivity is not considered.
9. All installations from the controlled zone are assumed to be contaminated until such time as control measurements show that no unacceptably high contamination is present. The relevant decision is based on the exemption limits specified in the current Swiss Radiological Protection Act [6].
10. All conventional structures and terrain at the site are checked for contamination. It is assumed that no contamination is present.
11. The technologies and tools used for decommissioning are assumed to be state-of-the-art.
12. It is assumed that suitable facilities are available either at the site (partly newly constructed for the purpose) or externally (incineration) for the treatment, conditioning and incineration of residual materials. Once the systems have been decontaminated, which leads to a reduction in dose, components are further decontaminated only for the purpose of subsequent clearance. Melting with a view to recycling is not considered.

Table 1 Structures of the individual plants considered in the decommissioning study (listed with their German nomenclature)

KKW Beznau	KKW Mühleberg	KKW Gösgen	KKW Leibstadt
Gebäude mit kontrollierter Zone:	**Gebäude mit kontrollierter Zone:**	**Gebäude mit kontrollierter Zone:**	**Gebäude mit kontrollierter Zone:**
Sicherheits-/Reaktorgebäude, Block 1 Sicherheits-/Reaktorgebäude, Block 2 Nukl. Hilfs- und Nebengebäude, Block 1 Nukl. Hilfs- und Nebengebäude, Block 2 Nukl. Teil des Betriebsgebäudes	Reaktorgebäude - Drywell Reaktorgebäude - ausserhalb Drywell Maschinenhaus Maschinenhaus - Anbau Süd Aufbereitungsgebäude Zwischenlager für radioaktive Abfälle Hochkamin Kaltkondensatbehälter Betriebsgebäude - kontrollierte Zone	Reaktorgebäude, Innenraum Reaktorgebäude, Ringraum Reaktorhilfsanlagengebäude, Abfallager Abluftkamin	Reaktorgebäude (Drywell) Reaktorgebäude Radwaste Abgasfiltergebäude Reaktorhilfsanlagen Notstandsbunker BE-Lagergebäude Dekont.-Gebäude Aktivwerkstatt Maschinenhaus Haupt- & Hilfstrafos 10 kV-Schaltanlage ZL für radioaktive Rückstände Fundament KAKO Fundament ZSW-Behälter
Gebäude ausserhalb kontrollierter Zone:	**Gebäude ausserhalb kontrollierter Zone:**	**Gebäude ausserhalb kontrollierter Zone:**	**Gebäude ausserhalb kontrollierter Zone:**
Maschinenhaus Trafoanlagen Konv. Teil des Betriebsgebäudes NANO-Gebäude mit SIDRENT BOTA-Gebäude Versorgungskanäle zum BOTA-Gebäude Dampferzeuger-Lager PRIGA-Gebäude ERGES-Gebäude Werkhalle OC Kühlwassereinlauf- und auslaufbauwerk Lager-/Werkstattgebäude Mehrzweckgebäude *einige Gebäude sind für jeden der Blöcke vorhanden (z.B. NANO), andere werden für beide Blöcke genutzt (z.B. Mehrzweckgebäude)*	Auslaufbauwerke Areal Aareuferweg Betriebsgebäude Bürocontainer-Ost Büropavillon Bürocontainer-Süd Bürocontainer-West Betriebsführungszentrum, inkl. Meteomast Fäkalienpumpwerk Garagengebäude Wächter- und altes Feuerwehrlokal Gerüst-Lagerhalle Hilfsgebäude Lagergebäude Holz- und Rohrlager Informationspavillon Kabelkanal Lagerhalle Montagehalle Mehrzweckgebäude Pumpenhaus Pumpenwerk Rewag Reservoir Runtigenrain SUSAN-Gebäude Unterstation West Verwaltungsgebäude Warenkontrollstelle Werkstattgebäude	Schaltanlagengebäude Maschinenhaus Nebenanlagengebäude-Notstromdiesel, Notstromdieselgebäude Nebenanlagengebäude-Wärmezentrale Werkstatt- und Lagergebäude Garagen- und Feuerwehrgebäude Einlaufbauwerk II Nebenkühlwasserpumpenhaus Hauptkühlwasserpumpenhaus Einlaufbauwerk I Entkarbonisierungsanlage Kühlturm Notspeisegebäude Kabel/Rohrkanäle, Düker (Kanal-Abschnitte) Notstandsgebäude Verwaltungsgebäude Kantine und Tiefgarage Sonstige	Betriebsgebäude Betriebsgebäudeanbau Vollentsalzungsanlage Haupt- und Hilfstranformatoren Umzäumung 380 kV-Freiluft-Schaltanlage Notstromdieselanlagen A, B, HPCS Werkstatt-und Lagergebäude Gasflaschenlager Eisensulfat-Dosieranlage Lagergebäude Lagerhalle MH Ost Revisions-Werkstatt Mehrzweckgebäude Lagerhalle bei Kühlturm Hauptkühlwasser Pumpengebäude Nebenkühlwasseranlage Kühlturmzusatzwasser-Aufbereitung Notkühlwasseranlage A, B, HPCS Kühlturm Abluftkamin Abwasser-Reinigungsanlage Strassen und Plätze Chalet Fremdpersonalgebäude Schleuse zum NKW (Tor-West) Fahrzeugschleuse Ringkanal und Verbindungskanäle 50 kV-Schaltanlage Eingangsgebäude, Garagen, Feuerwehr Meteo-Turm Ausbildungs-und Informationszentrum

13. The radioactive wastes arising during decommissioning are conditioned and packaged in accordance with currently applicable regulations and agreements with the Swiss Federal Nuclear Safety Inspectorate (HSK) and Nagra. It is assumed that a repository will be available at the time of decommissioning and the costs of interim storage are therefore ignored in the studies. These are already contained in waste management costs and in the operating costs for the centralised interim storage facility (ZWILAG) at Würenlingen.
14. The containers for packaging radioactive waste (Table 2) are assumed to correspond to Nagra's requirements (chapter 4.1).
15. The costs of transporting waste from the power plants to the repository are assumed to be 2’600 € per container, irrespective of the distance of the individual plants from the repository.
16. In principle, dismantling of the building structures should be carried out down to a depth of 2 m below the surface of the NPP site. Facilities and installations are also dismantled to greater depth and the building surfaces are decontaminated where necessary.
17. Wherever possible, non-radioactive concrete rubble generated by demolition of structures is used to fill excavations and voids. Of the remainder, 50% is transported to a disposal site and 50% is recycled (e.g. in road construction).
18. Suitably qualified personnel and standard compensation rates are assumed for performance of the work. It is assumed that persons with knowledge of the plants will be available.

19. Dismantling of contaminated and activated components and demolishing the activated biological shield and the drywell (BWR) are carried out in two-shift operation.
20. Guarding of the facility, at an appropriate level, is carried out around the clock.
21. Taking into account the above boundary conditions and assumptions, the accuracy of the overall results of the decommissioning studies will be in the range of ± 10%.
22. The price basis for determining costs is the 4th quarter of the year 2000.
23. All costs are given without value added tax. This is shown separately in the study (as per 1st January 2001).

3 Decommissioning Concept and Cost Structuring Plan

Based on the boundary conditions and assumptions mentioned above, a decommissioning plan was drawn up for each of the plants. These plans take into account practical experience from ongoing decommissioning projects and national conditions in Switzerland, such as the legal framework, waste management strategies, working conditions, etc. This also includes selection of the technologies to be applied (taking into account radiation exposure of personnel), the required personnel capacity, the duration and sequence of the individual measures and the handling and management of dismantled components and parts.

Taking into account considerations of economic viability, the technologies and procedures required for decommissioning are selected in accordance with the principle of avoiding unnecessary exposure to personnel and avoiding production of radioactive waste. These targets can be achieved by

- employing procedures and technologies which release no, or very little, aerosols,
- implementing measures for retention of aerosols,
- using procedures which require spending no (or only a short) time in areas with a high local dose rate (e.g. use of remote handling equipment),
- using procedures which produce low volumes of secondary waste,
- using procedures which contaminate building structures and components either only slightly or not at all.

Mechanical Separation Procedures

These include all metal removing separation techniques such as sawing, milling, shaving, grinding, etc. The material produced during separation is in the form of cuttings or splinters. No slag is produced and only very few aerosols.

In principle, all components can be dismantled using such mechanical procedures. However, with increasing wall thickness, large reactive forces occur, making massive construction of the tool mounts necessary.

As tools wear out during separation procedures, when constructing the tool mounts and in the planned guidance for cutting, it is important to be able to change tools without any complications. There must be the possibility for intervention in the case of defects.

Mechanical separation procedures can be used in air and underwater.

Thermal Separation Procedures

These include procedures such as oxyacetylene cutting or plasma cutting. It is possible using these techniques to have guidance for cutting on components with complex geometry.

If thermal separation techniques are used in air, dust and aerosols are released, which can cause contamination of surrounding surfaces. It is necessary to use additional suction equipment or dismantling boxes (Caissons) to retain the aerosols.

Applying the techniques underwater also releases particles and aerosols, but these are retained to a large extent in the water.

Hydraulic Separation Procedures

These procedures can be used to dismantle metallic materials and concrete. Of the wide range of techniques belonging to this group, the high-pressure water techniques are of particular interest. This involves adding abrasive materials to high-pressure water jets, which are used for material removal.

The abrasive materials are not regenerated as the grain size of the particles is reduced and the materials cannot be reused. They are suctioned off together with the abraded material and disposed of as radioactive waste.

This technique can be used in air or underwater for wall thicknesses up to 300 mm. It has a particularly low dust and aerosol production, but has the disadvantage that it generates relatively large amounts of secondary radioactive waste.

Remote Handling

Particularly in the case of activated or highly contaminated components, working by remote handling is often the only possibility. A wide range of techniques is available, e.g. extension mast, self-stressing ring supports, electro-master-slave manipulators (EMSM) and special gripping and lifting equipment. These remote handling tools can be used as supports for mechanical, hydraulic or thermal separation equipment.

In this case, conventional remote handling tools are most suitable as they can be adapted to the special technical, radiological and local conditions.

The following features are important:

- good handling capability for the separation equipment,
- easy tool change, possibility for intervention,
- easy handling of dismantled pieces during outward transfer and packaging,
- easy means of further treatment (in situ dismantling or dismantling at a separate location),
- good accessibility in the case of intervention.

Shielding

Shielding measures serve as an aid during dismantling and have the effect of reducing the radiation exposure of the workers. A distinction is drawn between temporary and permanent shielding.

Temporary shielding is set up for individual, sometimes short-duration, work tasks. It usually takes the form of walls made up of individual elements which can be constructed and dismantled rapidly.

Permanent shielding, e.g. caissons, provides protection from direct radiation but also creates a defined environment which is separated, in terms of ventilation, from the rest of the controlled zone, thus preventing spreading of aerosols. For example, permanently installed caissons with remote handling equipment are used for dismantling the reactor pressure vessel and its internals.

Decontamination

Particular significance is attached to decontamination during decommissioning. On the one hand, decontamination before and during dismantling work has the effect of reducing the local dose rate at the work location, with an associated reduction in exposure to personnel; on the other hand, effective decontamination procedures reduce the mass of radioactive waste which will ultimately require to be disposed of.

The appropriateness of a procedure depends, in each case, on the particular application and is determined principally by the expected level of success, the necessary handling duration, the arising of secondary waste and the dose to decontamination personnel. The geometry, surface composition and material of the component being handled, as well as the type of contamination, also require to be taken into consideration.

In addition to classification of decontamination procedures according to type, i.e. into

- mechanical and
- chemical or electrochemical procedures,

decontamination techniques are also divided according to area of application into:

- system decontamination,
- decontamination accompanying dismantling work,
- decontamination of removed parts,
- decontamination of building structures,
- decontamination of tools and equipment,
- decontamination of transport installations and containers for disposal.

Mechanical procedures range from simple washing and brushing down to abrading, removal of the surface using jets containing abrasive materials or mechanical procedures producing shavings. These procedures are used in the case of external, easily accessible surfaces of all materials with loose, dust-type to strongly adhering contamination. Partial decontamination of surfaces is possible using mechanical procedures but the disadvantages of these are their restriction to accessible surfaces, the intensive work effort (in terms of personnel) and the measures which have to be taken against spreading of dust.

The success of chemical decontamination procedures depends on the aggressiveness of the material used, the period of application and the temperature. One advantage is the possibility to decontaminate internal surfaces which are difficult to access. The long reaction times, the diminishing effect of the decontaminant with increasing chemical saturation and, depending on the procedure used, the arising of secondary waste, are all potential disadvantages.

Electrochemical decontamination allows large amounts of material to be removed, meaning that surfaces where radionuclides have penetrated into the base material via diffusion processes or which react insufficiently to chemical procedures can also be decontaminated.

Recycling and Management of Radioactive Residues

Once they have been dismantled, plant components have the status of a residue. Different criteria are used to decide whether and how the dismantled component can be recycled without any risk. For all structural parts and components from the controlled zone, it has to be demonstrated by appropriate measurements that their specific radioactivity is below an exemption limit. Depending on the level and type of radioactivity of a residual material, the following management pathways are possible:

- unrestricted clearance,
- disposal as radioactive waste.

Radioactive residues and dismantled plant components can be recycled as conventional material provided their activity levels do not exceed the nuclide-specific exemption limits specified in the Swiss Radiation Protection Act [6] (e.g. 1 Bq/g or 3 Bq/cm^2 for Co-60) and the local dose rate 10 cm from the surface after background subtraction is less than 0.1 µSv/h. Measurements are carried out to demonstrate that the exemption limits have not been exceeded. For clearance of a material, it has to be shown that both the surface-specific and mass-specific values (taking into account the nuclide-specific additive formula), as well as the dose rate criterion have been observed. For this purpose, the measured specific values (mass- and surface-specific) can be determined over a larger mass or surface area.

All materials which are below the exemption limits are suitable for unrestricted clearance; decontamination can be carried out prior to the clearance measurements. Demonstrating that the materials are below the limits is done in several steps:

- preliminary investigation to determine the nuclide vector,
- pre-treatment of the item to be measured,
- outward transfer measurement,
- deciding measurement,

- control measurement,
- clearance by radiation protection of the plant,
- granting of clearance by supervisory authority,

In the case of unrestricted clearance, the further use of the material is irrelevant. Once they have been cleared, materials are no longer considered to be radioactive and can be recycled without restriction or disposed of as conventional waste.

If recycling of a radioactive residue is technically unfeasible or economically unjustifiable, then it has to be disposed of as radioactive waste.

The studies assume that arising radioactive wastes will be disposed of in accordance with Nagra's guidelines.

Sequence of Activities for Decommissioning

Planning activities associated with the selected decommissioning variant (i.e. immediate dismantling) begin during the operational phase. Immediately after the end of the post-operational phase, all installations are dismantled, residual materials are recycled wherever possible and radioactive waste is managed appropriately.

When dismantling begins, the installations are still in an operational state and can thus be used directly as they are for the dismantling work. Conversion measures and introduction of new installations are essentially restricted to the conditioning and (waste)management facilities.

Dismantling of the plant is carried out in the following sequence:

- dismantling contaminated systems and components,
- dismantling activated internals of the reactor pressure vessel,
- dismantling the reactor pressure vessel,
- dismantling the activated part of the biological shield,
- dismantling the drywell internals (BWR only),
- removal of the remaining steel installations,
- decontamination and clearance of structures and site,
- conventional demolition of structures or their reuse respectively.

Work on recycling of residual materials and conditioning of radioactive wastes is carried out in parallel with the above activities.

The dismantling work is carried out in such a way as to ensure protection of personnel and the environment at all times. This objective is achieved mainly by using existing barriers and the filters of the ventilation facilities.

Planned measures are defined within the framework of individual work steps and a plant-specific activity plan and time schedule are prepared. The work steps are clearly structured, using a cost structuring plan, into different project levels such as

- work packages (e.g. planning, preparation, dismantling, radiation protection, (waste)management),
- work areas (e.g. drywell, reactor building, turbine hall, service buildings),
- work steps (e.g. planning the conditioning facilities, installing dismantling tools, dismantling the steam generator, dismantling the reactor pressure vessel, clearance measurements for building surfaces, container costs, allocated disposal costs).

4 Activity Inventories and Final Disposal

4.1 Decommissioning Containers for the Swiss Repository

With the exception of the fuel elements (and waste from reprocessing), the decommissioning waste from the NPPs will be disposed of in a deep geological repository for low- and intermediate-level waste

(L/ILW). The simple working procedures and optimum waste configuration foreseen for the caverns will be achieved partly by adopting a container concept in which only two standardised container types (see Table 2) are emplaced; these have different dimensions and are designed on the basis of shipping class IP-3. In the case of direct emplacement of waste, it is planned to use container type EC1 for waste which is bulky but not too heavy and the smaller container type EC2 for compact, heavy individual pieces (in each case with subsequent cementation). Delivered 200-l drums or e.g. mosaic-type containers (for strongly activated wastes) are not directly disposed of but are put into such EC containers and the voids filled with cement. The activities per container are limited by the relevant transport regulations [4,5] and not by the acceptance criteria of the repository. In addition the specific heat production per container volume should not exceed a target value of 5 W/m^3.

Table 2 Main types of containers used for decommissioning waste and the costs of their disposal

		Container types	
Containers		EC1	EC2
External dimensions	l [mm]	4'440	2'438
	w [mm]	2'438	2'438
	h [mm]	2'400	2'402
Internal dimensions	l [mm]	4'040	2'038
	w [mm]	2'038	2'038
	h [mm]	1'952	1'951
Material		Concrete	
Volume	[m^3]	26	14
Maximum mass (loaded)	[Mg]	80	56
Acquisition costs	[€]	9'600	7'600
Disposal costs			
(theoretical) full costs	[€/m^3]	10'500	10'600
allocatable costs	[€/m^3]	3'200	3'300

4.2 Costing Model for Decommissioning Waste

Various models, which are dependent on country-specific boundary conditions, can be used to calculate disposal costs. The most simple is a "full costing model" in which the volume-specific costs (costs/m^3) are derived from splitting the total costs of the repository over the waste volume. At present, separate funds are foreseen in Switzerland for the financing of waste management and for decommissioning. Accordingly, the total costs of waste disposal can be divided into a fixed component and a variable component; in the case of decommissioning waste, the former is allocated to the waste management fund and the latter to the decommissioning fund.

The fixed costs (waste management fund) arise from the actual construction of the repository (e.g. preparatory measures, construction of the repository excluding break-out of the cavern volume for decommissioning waste, filling and closing the caverns, decommissioning of the repository, compensation payments, supervision). The calculation of these costs takes account of the concept for the facility and its operation and of the (design-) total waste volume of all Swiss wastes.

The decommissioning costs (decommissioning fund) are made up of the decommissioning and conditioning costs and "disposal costs allocated to decommissioning waste". The latter result from variable additional expenditures which can be allocated directly to the produced waste packages and consist of two elements:

- The costs which are coupled directly with the waste package in question, in the sense of "what is the cost of disposing of a special package or what could be saved if producing this package could be avoided?"
- The component of disposal costs which is indirectly coupled with decommissioning, such as e.g. the need for (additional) disposal zones, acquisition costs for containers, personnel costs, shielding measures for these packages.

Using this model results in costs allocated to decommissioning waste which are specific to package classes. For the package types principally used, these specific costs are shown in Table 2 as disposal costs per m^3 of delivered package (status as of 2000) for the "allocated cost" model used here. For comparison purposes, the values for a purely theoretical "full cost model" are also shown.

It is clear that, particularly compared with the mosaic-type containers (which are however essential for strongly activated components), the decommissioning containers EC1 and EC2 represent a more economic option. An optimised packaging concept should be pursued to minimise costs, in which case the decommissioning logistics of the power plant in question have to be taken into account.

4.3 Determining the Radiological Inventory

The conditioning and disposal costs associated with decommissioning waste are calculated based on a re-evaluation of volumes and inventories previously based on modelling assumptions. The dose- and disposal-relevant nuclide inventories of the base material of the decommissioning components which are required for this purpose are determined by activation calculations carried out by Nagra, and are verified by random measurements. One important question relates to optimisation of the collective dose and the loading of the containers foreseen for disposal (see section 4.1). Reactor components are broken down into partial volumes for which integrated (and constant) neutron fluxes are then determined (by neutron transport calculations) in the thermal, epithermal and fast range. The 3-group activation program which is then used works with spectral indices THERM, RES, FAST and precondensed "infinite dilution" activation cross-section libraries [7]. The material inventories are taken from a comprehensive databank managed by Nagra, which contains specific sample measurements of inactive material of the components, supplemented by data collected worldwide.

Figure 1 shows the procedure for the reactor of KKM. For all partial volumes

- E1 - E28 of the internals of the reactor pressure vessel,
- R1 - R18 of the reactor pressure vessel,
- B1 - B36 of the biological shield,
- D1 - D9 (with further subdivisions) of the drywell

specific activities are determined which, given the extreme variations in neutron fluxes, cover several orders of magnitude. The degree of detail reflected in the sizes of the partial volumes represents an acceptable compromise between the desired level of accuracy and the intensive effort involved in the activation calculations. It should also be noted that materials in the areas between the reactor pressure vessel and the biological shield and between the biological shield and the concrete of the drywell, as well as components outside the regions covered in Figure 1, are also inventoried with the activation calculations.

Table 3 shows examples of calculated activities for the central radial areas. It should be noted (see [7]) that, because of activation and fission of uranium impurities, fission products and actinides are also present in the base material.

These calculations for the NPPs Beznau, Gösgen, Leibstadt and Mühleberg are supplemented by estimates of the inventories for surface contamination and form the basis for preparing a complete inventory of reactor components.

Table 3 Specific activities in [Bq/g] 5 years after 40 years operation time for partial volumes of the KKM reactor in the central radial area. "$\Sigma\alpha$" gives the activities of all alpha-emitters, "total" gives the total activity including nuclides which were calculated but are not shown.

Nuclide	Internals E 16	Pressure vessel R 10	Biological shield mean value B 17 / 18	Drywell (Concrete) D 6-1
Co-60	4.3 E+9	8.2 E+5	3.6 E+3	5.1 E+0
Fe-55	6.4 E+9	6.6 E+6	1.2 E+3	8.9 E+0
Ni-63	1.8 E+9	1.6 E+5	4.5 E+1	< 1.0 E+0
Cs137	1.1 E+5	9.5 E+0	< 1.0 E+1	< 1.0 E+0
$\Sigma\alpha$	5.8 E+3	9.1 E+0	9.4 E-1	2.5 E-1
total	1.3 E+10	7.8 E+6	5.3 E+4	1.8 E+2

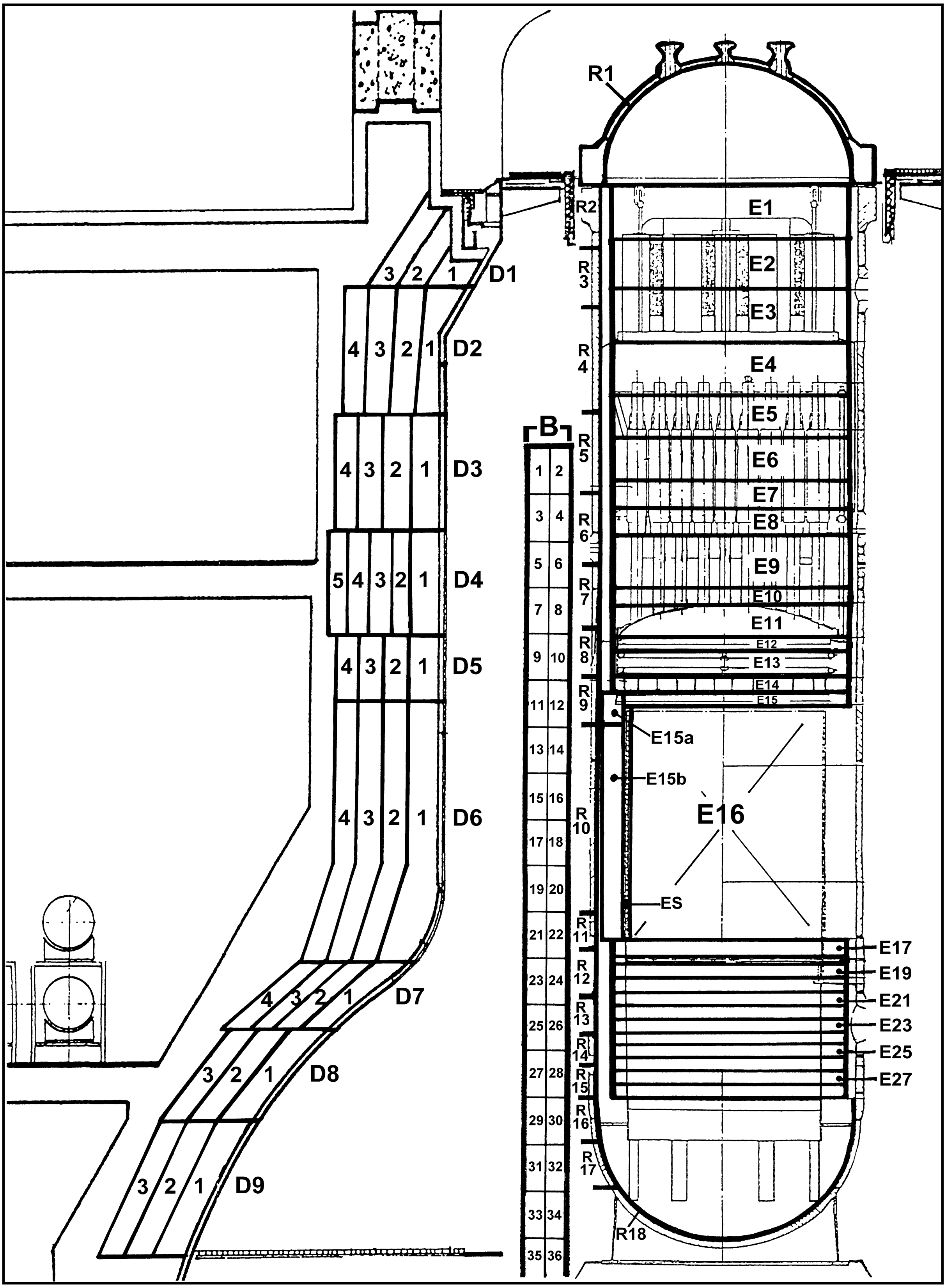

Figure 1 Division of the KKM reactor into partial volumes for the activation calculations:
E = reactor pressure vessel internals; R = reactor pressure vessel;
B = Biological shield; D = Drywell

5 Determining Decommissioning Costs

Decommissioning costs are calculated using the STILLKO 2 program, which was developed by NIS Ingenieurgesellschaft mbH on behalf of the German electricity utilities [8-10]. Decommissioning concepts, procedures and time schedules, determined as a function of plant conditions, are input to the program. The costs are calculated using plant-specific data (masses, surface areas, activation and contamination values, etc.). The work steps defined in the cost structuring plan are calculated individually using specific work and costing factors derived from practice.

The following are determined for each work step:

- the required work effort,
- the number and qualifications of required personnel, taking into account local conditions and the expected radiation exposure,
- the duration of the work step,
- the costs,
- the expected collective dose, taking into account the principles of justification and optimisation set out in articles 5 and 6 of the Radiation Protection Act [6].

Adding together the results for the different work steps gives the results for different areas, which are in turn added together to give the total results for work packages and for the whole project.

A detailed presentation of the STILLKO 2 program can be found in several other publications [11-13] and, for this reason, it is not discussed further here.

6 Results of the Decommissioning Studies

Calculation of decommissioning costs using the STILLKO 2 program, and taking into account the boundary conditions, assumptions and procedures mentioned above, gives the results presented in Table 4 for the individual Swiss power plants.

The duration of the planning and licensing phase for decommissioning, which to some extent runs parallel with the post-operational phase, is largely the same for all the power plants. The exception is the two-unit plant Beznau, for which it will be somewhat longer. While the dismantling of contaminated installations and structures in the case of the not very complex structures of the Mühleberg plant will take less time than for the newer plants at Gösgen and Leibstadt, the time required for demolition of structures is more or less the same for all the plants.

There are considerable differences in terms of the masses to be dismantled and demolished. For the newer plants at Gösgen and particularly Leibstadt, these masses will be significantly larger than for the older plants at Beznau and Mühleberg. The mass for disposal, and consequently the required disposal volume and allocated disposal costs, are only slightly larger for the 1’020 MW_{el} Gösgen PWR than for

Table 4 Key results of decommissioning studies

Results		Nuclear Power Plant			
		Beznau	Mühleberg	Gösgen	Leibstadt
Duration					
Planning and licensing	[a]	4	3	3	3
Dismantling of cont. Install., incl. building clearance	[a]	6.5	4.5	7	8
Demolition of structures with controlled zone	[a]	2.5	1.5	2	2.5
Personnel time requirements, collective	[a]	1'610	1'100	1'560	2'240
Mass to be dismantled or demolished	[Mg]	279'000	123'000	420'000	559'000
Mass for disposal	[Mg]	5'190	3'070	3'360	6'990
Number of disposal containers		540	260	320	560
Disposal volume	[m³]	12'400	4'320	5'470	9'870
Allocatable disposal costs	[million €]	43	14	18	32
Costs	[million €]	320	200	280	390

the 355 MW_{el} Mühleberg BWR; for the 1'145 MW_{el} Leibstadt BWR, however, they are around double. Per t of material for disposal, the required disposal volume is 1.41 m^3 for the two SWRs and 1.63 m^3 for the Gösgen PWR. For the Beznau plant, the volume for disposal, and hence the allocated disposal costs, cannot (yet) be compared with the Figures for the other plants; this is because the study carried out for Beznau in 1998 assumed different boundary conditions (from those for Gösgen, Leibstadt and Mühleberg) for the packaging of mosaic-type containers in the disposal containers. It is expected that modifying the Beznau study to bring it into line with the others will result in a significant reduction in the number of containers and the disposal volume, as well as in the allocated disposal costs.

While the total costs for the two BWRs are very different, with 200 million € for Mühleberg and 390 million € for Leibstadt, they are almost the same for the two PWRs Beznau and Gösgen (280 million € and 320 million € respectively), particularly given the fact that adjustments still have to be made for Beznau.

The results presented here should be considered as preliminary. This is partly because it is not yet possible to make a full comparison between the power plants, but also because of ongoing discussions with the responsible authorities as to which of the conventional structures listed in Table 1 can be decommissioned or converted for further use without placing a demand on the decommissioning fund. These discussions could lead to a reduction in decommissioning costs which could amount to as much as several 10 million € for the larger plants.

7 International Comparison of Decommissioning Costs

Figure 2 shows a comparison of the decommissioning costs determined for the Swiss nuclear power plants with costs in other countries.

International comparisons are difficult because of the differences in decommissioning concepts and boundary conditions in the different countries. Various studies on this topic have been published (see e.g. NIS, VEW, PreussenElektra [14], UNIPEDE [15]), which highlight the following reasons for the differences between the individual countries.

The scope of the measures taken into account in the decommissioning costs has a significant influence on the costs. In some countries (e.g. the USA), decommissioning costs often cover only dismantling and removal of contaminated and activated components of the plant; in other countries, the costs associated with the post-operational phase (partly including management of spent fuel) are also included. The costs determined as part of the present Swiss studies do not include the post-operational phases.

Selection of the decommissioning variant, i.e. with or without safe enclosure, also has an impact on costs. Depending on the boundary conditions in the different countries (e.g. duration of safe enclosure period, safety requirements during safe enclosure), costs arising during the enclosure period can vary widely. The costs shown in Figure 2 are for the immediate dismantling variant.

The different reactor types (e.g. PWR or BWR) and the scope of their construction also have an impact on

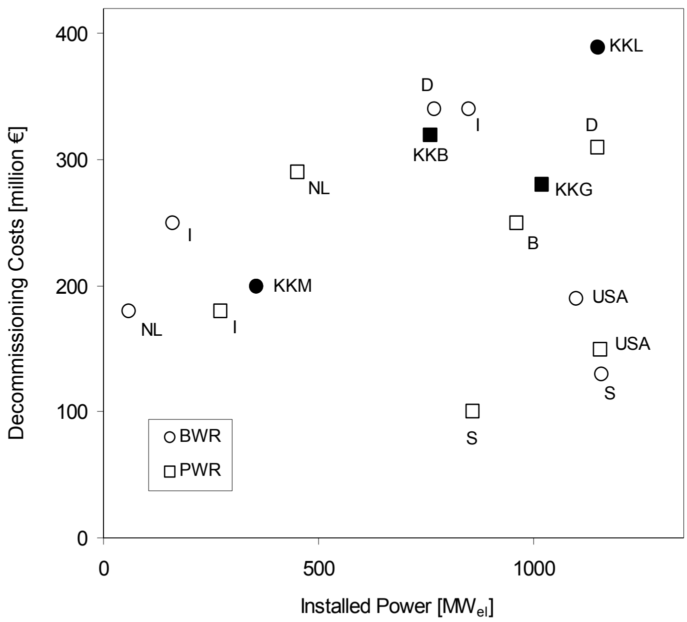

Figure 2 International comparison of decommissioning costs for the Swiss nuclear power plants. Price basis 1994 for S, USA; 1995 for NL; 1998 for KKB; 1999 for B, I(2); 2000 for D, I(1), KKG, KKL, KKM. For D without disposal charges.

the costs. One example is the turbine hall, which belongs to the controlled zone in the case of a BWR but not in the case of a PWR, leading to completely different requirements in the case of removal.

A key difference in waste management concepts is the selection of the repository type. In countries such as the USA and Belgium, the bulk of the waste is disposed of in near-surface facilities; in Germany and Switzerland the selected concept is deep geological disposal.

The legal framework and boundary conditions in force in individual countries also affect the level of decommissioning costs. One example are the exemption limits for materials from the controlled zone. The lower the limit, the more costly it is to demonstrate that the limit has not been exceeded and the greater the increase in the component of waste destined for disposal.

Decommissioning a nuclear power plant is a very work-intensive project, i.e. the personnel costs play a substantial role. The assumed compensation rates therefore have a large influence on the end-result.

When comparing decommissioning costs, the conversion rate to the currency on which the comparison is based also plays a role, as does the price basis on which the costs were determined. A further factor may be how the costs are treated for tax purposes in the different countries.

It is generally the case that a meaningful analysis of decommissioning costs is possible only with knowledge of the boundary conditions underlying the cost calculations. The comparison in Figure 2 should therefore be seen in perspective. Despite its limitations, the Figure shows that the decommissioning costs for the Swiss nuclear power plants are on par with costs in other countries.

8 Accumulation of the Decommissioning Fund

Although the results of the Swiss decommissioning studies presented here are preliminary in nature, it is nevertheless meaningful to compare them with the values used for calculating payments into the decommissioning fund. Such a comparison is shown in Figure 3. The first Swiss decommissioning studies dating from 1980 are used as a basis. The decommissioning costs based on these studies were adjusted every three years (for the first time in 1984) taking into account inflation and general trends in technologies and costs in the field of decommissioning [16]. These costs are shown in Figure 3 together with the results of the present study. Figure 3 also shows the evolution with time of the amounts effectively accumulated in the fund since 1984 [17].

Comparing the previous decommissioning costs, extrapolated into the present, with the results of the present study shows that, up till now, the costs for the BWRs Mühleberg and Leibstadt have been somewhat underestimated and those for the PWR Gösgen slightly overestimated. In the case of Beznau (with two PWRs), decommissioning costs will be adjusted rather upwards but, for the reasons given in section 6 (no full comparability as yet), this adjustment will turn out to be significantly smaller than indicated by Figure 3. The sum of the decommissioning costs, also shown in Figure 3, is somewhat larger overall in the new study than the extrapolation of the sum on which the decommissioning fund has been based up till now. However, the dif-

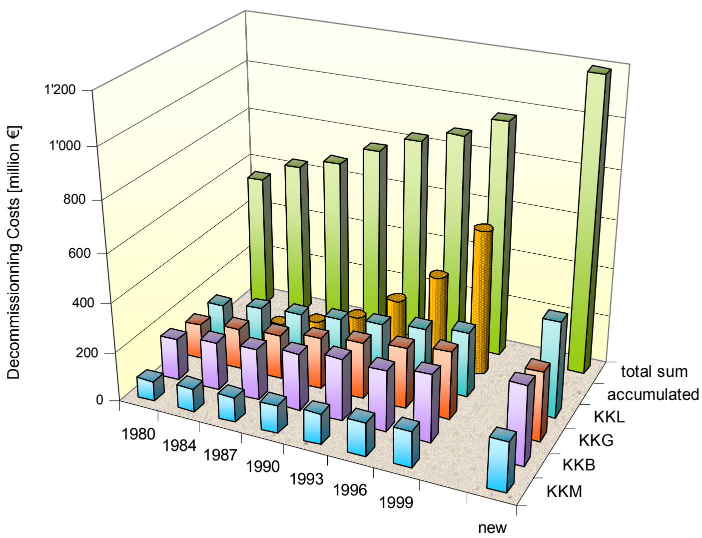

Figure 3 Comparison of the decommissioning costs based on the 1980 studies and updated every 3 years as from 1984 with the results of the new studies. In the background is the total sum on which the fund is based and in the foreground the total effective amounts held in the fund.

ference is small, particularly taking into account that the original studies on which the fund was based are more than 20 years old and the decommissioning costs have been adjusted since then on the basis of general developments without any further technical investigations.

The results of the study presented here will be taken into consideration in the next update of the model on which the fund is based. Since there is still sufficient time available before actual decommissioning of the Swiss plants, any corrections which may require to be made to the level of contributions to the fund will not have a significant impact on electricity production costs.

Finally, it should be noted that the decommissioning costs of the Swiss nuclear power plants have, for a long time, been monitored seriously and closely by the electricity supply utilities together with the federal authorities and that the financial reserves have been made showing an appropriate responsibility towards coming generations.

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