SKB
TECHNICAL
REPORT
94-20

Technology and costs for decommissioning of Swedish nuclear power plants

Swedish Nuclear Fuel and Waste Management Co

June 1994

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TECHNOLOGY AND COSTS FOR DECOMMISSIONING OF SWEDISH NUCLEAR POWER PLANTS

Prepared by a working group within the
Swedish Power Industry

June 1994

Information on SKB technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20), 1986 (TR 86-31), 1987 (TR 87-33), 1988 (TR 88-32), 1989 (TR 89-40), 1990 (TR 90-46), 1991 (TR 91-64) and 1992 (TR 92-46) is available through SKB.

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Keywords: Decommissioning study, dismantling, decommissioning costs, decommissioning waste

ABSTRACT

This decommissioning study for the Swedish nuclear power plants has been carried out during 1992 to 1994 and the work has been led by a steering group consisting of people from the nuclear utilities and SKB.

The study has been focused on two reference plants, Oskarshamn 3 and Ringhals 2. Oskarshamn 3 is a boiling water reactor (BWR) and Ringhals 2 is a pressurized water reactor (PWR). Subsequently, the result from these plants have been translated to the other Swedish plants.

The study gives an account of the procedures, costs, waste quantities and occupational doses associated with decommissioning of the Swedish nuclear power plants. Dismantling is assumed to start immediately after removal of the spent fuel. No attempts at optimization, in terms of technology or costs, have been made. The nuclear power plant site is restored after decommissioning so that it can be released for use without restriction for other industrial activities.

The study shows that a reactor can be dismantled in about five years, with an average labour force of about 150 persons. The maximum labour force required for Oskarshamn 3 has been estimated to about 300 persons. This peak load occurred the first years bus is reduced to about 50 persons during the demolishing of the buildings.

The cost of decommissioning Oskarshamn 3 has been estimated to be about MSEK 940 in January 1994 prices. The decommissioning of Ringhals 2 has been estimated to be MSEK 640. The costs for the other Swedish nuclear power plants lie in the range MSEK 590-960.

SAMMANFATTNING

Denna rivningsstudie av de svenska kärnkraftverken har genomförts under perioden 1992 - 1994 och arbetet har letts av en styrgrupp från kraftföretagen och SKB.

Studien har inriktats på två referensanläggningar, Oskarshamn 3 (O3) och Ringhals 2 (R2). O3 utgör referensanläggning för kokarvattenreaktorer (BWR) och R2 för tryckvattenreaktorer (PWR). Därefter har resultaten för dessa översatts till övriga anläggningar.

I rivningsstudien redovisas tillvägagångssätt, kostnader, avfallsmängder och persondoser vid rivning av de svenska kärnkraftverken. Rivningen antages starta så snart bränslet är borttransporterat. Några försök till optimering, tekniskt eller kostnadsmässigt, har inte gjorts i denna studie. Kraftverksplatsen återställs efter rivningen så att den fritt kan användas för annan industriell verksamhet.

Studien visar att rivningen av ett reaktorblock kan genomföras på ca 5 år, med en genomsnittlig personalinsats på ca 150 man. Maximalt har för Oskarshamn 3, personalstyrkan beräknats uppgå till 300 man. detta inträffar under de första åren för att sedan minska till ca 50 man under den avslutande byggnadsrivningen.

Kostnaden för att riva Oskarshamn 3 har beräknats till ca 940 MSEK i penning värde januari 1994. Rivningskostnaden för Ringhals 2 har beräknats till ca 640 MSEK. För de övriga svenska kärnkraftverken ligger kostnaden i intervallet 590-960 MSEK.

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SUMMARY

When a nuclear power plant is retired from service, parts of it are radioactive and must be dismantled and disposed of in a safe manner. This study gives an account of the procedures, costs, waste quantities and occupational dose associated with decommissioning of the Swedish nuclear power plants. No attempts at optimization, in terms of technology or costs, have been made.

The study has been focused on two reference plants, Oskarshamn 3 (O3) and Ringhals 2 (R2). O3 is the reference plant for boiling water reactors (BWR) and R2 for pressurized water reactors (PWR). Subsequently, the results from these plants have been translated to other plants.

Dismantlement is assumed to start immediately after removal of spent fuel, control rods, neutron detectors and operational waste. This means that dismantling can be commenced one to four years after final shutdown. The nuclear power plant site is restored after decommissioning so that it can be released for use without restriction for other industrial activities.

The study shows that a nuclear power plant can be decommissioned in a radiologically safe manner. Most of the equipment that is required for decommissioning is already available and is used routinely for maintenance and alterations at nuclear power plants. However, some special equipment is foreseen to be needed, which must be specially manufactured or modified. This includes, for example, equipment for cutting of the reactor pressure vessel (RPV) and its internals. Equipment for some building demolition may also have to be specially manufactured. The study gives examples of equipment and work methodology than can be used for dismantling.

The dismantling of a reactor unit can be accomplished in about 5 years, with an average labour force of about 150 persons. The maximum labour force required for Oskarshamn 3 has been estimated to be about 300 persons. This peak occurs during the first few years when active systems are being dismantled on several fronts in the plant. During the last few years when the buildings are being demolished, approximately 50 persons are required.

To limit the manpower need and the radiation dose to the personnel, the material is taken out in as large pieces as possible. This means, for example, that pipes are cut into lengths of about 2 m and then packaged in ISO freight containers. A number of large components are taken out and shipped intact or with only moderate segmentation. These include, for example, large heat exchangers and certain turbine parts, where segmenting would cause unnecessary spreading of radioactivity.

The cost of decommissioning Oskarshamn 3 has been estimated to be about MSEK 940 in January 1994 prices. The decommissioning cost for Ringhals 2 has been estimated to be MSEK 640. The costs for the other Swedish nuclear power plants lie in the range MSEK 590-960. These are the direct costs for the dismantling work.

Additional costs are incurred for the shutdown period from the time the nuclear power plant is taken out of service until the dismantling work is begun. The activities during this period are dominated by removal of the fuel and the system decontamination that is judged to be needed to facilitate the work of dismantlement. Final planning of decommissioning is also done during shutdown operation. The costs of shutdown operation are highly dependent on the pace at which the units are shut down and how quickly the fuel can be shipped away.

The total costs of shipping away and disposing of the decommissioning waste have been estimated to be about MSEK 980. The total repository volume in SFR 3 has been estimated to be about 140,000 m^3. There are considerable quantities of material and equipment at the plants that can be used after shutdown and decommissioning. No residual values have been taken into account in this study.

A summary of the decommissioning costs for immediate dismantling of the Swedish nuclear power plants is given in the table below.

Table 2.1 Summary of costs for decommissioning etc. of the Swedish nuclear power plants (MSEK).

	Barsebäck 1-2	Forsmark 1-3	Oskarshamn 1-3	Ringhals 1-4
Shutdown operation	340	750	750	1,170
Dismantling	1,290	2,690	2,180	2,640
Transportation and final disposal of waste	130	330	230	280
Total	1,760	3,770	3,160	4,090

1 BACKGROUND

According to the Act on Nuclear Activities (SFS 1984:3), the nuclear power utilities are responsible for adopting all measures that are needed to safely decommission and dismantle plants whose operation is to be discontinued. According to the Financing Act (SFS 1992:1537), a reactor owner is also obliged to carry out a calculation of the costs of decommissioning and dismantling the plant.

The Swedish nuclear power utilities have assigned Svensk Kärnbränslehantering AB (the Swedish Nuclear Fuel and Waste Management Company, SKB) the task of coordinating and conducting the necessary activities to fulfil these obligations. SKB therefore publishes annually a cost estimate of the measures that need to be taken in order to manage and dispose of the radioactive waste from nuclear power (ref. 2). The costs include planning, building and operating the facilities that are required, pursuing the necessary research and development, and decommissioning and dismantling the nuclear power plants.

The cost estimate for decommissioning has previously been based on a study carried out by SKB in 1986 (ref. 1). This study has now been updated to incorporate new experience.

The Swedish nuclear power programme includes twelve reactors, nine BWRs of ABB Atom design and three PWRs of Westinghouse design. The first unit, Oskarshamn 1, was commissioned in 1972 and the last two, Oskarshamn 3 and Forsmark 3, in 1985.

This study is based on the assumption that all nuclear power plants are operated until 2010. The direct cost for decommissioning a nuclear power unit is affected only marginally by this assumption. But it is of importance for the costs whether all reactors are shut down simultaneously or one at a time. Simultaneous shutdown entails a longer period of surveillance before dismantling can begin, and thereby a higher cost. The longer period of surveillance stems from the fact that it takes a longer time to remove the final core in this case. The receiving capacity of CLAB is a limiting factor. Calculations have been carried out for both alternatives.

The costs include decommissioning of all Swedish nuclear power plants. Calculations have been carried out in detail for Oskarshamn 3 and Ringhals 2. Oskarshamn 3 has been chosen due to access to extensive documentation on this reactor in the form of databases. This reactor is representative of a modern BWR. Ringhals 2 is representative of the Swedish PWRs.

The decommissioning costs for the other reactors have been translated from those for the reference plants by proportioning the costs according to the quantities of material involved and by means of estimates based on design differences.

The study has been carried out in close cooperation with personnel at the nuclear power plants.

The work has been divided up as follows:

- Shutdown and service operation for Ringhals 1-4
  Vattenfall Ringhals

- Dismantlement of systems in Ringhals 2
  Vattenfall Ringhals

- Waste management in connection with decommissioning of Ringhals 2
  Vattenfall Ringhals

- Dismantlement of systems in Oskarshamn 3
  ABB Atom

- Building demolition
  Rivteknik AB

- Segmentation of RPV and internals in Forsmark 1
  Siemens

- Study for dismantlement and lift-out of intact RPV in Ringhals 1 and 3
  Vattenfall Energisystem AB

- Study of melting of contaminated scrap
  Menon Consulting AB and Stensand AB

Studies of the different sub-areas have been reported in a number of work reports (ref. 4-11).

The work has been led by a steering group consisting of:

Mats Clementz	Barsebäck Kraft AB
Hans Forsström	SKB
Milan Korostenski	Forsmarks Kraftgrupp AB
Bengt Löwendahl	OKG AB
Shankar Menon	Menon Consulting AB
Stig Pettersson	SKB
Gunnar Wickström	Vattenfall, Ringhals NPP

Compilation of report and calculations:

Maria Wikström	SKB

2 PROGRAMME AND STRATEGY FOR THE DECOMMISSIONING SITE

2.1 GENERAL

The planning for the decommissioning study for the Swedish nuclear power plants is based on operation of all reactors through the year 2010. In Sweden, SKB has responsibility for the decommissioning study on behalf of the nuclear power industry.

This report, like previous studies, is based on the assumption that the work of dismantling the nuclear power plants is begun as soon as possible after termination of electricity generation. The judgement is based, among other things, on the fact that it is then possible to utilize skilled and plant-knowledgeable personnel and thereby show that the plants can be dismantled and the site restored in a safe and otherwise fully acceptable manner. No optimization with regard to the time of dismantlement has yet been done.

The option of postponing dismantlement has been elected by other countries, such as the UK. This option takes advantage of the radiological decay of activated and contaminated materials so that the dismantling work can be carried out in a less dose-intensive environment and waste management can be simplified.

Planning and execution of decommissioning of the Swedish nuclear power plants is planned to follow the steps and principles described below. This does not include the preliminary work in the form of R&D activities and other work that has already been done and is being done by SKB within the decommissioning field.

- Creation of a specific project group charged with the task of preparing for and planning the decommissioning. This is done 3—4 years before production operation of the nuclear power unit ceases. The project organization then exists and operates until the entire work of decommissioning is concluded and restoration of the NPP site has been carried out. The time from the termination of electricity generation until completed restoration is estimated to be about 7 years for the first unit on a site.

- Shutdown operation starts on termination of power generation and lasts until dismantlement of the unit has begun. During this time all fissile material (fuel) is removed from the plant and preparations are made for dismantling, e.g. decontamination. The workforce is reduced gradually during this period.

- Service operation starts when the dismantling work begins and is maintained by a reduced operating organization.

- Dismantlement of systems, demolition of buildings and site restoration.

Figure 2.1 shows the main phases for decommissioning of a reactor unit if the work is begun as soon as possible after termination of power generation.

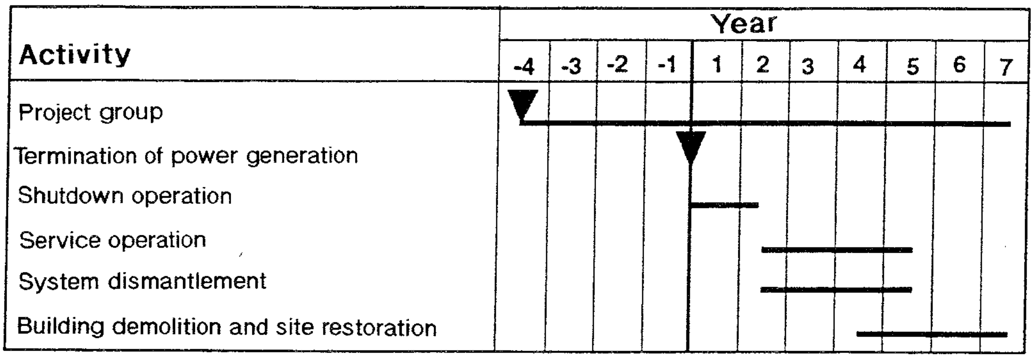


Figure 2.1 The main phases in the decommissioning of a reactor unit

Depending on, among other things, the availability of resources to execute decommissioning, a successive decommissioning of the Swedish NPPs is preferable. SKB estimates that the entire decommissioning programme in Sweden will take about fifteen years.

2.2 PLANNING FOR THE DIFFERENT PHASES OF DECOMMISSIONING

When it comes to methods and technology, international developments in the field of decommissioning are primarily followed up through an active involvement in the OECD/NEA's Technical Advisory Group. SKB is also represented in UNIPEDE's committee for waste management and decommissioning.

Different alternatives for dismantling the RPV (reactor pressure vessel) have been studied. Handling and disposal of an intact RPV was described in a 1992 study (ref. 10), and a study of the segmenting option was carried out in 1993 (ref. 12). This study also deals with technology for segmenting internals.

It is projected that other necessary technology and method studies will be carried out about five years prior to shutdown.

Site-specific decommissioning studies will be started by the power utilities and are expected to take about five years. These studies will then serve as a basis for preparation of a dismantling logic for the other plants. A finished dismantling logic will exist 2-3 years before the dismantling work begins. This will then also include joint planning of the different Swedish decommissioning projects.

An overhaul of SKB's transportation system, which is designed today for operational waste, must be done to adapt it to the decommissioning waste. The decommissioning waste differs to some extent in character but mainly in its large quantity from the operational waste. It is estimated that the work of overhauling the transportation system will take five years and that a report on the results will be submitted about 2-3 years before final shutdown. The report will also contain a proposal for supplementary equipment, e.g. site-specific equipment, equipment for sea transportation, equipment in the final repository and transport containers.

An inventory of the need for special equipment for the dismantling work is projected to begin about 5 years before final shutdown and to proceed with varying intensity until the dismantling work begins. The objective is that dismantlement shall be carried out with known and proven technology. However, some equipment must be tailor-made for its special applications and be adapted to station-specific needs.

An expansion of the existing SFR is planned for final disposal of the decommissioning waste, see Figure 2.2.

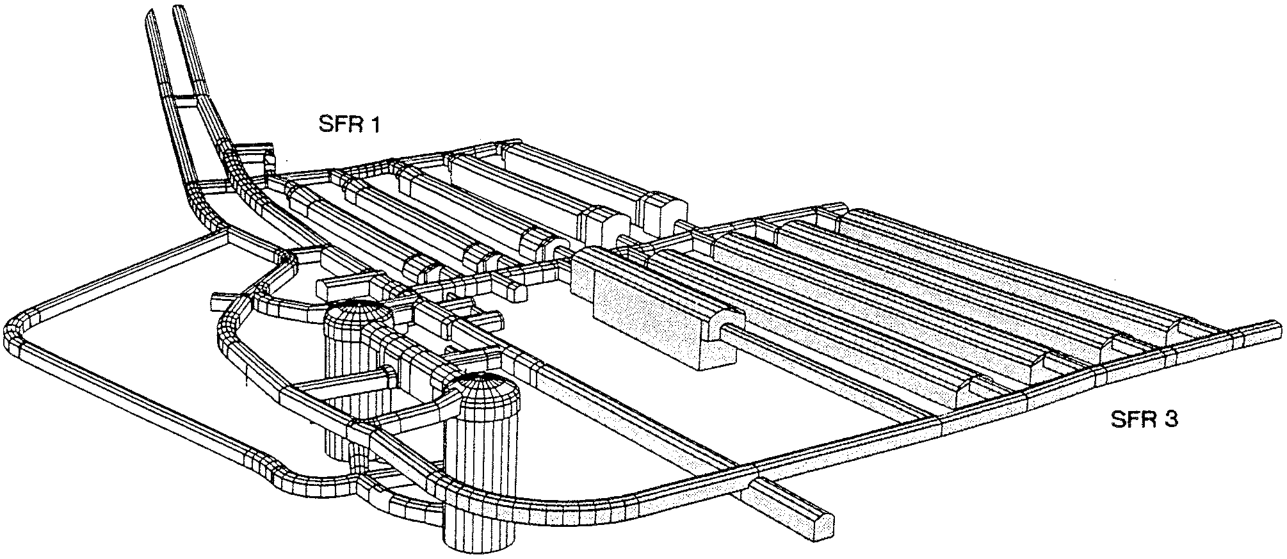


Figure 2.2 Final repository for radioactive operational waste, SFR. Operational waste SFR 1 and decommissioning waste SFR 3.

Assuming operation of all reactors through the year 2010, the work of designing SFR 3 will begin in around 2005. It is estimated that the facility will be able to start receiving decommissioning waste in 2012. Deposition of decommissioning waste in SFR 3 will proceed throughout the dismantling work up to the year 2025, when the facility will be closed.

Core components that have been activated by neutron bombardment and are in need of heavy radiation shielding will be stored temporarily in CLAB for later encapsulation and deposition in the deep repository.

In the planning of decommissioning it is assumed, as mentioned, that dismantlement of the first nuclear power unit will begin about one year after the termination of power generation, when the fuel and control rods have been removed and shipped away from the plant.

A crucial factor in determining when dismantling of the other units can begin will be the transport and receiving capacity of CLAB and the availability of resources for the dismantling work.

By modification of the operating shift, CLAB can receive a maximum of 600 tonnes of fuel per year. In parallel with the fuel transports, shipments of RPV internals and core components will also begin from other plants where dismantling has already been commenced.

If special resources for removal and disposal of spent fuel and reactor internals are limited, it may prove rational to empty one site at a time. This may also apply to the utilization of necessary special resources in the form of equipment and staff for dismantlement and building demolition. Disposal of the RPV, whether it is segmented or taken out as an intact unit, is an example of a special task where it is likely that neither equipment nor manpower will be available to carry out parallel operations at all nuclear power units.

When it comes to the order in which the Swedish NPPs will be decommissioned and dismantled, it is very difficult today to make any plans. Many factors can affect the sequence.

In conjunction with the planning of the decommissioning work, a number of reports and licence applications must be prepared. Different authorities have to review and give their permission for decommissioning in accordance with e.g. the Act on Nuclear Activities and the Environment Protection Act.

In order to obtain a rational utilization of the decommissioning personnel it may be appropriate to stagger the starting times for dismantling. In this report it is assumed that dismantling of the first reactor unit on each site is commenced no sooner than one year after power generation ceases. Dismantlement of the other units on the same site is then commenced at two-year intervals. In this way, resources can be moved in succession from plant to plant.

Figure 2.3 shows a possible schedule for decommissioning of the Swedish NPPs in the case of simultaneous shutdown. An equivalent schedule for successive shutdown is shown in Figure 2.4. In the latter case it has been assumed that all reactors will be operated for an equally long period of time. In the case of reactors that are situated near each other and that may have certain common systems, it has been assumed that dismantling is not begun in the first unit until the fuel has been removed from the "twin unit". This is true, for example, in the case of Oskarshamn 1 and 2.

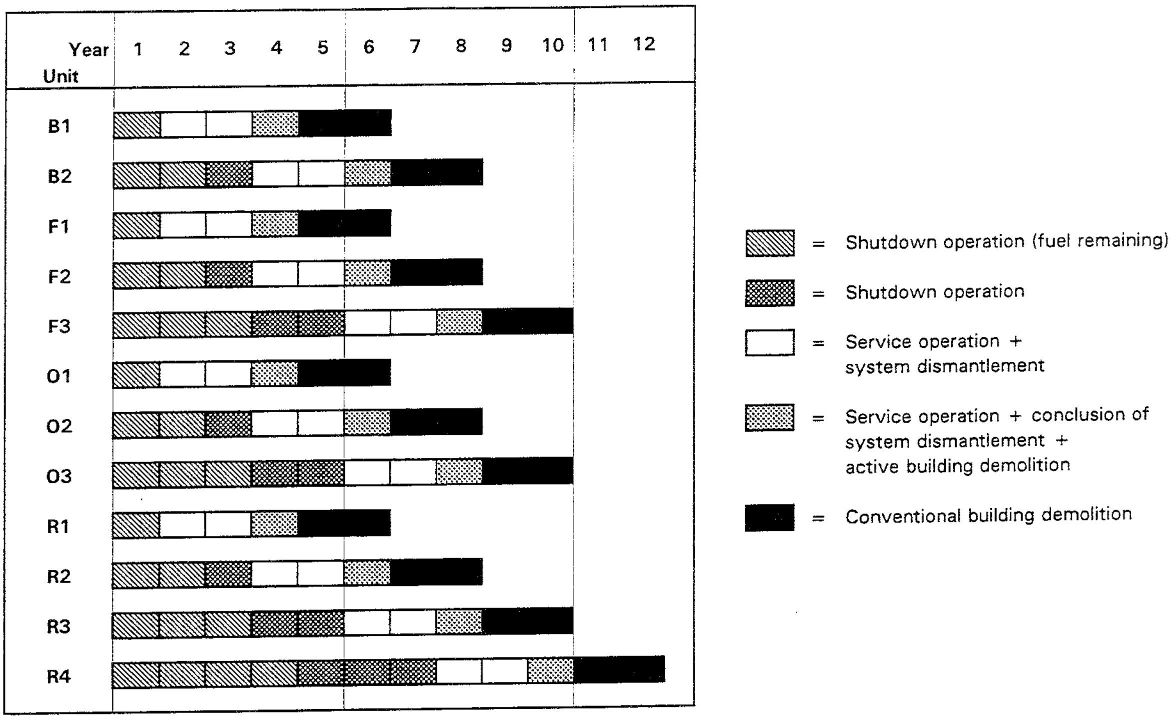


Figure 2.3. Example of schedule for decommissioning of the Swedish nuclear power plants if all units are shut down simultaneously.

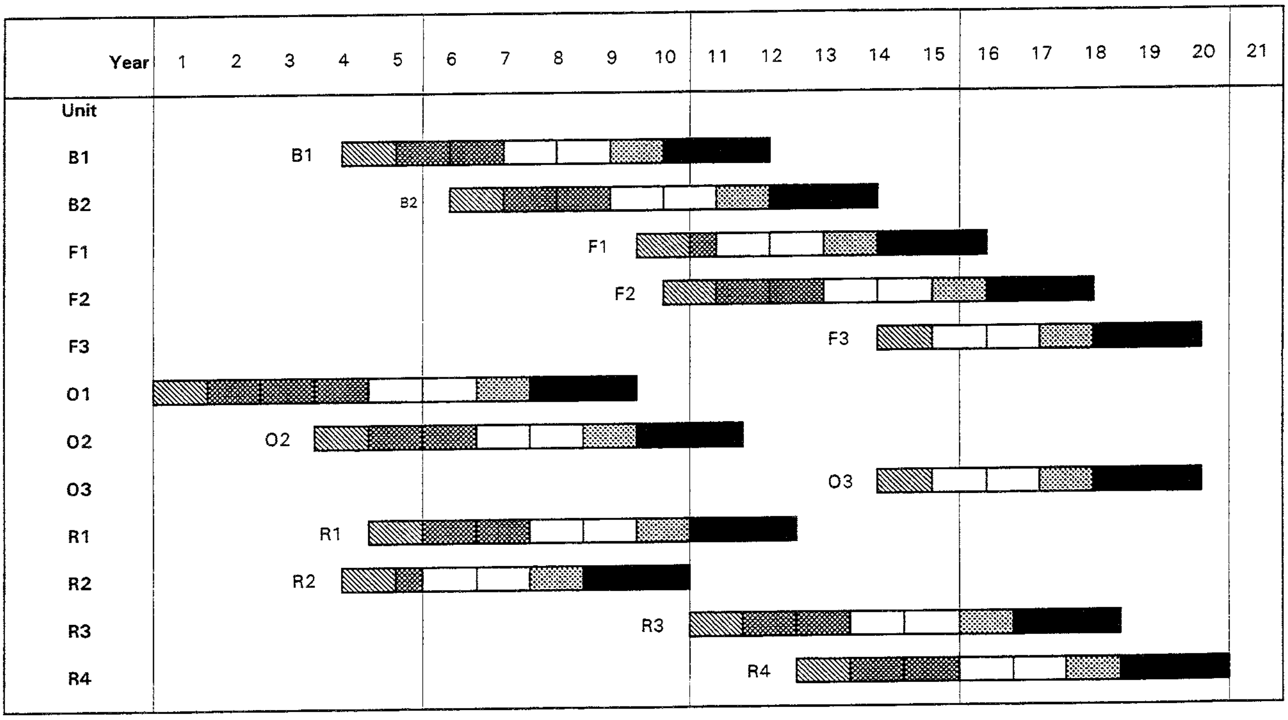


Figure 2.4. Example of schedule for decommissioning of the Swedish nuclear power plants in the case of successive shutdown.

2.3 EXECUTION OF DECOMMISSIONING

A project group appointed by the power plant owner is in charge of coordinating decommissioning. The project group carries out the detailed planning, prepares the required technical documentation and safety reports, and has contacts with authorities etc. The project group is formed about 3—4 years prior to the start of the dismantling work, and the size of the group varies during the different phases. Organizationally, the project group belongs to the licensee and is responsible for reporting and licensing matters vis-à-vis the regulatory authorities. The way this is organized in detail can vary between the different utilities.

In the detailed planning of the decommissioning, it is important that sufficiently large areas are set aside inside the plant for interim storage of materials, holding of transport containers etc. Decommissioning should be divided into a number of sub-projects so that the work can be pursued on several fronts and the total decommissioning time thereby shortened.

After system decontamination, a thorough radiological survey is made of the plant's different system parts. After this the dismantling work can be commenced. The purpose of the survey is firstly to provide a basis for planning of radiation protection measures during the dismantling work, and secondly to reduce the need for nuclide-specific measurements on individual waste packages and transport containers prior to shipment. Each transport container must, however, be checked with regard to dose rate and possible presence of surface contamination prior to shipment. During the dismantling work, the active material is sorted with respect to its further handling.

The critical line for the dismantling work goes via the work with the RPV with internals, the biological shield, contaminated concrete and free release of areas.

The decommissioning plan for a PWR unit largely coincides with that for a BWR unit. The scope of the radioactive systems is smaller, however, since the turbine plant is completely inactive in a PWR unit. The bottleneck in the dismantling process for a PWR as well is removal of reactor internals and the RPV itself. The total time for dismantling PWR units is estimated to be roughly the same as for BWRs.

In connection with the planning and dismantling work, the following reports may have to be prepared to serve as a basis for the planning and for different licence applications:

- The shutdown report or status report is an initial document which is produced by the established project group to describe the conditions for shutdown and service operation. The report shall be appended to the application for a licence for shutdown and service operation.

- An environmental report, which shall describe conditions and problems as set forth in the Environment Protection Act and the Workers' Protection Act. The environmental report is also appended to the application for a licence for shutdown and service operation.

- A safety report as prescribed in the Act on Nuclear Activities that describes how existing safety functions in connection with the handling of fissile and radioactive material can be simplified with time.

- The decommissioning report is a technology report that describes methods and equipment and how the different steps have to be planned to guarantee a safe and efficient decommissioning and restoration of the nuclear power plant site. The technology report should include classification of waste types, activity monitoring methods and a description of criteria for free release. The decommissioning report shall comprise a supporting document for an application for a decommissioning licence.

An application for a licence for shutdown and service operation shall also deal with such matters as reduction of the workforce at the nuclear power unit.

3 OVERALL PREMISES

3.1 GENERAL

The objective of the study has been to make an estimate of waste quantities, occupational dose and costs for decommissioning and dismantling the Swedish nuclear power plants. No attempts at optimization, in terms of technology or costs, have been made. The costs are needed to determine the required fees.

The study has focused on two reference plants, Oskarshamn 3 and Ringhals 2. Then the results from these plants have been translated to other plants.

Dismantlement is assumed to start immediately after removal of spent fuel, control rods, neutron detectors and operational waste. This means that dismantling can be commenced one to four years after final shutdown.

The nuclear power plant site is restored after dismantlement so that it can be released for use without restriction for other industrial activities.

3.2 TECHNOLOGY

In the study it is assumed that dismantling is carried out using currently known technology. The choice of working method is made with a view towards occupational safety and prevention of releases to the environment, as is normal in connection with alteration work at NPPs. No other activities that disturb the decommissioning work are allowed during decommissioning.

3.3 ACTIVITY AND WASTE

Events that lead to major releases of radioactivity have not occurred during the operating period. Accordingly, releases of radioactivity within the controlled area have been limited to normal leakage. An estimate of the activity inventory is done based on previous studies, measurements and estimates. This activity estimate is based on an assumption of 40 years' operation. The following is assumed concerning contamination of concrete:

- In large pools with stainless steel linings, leakage is assumed to have led to a penetration of activity to a depth of 5 cm over the entire surface behind the lining. Furthermore, cracks in the concrete are assumed to have led to contamination of an additional 5 m^3 of concrete.

- In pump sumps, the concrete is assumed to have been contaminated to a depth of 10 cm, and cracking has led to the contamination of an additional 1 m^3 of concrete.

- Spillage in rooms with a limited amount of radioactive process equipment has led to contamination of 1% of the floor area. In rooms with higher leakage risks, 10% of the floor area is assumed to be contaminated.

These assumptions are rough and lead to an overestimation of the quantity of radioactive material.

A decontamination of the reactor systems is done before dismantlement is commenced. Decontamination agents that are suitable in terms of both effectiveness and waste management are assumed to be used. Experience from e.g. system decontamination in Oskarshamn 1 during 1994 is drawn upon.

The possibility of decontaminating turbines and turbine systems by means of simple decontamination methods, such as high-pressure spraying, is considered.

Decontamination of scrap following disassembly is applied where this is deemed economically interesting. Electrochemical methods can be used for this.

The active waste from decontamination is divided into three categories:

- Waste that can be cleared for free release
- Waste that can be disposed of on the site
- Waste that must be taken to a final repository

Material is regarded as clean if it meets the regulatory authorities' requirements for unrestricted release. Today, molten contaminated material is released from case to case. The highest permitted activity concentration for free release up to now has been 0.8 Bq/g. The consequences of raising the free release limit have also been explored in the study.

Inactive decommissioning waste is dealt with in a conventional manner. The possibility of using such waste as fill for restoration of the nuclear power plant site is being considered.

3.4 COSTS

The costs are calculated in January 1994 values.

The costs of decommissioning include:

- Shutdown operation
- Service operation
- System dismantlement
- Building demolition and site restoration

Shutdown operation entails operation of the plant from final shutdown until dismantling of systems commences. Service operation entails operation and maintenance of the plant during dismantlement of process equipment and demolition of active building components until the site can be released for unrestricted use. The personnel during shutdown and service operation come from the regular operating organization and therefore possess the requisite knowledge of the plant and its systems. The costs include operation of requisite systems, maintenance of the plant, radiation protection activities, and direction of the decommissioning activities.

3.5 THE SITE AFTER DECOMMISSIONING

After demolition of the buildings, the site of the nuclear power plant will be restored to its original state. After restoration, the site shall be able to be re-used without restriction as an industrial site.

4 ACTIVITY CONTENT

4.1 GENERAL

Knowledge of the content and distribution of radioactivity is necessary for many aspects of nuclear power plant decommissioning. It is needed for planning of dismantlement of systems and components, for waste management during and after the dismantling work and as a basis for unrestricted release of the plant site after decommissioning.

After the spent fuel has been shipped off-site, the active material can be classified as follows:

- material with induced activity that has become activated by neutron bombardment from the reactor core;
- material that is contaminated with radioactive corrosion products and fission products that are transported with reactor water, steam and fuel out into systems and pools.

Figure 4.1 shows the main systems in Oskarshamn 3 with colour codes for different activity levels one year after shutdown.

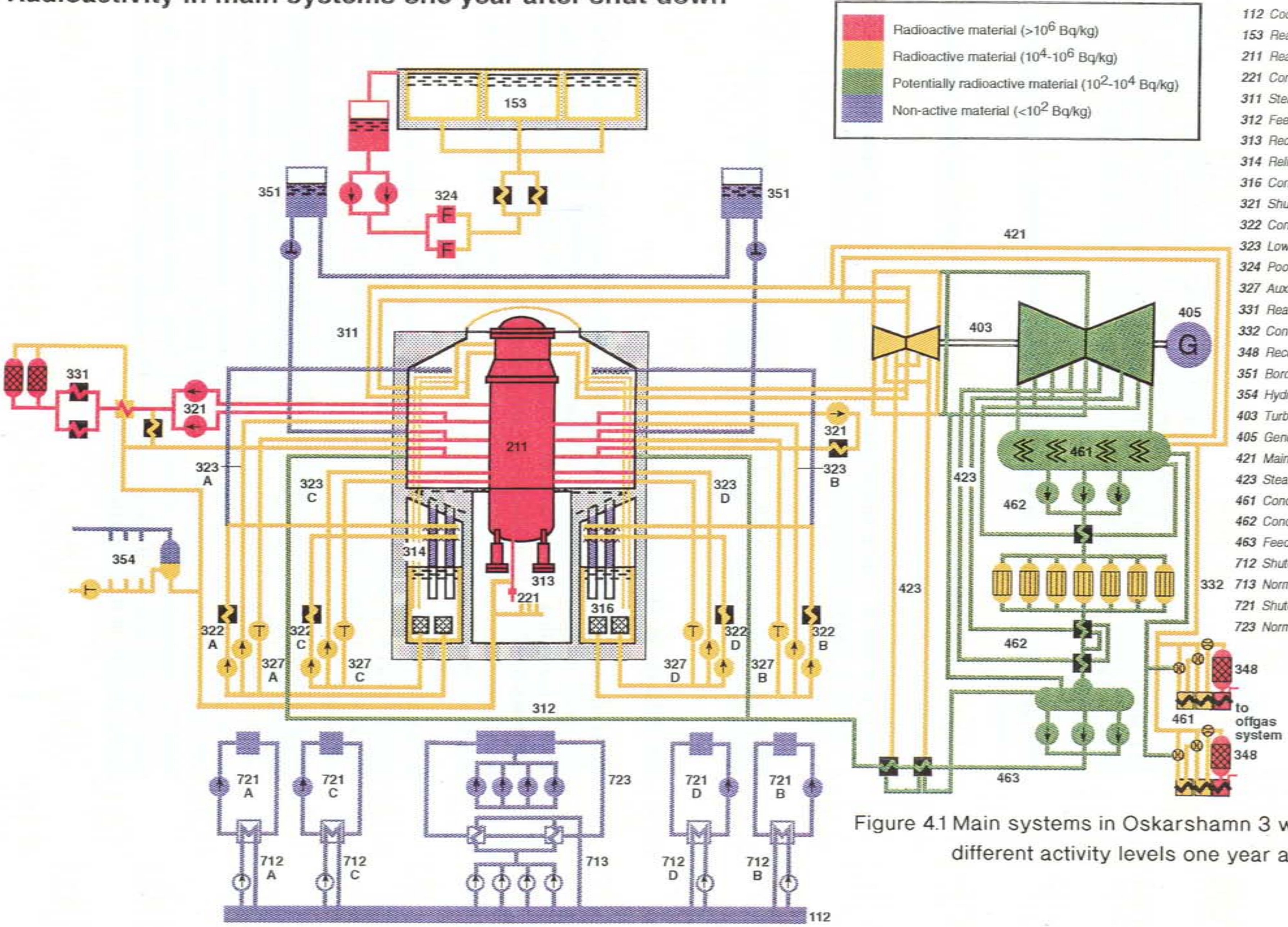
4.2 MATERIAL WITH INDUCED ACTIVITY

There are many programs for calculating the induced activity in reactor material. Important input data for these calculations are the neutron fluxes and energy spectra prevailing in the reactor. Another important element is the material composition of the constituent structural parts. When it comes to the core and its immediate surroundings, many of the existing programs have been validated by means of reactor-physical calculations and measurements.

In areas further away from the core it is more difficult to calculate the induced activity exactly, since it is more difficult to determine the neutron density there. Therefore, in order to check calculation programs and the induced activity in the concrete in the biological shield, foils of diverse materials as well as cement samples were exposed in a vertical channel in the biological shield of Oskarshamn 1 during 1987-88. The neutron flux density in the channel was calculated with an ANISN program and the induced activity in foils and cement was estimated based on the calculated flux. Then the calculated activity concentrations were compared with the measured concentrations in sample material by means of ABB Atom's MADAC equipment. The results showed fairly good agreement between the measured and calculated values (ref. 15). The project report recommends certain improvements in the calculation model.

Oskarshamn 3

Radioactivity in main systems one year after shut-down



🟥 Radioactive material (>10^6 Bq/kg)

🟨 Radioactive material (10^4-10^6 Bq/kg)

🟩 Potentially radioactive material (10^2-10^4 Bq/kg)

🟪 Non-active material (<10^2 Bq/kg)

112	*Cooling water channel*
153	*Reactor pools and fuel pools*
211	*Reactor pressure vessel*
221	*Control rod drives*
311	*Steam lines*
312	*Feedwater lines*
313	*Recirculation system*
314	*Relief system*
316	*Condensation system*
321	*Shutdown cooling system*
322	*Containment vessel spray system*
323	*Low pressure coolant injection system*
324	*Pool water cooling and cleanup system*
327	*Auxiliary feedwater system*
331	*Reactor water cleanup system*
332	*Condensate cleanup system*
348	*Recombiner system*
351	*Boron system*
354	*Hydraulic scram system*
403	*Turbine*
405	*Generator*
421	*Main steam system*
423	*Steam extraction system*
461	*Condenser and vacuum system*
462	*Condensate system*
463	*Feedwater system*
712	*Shutdown cooling water system*
713	*Normal operation cooling water system*
721	*Shutdown secondary cooling system*
723	*Normal operation secondary cooling system*

Figure 4.1 Main systems in Oskarshamn 3 with colour codes for different activity levels one year after shutdown.

Induced radioactivity is present in the RPV and its internals. The neutron flux, and thereby activation, declines very rapidly outside the actual reactor core. The crud activity dominates at a distance of only a few metres. A calculation of the induced activity has been carried out for the RPV and internals for the Oskarshamn 3 reactor. The activity content is shown in Table 4.1. The induced activity is dominated from a dose viewpoint by ^{60}Co. In the most active parts, for example the core grid and the moderator tank, the calculated specific activity (as shown by Table 4.1) can be 1-4 GBq/g, which is equivalent to surface dose rates of considerably more than 100 Sv/h.

The ^{60}Co activity in the biological shield is significantly lower, about 70 kBq/g, with the result that the dose rate on the inside of the shield is considerably lower than at the moderator tank. Besides ^{60}Co, ^{152}Eu and ^{3}H are also present. One metre into the biological shield, the induced activity is negligible.

Table 4.1 Activity content (induced and crud) in RPV and internals at Oskarshamn 3 reactor, 40 years' operation, one year's decay

Component	Weight tonnes	Activity concentration Bq/g	Total activity Bq
Control rod guide tubes	32	$1.0*10^6$	$3.3*10^{13}$
Moderator tank	32	$1.3*10^9$	$4.2*10^{16}$
Moderator tank cover	56	$4.1*10^6$	$2.3*10^{14}$
Core grid	6	$4.1*10^9$	$2.5*10^{16}$
Core spray w frame	9	$5.6*10^7$	$4.8*10^{14}$
Steam separator	34	$1.3*10^5$	$4.5*10^{12}$
Steam dryer	48	$1.3*10^4$	$6.0*10^{11}$
Instrument tubes	6	$1.6*10^5$	$1.0*10^{12}$
Feedwater sparger	2	$5.0*10^4$	$1.0*10^{11}$
Core spray pipe	1	$1.3*10^4$	$1.3*10^{10}$
Main circ. pump impeller	6	$1.7*10^2$	$1.0*10^9$
Total internals	232		$6.8*10^{16}$
Reactor vessel			$2.0*10^{13}$

A similar calculation has been done on a reference plant for a PWR reactor in a study for US NRC (ref. 22). The total activity content in the RPV and internals according to the study is $1.8*10^{17}$ Bq.

4.3 MATERIAL WITH SURFACE CONTAMINATION

All system surfaces wetted by reactor water become contaminated with radioactivity to some extent. The normal experience from BWRs is that the level of contamination is determined by the quantity of activated corrosion products. Gamma-emitting nuclides such as ^{60}Co, ^{58}Co, ^{65}Zn and ^{54}Mn have been found to be the main sources of the radiation field around system equipment during the short time perspective (< 30 years' decay).

The contamination level is of great importance from the viewpoint of radiation protection. Thus, knowledge of activity and dose rate levels is necessary to determine the need for decontamination and a suitable dismantling method.

To quantify and predict activity and dose levels in different systems at different points in time up to the end of the reactor's service life, ABB Atom has:

- developed the calculation program BKM-CRUD, which predicts the quantity of activated corrosion products on different system surfaces;

- followed the activity build-up on system surfaces through an extensive monitoring programme on all BWRs delivered by ABB Atom in Sweden and Finland.

Calculations with the program BKM-CRUD (ref. 16) have been carried out assuming operation up to the year 2010. The calculation model is based on a number of transport processes for nuclides between the reactor water and different parts of the primary system. Activation, decay and burnup are taken into consideration.

These calculations have been supplemented by means of extensive measurements over many years of activity and dose levels in different systems in BWRs delivered by ABB Atom using MADAC (Mobile Analyses for Detection of Activity in Crud). The measurements have been used to fine-adjust and verify the BKM-CRUD calculations. A comparison between calculation and measurement results for dose rates on system 321 pipes at the Oskarshamn 2 BWR is shown in Fig. 4.2 (ref. 16).

The estimates and measurements mentioned above have been supplemented with calculations of leakage of fission products from damaged fuel, where two scenarios have been considered:

- a scenario with a leaking fuel pin
- a scenario with the assumption that more serious fuel damages occur every 10 years.

Fuel damages are not included in the current BKM-CRUD model, which explains the high measured values (compared with the calculated values) after fuel leakage during 1987-88.

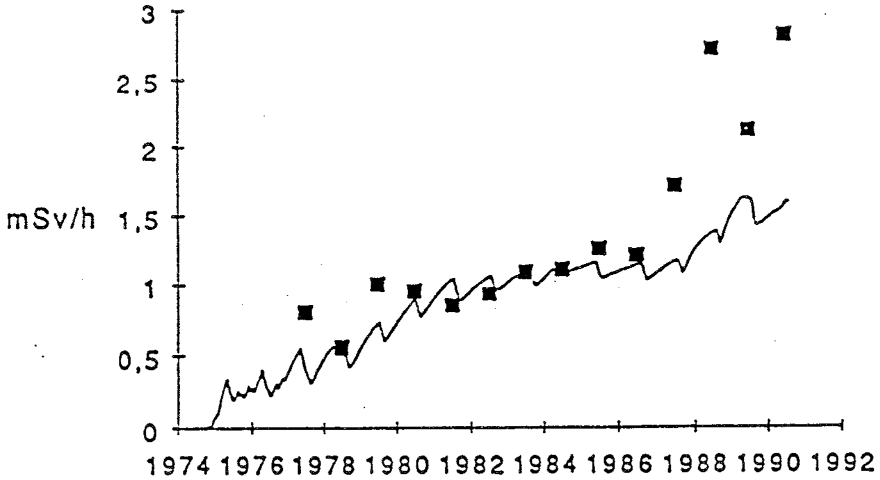


Fig. 4.2 Comparison between calculated (—) and measured (■) dose rate levels on system 321 (Cooling system for shutdown reactor), Oskarshamn 2

The activity contents in the different systems have been obtained for Oskarshamn 3. The most important systems from the viewpoint of decommissioning are presented in Table 4.2.

Table 4.2 Activity content in several systems at Oskarshamn 3

System	Dose rate µSv/h	Activity concentration Bq/m² ^{60}Co	Activity Bq ^{60}Co
Main steamlines	20	$1.1*10^{8}$	$8.2*10^{10}$
Feedwater	40	$2.5*10^{8}$	$2.4*10^{10}$
Cleanup system for fuel storage pools	70	$2.5*10^{8}$	$1.2*10^{11}$
Cooling system for shutdown reactor	650	$4.0*10^{9}$	$3.3*10^{11}$
Cleanup system for reactor water	410	$2.5*10^{9}$	$7.3*10^{10}$

In the case of PWR reactors, the activity inventories have been estimated for Ringhals 2. These inventories are based on gamma spectrometric measurements on steam generators, manway inserts and circulation lines, as well as radiochemical analyses during shutdown and on corrosion products from fuel cladding (ref. 17). Estimates in connection with the 1993 refuelling outage yielded data that is presented in Table 4.3.

Table 4.3 Gamma activity in different system parts (1993), Ringhals 2

System	Area (m^2)	Activity concentration Bq/m^2 ^{60}Co	Activity Bq ^{60}Co
Tube surface in steam generator	15315	$4.7*10^8$	$8.2*10^{10}$
Stainless steel surface	2240	$1.7*10^{10}$	$3.1*10^{13}$
Total			$3.8*10^{13}$

An estimation that was made regarding a reference plant, PWR (ref. 22), shows results presented in Table 4.4.

Table 4.4 PWR. Surface activity in different systems

System	Area (m^2)	Activity concentration Bq/m^2	Activity Bq
RPV + internals	570	$8.5*10^9$	$4.8*10^{12}$
Steam generators	19,000	$8.5*10^9$	$1.6*10^{14}$
Pressurizer	87	$1.5*10^9$	$1.5*10^{11}$
Reactor cooling system	190	$3.2*10^{10}$	$5.9*10^{12}$
Other pipe surfaces	1,100	$2.2*10^9$	$2.2*10^{12}$
Total	20,950		$1.8*10^{14}$

The lower values of surface activity at Ringhals 2 can be assumed to be due to the fact that:

- the ^{60}Co content of the crud was halved in connection with a steam generator replacement in 1989
- "high Ph" water chemistry has been employed
- there is a generally lower surface activity at the Ringhals PWR than at American PWRs.

5 TECHNICAL DESCRIPTION OF DECOMMISSIONING

5.1 GENERAL

The different main phases in the decommissioning of Swedish nuclear power plants have been described in general terms in chapter 2 and are as follows:

- Shutdown operation
- System dismantlement
- Building demolition and site restoration

Service operation is the operation that is maintained during system dismantlement and demolition of active building components and that is necessary to support these activities.

Figure 5.1 shows an overall logic for the activities pursued during shutdown and service operation until the site has been restored. The logic is made for a BWR unit.

The decommissioning project group is responsible for planning and coordination of activities during these phases. The group carries out detailed planning of the decommissioning, prepares the requisite technical documentation and safety reports, and has contacts with authorities etc. The project group is established about 3—4 years prior to the termination of electricity generation, and the size of the group varies during the different phases as needed. Organizationally, the project group belongs to the licensee and is responsible for reporting and licensing matters vis-à-vis the regulatory authorities.

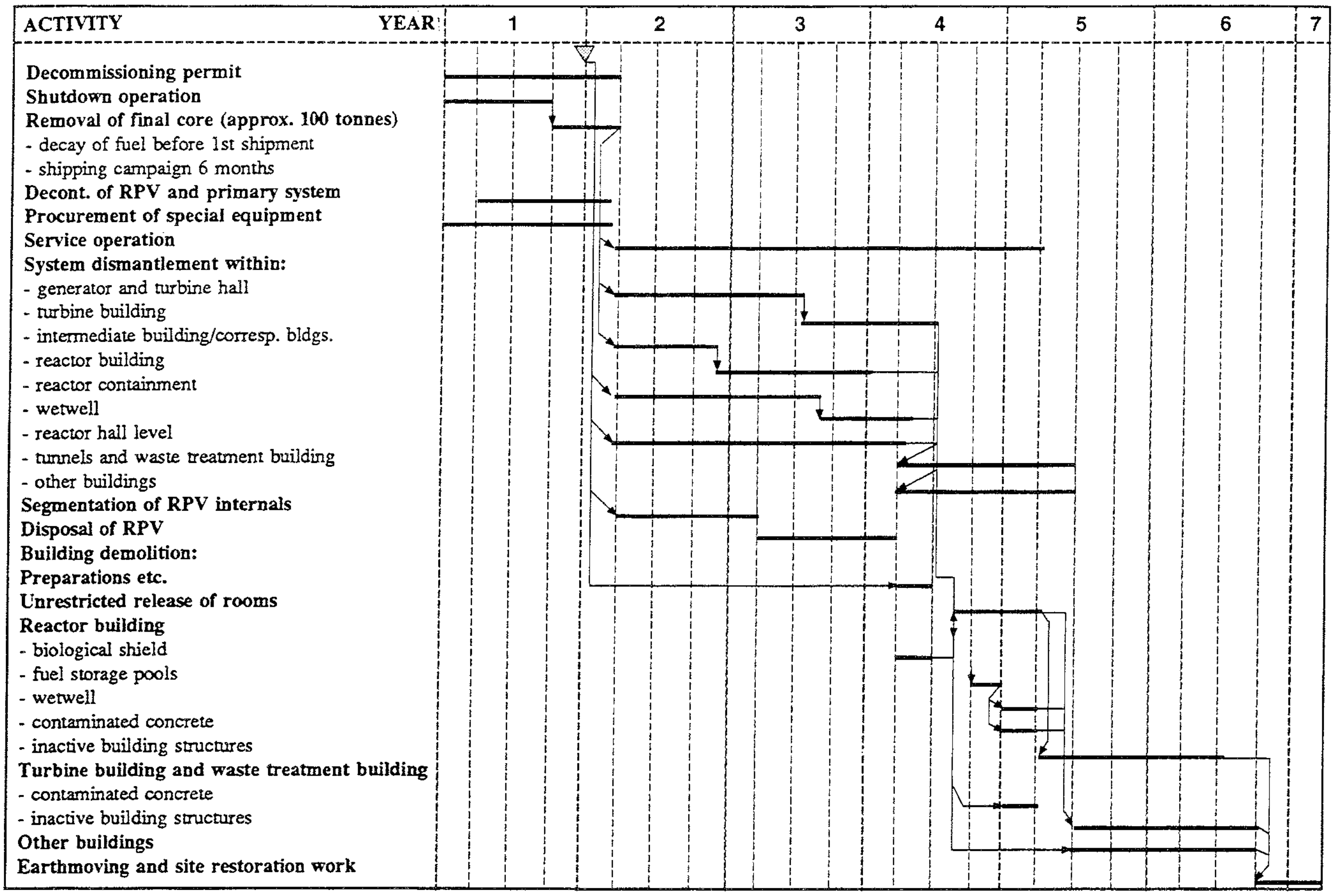


Figure 5.1 Overall plan for activities during shutdown and service operation. BWR unit

5.2 ACTIVITIES IN CONNECTION WITH SHUTDOWN OPERATION

5.2.1 General

Activities during shutdown operation are dominated by the discharged fuel shipments and the system decontamination that are deemed necessary to facilitate the subsequent dismantling work. Final decommissioning planning also takes place during shutdown operation.

5.2.2 Fuel handling

When it comes to fuel handling and shipment of fuel to CLAB for interim storage, this will take place in accordance with the routines and regulations that currently apply during production operation of the NPPs. Nor is any procurement of supplementary handling or transport equipment foreseen for the final fuel charge. The planning of this activity has to be adapted to and optimized against the available transport capacity. Coordination between the different decommissioning projects is naturally important in this context.

Shutdown of the different NPPs has been prepared for in such a manner that the fuel storage pools only contain fuel from the immediately preceding year's refuelling. Fuel from previous years' refuellings has been shipped away. It is also assumed that the fuel storage pools have been cleaned out to remove replaced internals and other material stored in them.

The fuel in the reactor core is transferred to the fuel storage pools immediately after the termination of electricity generation for decay of residual heat. The fuel from the preceding year's refuelling has been stored for one year, which simplifies handling and transport to CLAB. This fuel can begin to be shipped immediately after shutdown. Shipment of the fuel from the shutdown cores, i.e. the fuel assemblies that have been installed in the reactor core during the last operating cycle, will be planned so that the units that are to be dismantled first have their pools emptied first.

The transportation system is assumed to have sufficient capacity so that the control rods can also be shipped during the period when the fuel shipments are in progress.

As long as fuel remains in the fuel storage pools at the unit, continuous manning of the unit with shift workers is assumed.

5.2.3 System decontamination

To reduce the general activity level within the unit, system decontamination will be performed on active reactor systems and the RPV.

Decontamination can be accomplished by means of different methods and it is important that the method and decontamination chemicals be chosen with a view towards suitable waste treatment. The principle of system decontamination is that a decontamination solution with a suitable composition and temperature for dissolution of the activity-containing oxide layer on the system surfaces is circulated in the system and transports the dissolved activity to a filter or ion exchange resin, which is subsequently disposed of. After completed system decontamination, the systems are rinsed out with water and dried.

Experience of system decontamination is good today when it comes to both typical BWR and typical PWR oxides. The method is used routinely for large maintenance jobs and in connection with e.g. steam generator replacements in PWR plants. Furthermore, more efficient methods with more easy-to-handle final products are constantly being developed.

An extensive system decontamination of the RPV in Oskarshamn 1 was carried out during the spring of 1994 with very good results, 99.88% of the radioactive surface contamination was removed.

The efficiency of a system decontamination is measured in terms of a decontamination factor, DF, which is the ratio between the dose rates on a given system surface before and after decontamination. Decontamination factors of between 10 and 100 are achieved with a reasonable treatment time.

In the case of system decontamination where one of the factors that influences the results is the flow rate of the decontamination solution, lower decontamination factors can be expected in large apparatuses such as tanks and heat exchangers and higher in, for example, small-bore piping systems and on the inside of heat exchanger tubes. Better results can be achieved by means of high-pressure spraying after decontamination.

5.2.4 Procurement of special equipment

The dismantling work will be carried out as far as possible with the aid of conventional standard equipment for cutting, lifting and transportation. However, some special equipment is foreseen to be needed, which must be specially manufactured or modified for its purpose. This includes, for example, equipment for cutting of the reactor pressure vessel into pieces if this alternative should be chosen, and equipment for cutting of RPV internals under water, where remote control is needed. Equipment for some building demolition may also have to be specially manufactured, such as equipment for removal of surface layers of activated concrete in the biological shield.

It is taken for granted in the planning of decommissioning that special equipment will be procured in such a way that it is in place in good time before use, its satisfactory function having been verified by means of full-scale tests in an inactive environment.

A large part of the work of specifying and procuring this equipment will be done during shutdown operation.

5.3 SYSTEM DISMANTLEMENT

5.3.1 General

System dismantlement includes all process systems in the plant's main complex, including RPV and internals. The following are not included in system dismantlement, but are left until building demolition:

- Grouted-in materials. Pool linings in the fuel, component storage and pressure suppression pools are included in system dismantlement, however. The linings are cut away, but the grouted-in materials are left

- Prestressed cables

- Overhead cranes in controlled areas
- Transformers outdoors
- Lighting, power outlets, fire alarms and communication systems. Associated cables are, however, removed in the system dismantlement together with other cables if they lie on the cable racks.

Dismantlement of the process systems proceeds simultaneously at several places in the plant. According to the logical dismantling sequence, the equipment in the reactor containment and the reactor building is removed in a given sequence. At the same time, dismantling is carried out in those parts of the reactor building and in those buildings that have no connection with the reactor containment. The waste treatment plant deals with all rinse water and drainage as long as there are radioactive parts left, and is dismantled last.

The dismantling work starts with preparation of the rooms for dismantling. This is done by a group that works with the work procedure named "Preparation of work site". It includes erection of scaffoldings and marking of activity levels. The group returns several times to the room during the course of dismantlement to rearrange the scaffoldings. At a later phase, the regular power and ventilation systems are replaced with temporary arrangements. Finally, the group's work includes restoration of the work site and reporting.

Ventilation and auxiliary power are retained in the rooms as long as this is practically possible. This means that the process systems can in general be dismantled with the aid of the regular power and lighting systems.

The actual dismantling work starts with the insulating material. Since it is assumed that a small portion of the insulation contains radioactivity due to leakage, the material must be scanned and the contaminated insulation given special treatment. Active material is wrapped in plastic bags. Other material is packaged in the simplest manner possible. After the insulation has been removed, a new marking of activity levels is done on the components.

In rooms with radioactive process systems, the most active components shall be removed first wherever possible in order to minimize the occupational dose.

Pipe cutting is divided into clean methods, for piping with a risk of radioactive contamination, and unclean methods, for other dismantlement. The clean methods are cutting with a circular pipe cutter, sawing and shearing. The pipe ends are provided with plastic caps that prevent spreading of radioactivity.

All waste material from controlled areas is taken to a scanning and packaging site. A suitable space for such a site is the passageway through the plant, with which most of the spaces in the plant have good contact. There are good spaces in the turbine building next to the generator. The waste material can be divided into material known to be radioactive and material that should be inactive. The former is packaged in ISO freight containers, which are provided with radiation shielding when necessary. The latter is scanned and inactive material is placed in suitable shipping cases. It has been assumed in the study that both containers hold 15 m^3.

Prior to shipment, the material is checked out and then it is discharged through airlocks to predetermined spaces outside the station building. There the material will be handled further for final disposal or conventional scrapping.

A number of large components are taken out of the station building without any segmentation, or with only moderate segmentation. These include large heat exchangers and certain turbine parts, where segmentation would cause unnecessary spreading of contamination.

The parts are best disposed of intact. Other non-contaminated large components are diesel engines and transformers, for which a subsequent use should be able to be found.

5.3.2 Systems needed during dismantlement

Dismantlement of systems is commenced when all fuel from the unit has been shipped away from the site. All systems and equipment that are not needed for dismantlement can be taken out of service and their electricity supply disconnected.

A number of systems and functions are needed during the dismantling work:

- The waste station is needed for cleanup of water and treatment of filter and ion exchange resins;
- Drainage systems are kept in operable condition until dismantlement renders this impossible;
- The ventilation systems are kept in normal operation as long as they are required. The risk of airborne activity being spread within the plant will be borne in mind during the dismantling work. Chimney monitoring will be retained even after the fuel is gone, but in simplified form, i.e. only particle collection for subsequent analysis;
- The electric power requirement will gradually diminish when the fuel is gone. Unnecessary busbars and equipment are disconnected and separate power supplies may be arranged to systems essential to dismantlement, such as certain ventilation systems. Power is supplied from existing switchgears;
- Monitoring equipment is adapted to needs during dismantlement. Delimitations are made in the control room so that only systems in operation are displayed. This makes it easy for the operator to keep the status of the system under surveillance;

- Maintenance of buildings and equipment is performed to the extent necessary to prevent personal injuries and water leakage;

- Surveillance and inspection rounds are performed to the requisite extent. The site perimeter fence is classified as an industrial fence as soon as the fuel has been shipped off site. Access control to active areas is retained until the fuel has been shipped off site;

- Service functions in the form of workshops, supply stores, storage facilities, active laundry, personnel quarters, housekeeping and radiological safety are retained to the requisite extent during the dismantlement period.

It is assumed that the dismantling work will be carried out in single shift during normal daytime hours. It is assumed that removal of materials from process areas will take place in double shift. Radiation protection workers and decontamination workers will also work in double shift.

5.3.3 Dismantling methods

Work methods and equipment for removal and cutting-up of piping systems and apparatus are chosen so that the personnel are not exposed to unnecessary radiation doses.

Pipes in active systems are cut into suitable lengths for ease of handling in the process room and other handling up to final disposal. Cutting methods are dependent on size and activity level. There are clean methods, where the surrounding environment has to be protected from radioactive spatter, and unclear methods, where cutting can be carried out faster because the surrounding environment does not have to be protected. The clean methods include cutting with a circular pipe cutter, shearing and sawing. Plasma-arc cutting and cutting with a rotary disc are unclean methods.

All insulating material is removed from piping systems and apparatus before active systems are opened. Most of the insulating material is inactive and can be cleared for free release. A limited quantity may be contaminated due to leakage from stuffing boxes and flange joints in active systems.

Normally, the rooms are also decontaminated before pipelines are cut. When deemed appropriate, extra protective painting or plastic coating of floors is done if there is a risk that active water will penetrate into the concrete during the dismantling work.

Large components (heat exchangers, tanks, ion exchange vessels, overhead cranes and the preheaters and reheaters on the turbine side, etc.) are taken out intact or with minimal segmentation.

Open pipe ends shall immediately be covered with heavy plastic caps, which are secured with tape to prevent spreading of radioactivity. Tight welding may occasionally be necessary. This mainly applies to apparatus that is intended to be transported without transport containers.

Dismantling shall be carried out with certain systems in operation. The electricity supply to ventilation fans and power outlets must not be affected by removal of cables in the plant. This may necessitate separate power supply paths to the equipment that has to be in operation.

The compressed air system will be kept intact until a late stage. Mobile compressors may be used in the final phase.

5.3.4 Communications and material transports

Control of personnel access to controlled areas is done in the same way as during normal operating and refuelling/maintenance work.

The flow of material out of the plant takes place for the most part through existing doors, gates and passageways. In connection with detailed planning of decommissioning, it is important to create large enough areas inside the plant and on the site for interim storage of materials, transport containers etc.

The dismantling work should be divided into a number of sub-projects so that the work can be carried out on several fronts, reducing the total dismantling time. Areas inside the plant that are emptied of equipment at an early stage can be used for buffer storage of materials.

Prior to the start of the dismantling work, a thorough radiological survey has been made of the plant's different system parts. This survey shall provide a basis for activity determination of the waste so that no nuclide-specific measurement has to be performed on each individual waste package or transport container prior to off-site shipment. However, each transport container is intended to be checked with regard to dose rate and presence of surface contamination prior to shipment off the site in accordance with the IAEA's transport recommendations. The surface dose rate on the transport container may not exceed 2 mSv/h and the dose rate at a distance of 2 m may not exceed 0.1 mSv/h.

During the dismantling work, the active material is sorted with regard to how it is to be handled from then on. The following rough classification is made:

- Some RPV material and internals have such high activity levels due to induced activity that they must be transported in a type B container;

- Other material that has to be transported to a final repository is placed in standard ISO freight containers. Depending on the material's activity level, it may be necessary to use an outer radiation shield;

- Low-level material is deposited wherever possible in shallow ground repositories on the site;

- Unrestricted release of material, possibly after decontamination, is done in accordance with limits stipulated by the licensing authorities.

5.3.5 Dismantling of piping and components in active piping systems

Large-diameter pipes are intended to be cut using circular pipe cutters in order to prevent airborne activity as far as possible. The use of circular cutters also means that the dismantling personnel do not have to work in direct connection with the process systems.

In Shippingport and on certain other decommissioning projects, most of the process piping has been cut down with plasma-arc or thermal cutting torches. Both manual and automatic equipment has been used. Thermal cutting methods such as plasma-arc or powder cutting torches have a very rapid metal removal rate, but give rise to aerosols and metal oxide fume that can cause airborne contamination. The metal gases also pose occupational hygiene problems. In the decommissioning cases in question, negative pressure has been created in the piping system and the gases have been filtered before being released to the environment. Within the EC's decommissioning programme, practical tests have been performed with different types of thermal cutting methods. These tests show that use of powder cutting torches with the addition of Al/Fe powder is the most effective method and the gases that are formed can be cleaned in filters.

Hydraulic shears are available for cutting smaller-bore and thin-walled pipes. These hydraulic shears can be mounted on a mobile platform/tractor with telescopic arm. In this way a good reach is obtained for disassembly of thin-gauge steel structures and frames. Thermal cutting methods will be used in the border zone between more active pipes and small-bore pipes.

The scope of different types of cutting will be determined prior to dismantlement of a particular plant. Different methods have been used in connection with alterations and additions, and in the normal case the circular pipe cutter is chosen for the reasons given above. No need for development work is deemed to exist at this point.

Limited disassembly is normally expected for components such as valves, pumps and motors. In cases where only some part is contaminated, this part will likely be removed while the rest of the material is treated for free release.

Very far-reaching disassembly and free release of the material is expected for very large components such as turbines and generators. This is also expected for turbines in BWR plants. Certain parts such as turbine blades may, however, need to be decontaminated before they can be released. Large heat exchangers, such as preheaters and steam dryers/reheaters in BWR plants should also be able to be cleared for unrestricted release. Free release may have to be preceded by a chemical decontamination. Cutting and melting can be a simple and sure method for determining the nuclide content of the material prior to free release. Decontamination and/or melting for free release will probably not be meaningful for heat exchangers and apparatus from the reactor's primary systems. Decontamination of these systems may, however, be valuable to reduce the occupational exposure of the decontamination personnel.

5.3.6 Removal and segmentation of RPV internals

When it comes to the steam separators and steam dryers in BWR plants, if these items cannot be decontaminated they must be segmented under water in order to prevent activity from spreading. RPV internals near the reactor core and core components have been exposed to strong neutron irradiation and become highly radioactive. Segmenting of RPV internals and core components must be done under water in order to obtain sufficient radiation shielding during the work. Owing to the high activity level of the material, it is assumed that it will be placed in cassettes adapted to the core component cask. This handling, filling of cassettes and placement of the cassettes in the core component cask, also takes place under water in a similar manner as fuel handling is currently done. Shipments of core component casks are made routinely to CLAB, so this is a proven handling procedure. It has been assumed that segmentation of the RPV internals takes place under water using the plasma-arc method. The method has been used in Shippingport (USA), JPDR (Japan), BR3 (Belgium) and is planned to be used in TMI (USA).

Hydraulic tools can also be used for smaller and thinner-gauge pieces, such as detector probes and guide tubes.

Plasma-arc cutting is a very efficient method but requires that the cutting nozzle can be held within a close distance from the workpiece. This can give rise to problems, since visibility in the water becomes poor due to the release of oxides and other particles during the cutting work. For further segmentation as a complement to plasma-arc cutting in order to achieve a high packing density in the cassettes, the use of mechanical cutting or electromechanical cutting (spark erosion) tools cannot be ruled out. Cutting with a high-pressure water jet is also a possibility.

Pursuing independent development work in this field in Sweden is not warranted at the present time. However, follow-up of experience from ongoing and planned segmentation of RPV internals in other countries is of great value for the Swedish decommissioning programme. The manipulators that are available on the market, e.g. the equipment from Noell (Germany) that was used in Niederaichbach during 1990-91, should be able to be used with some modifications for segmentation of RPV interns in BWRs and PWRs.

The number of cassettes obtained from segmentation is highly dependent on the packing density achieved.

Considerable savings can be made by achieving a higher maximum weight per cassette, which is an incentive to develop technology for good segmentation of the RPV internals with high activity. It is assumed that these cassettes will be shipped to CLAB for interim storage and then conditioned in the encapsulation plant and deposited in the deep repository.

RPV internals with lower activity levels, e.g. steam dryers and the lower part of the control rod guide tubes in BWR reactors, are deemed to be able to be handled in less qualified shipping cases for deposition in SFR3.

Equipment for cutting and lifting of RPV internals for Forsmark 1 is shown in Figure 5.2 (ref. 12).

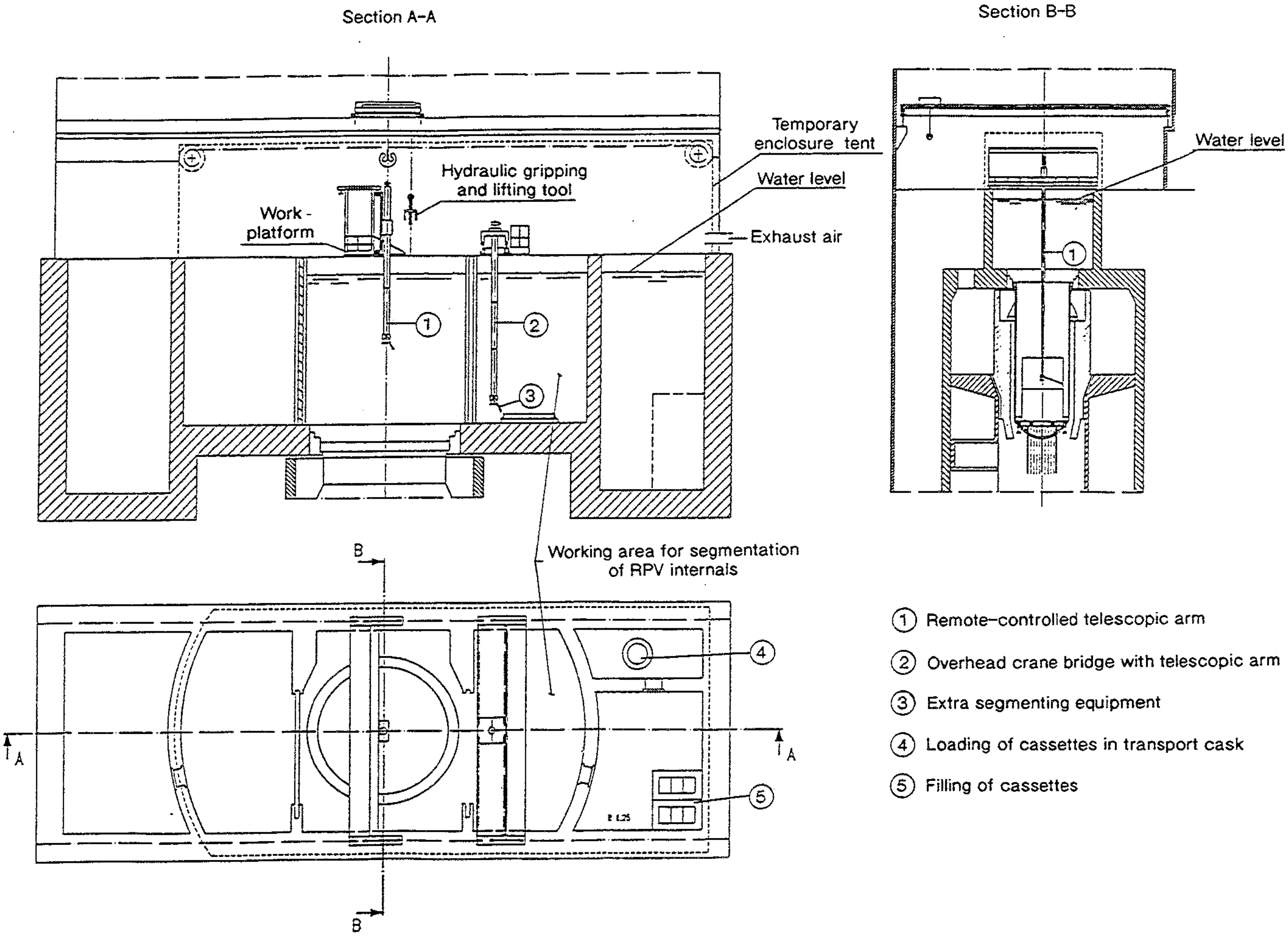


Figure 5.2 Equipment for lifting and cutting of RPV internals in Forsmark 1

Figure 5.3 shows how the core grid in Oskarshamn 3 can be divided into 11 parts plus the ring, which is divided into 8 (ref. 14). Figure 5.4 shows a CLAB transport cassette that is intended to be used for transport of core components. The transport cassette is carried in a special transport cask and is filled in a special position in the fuel pools.

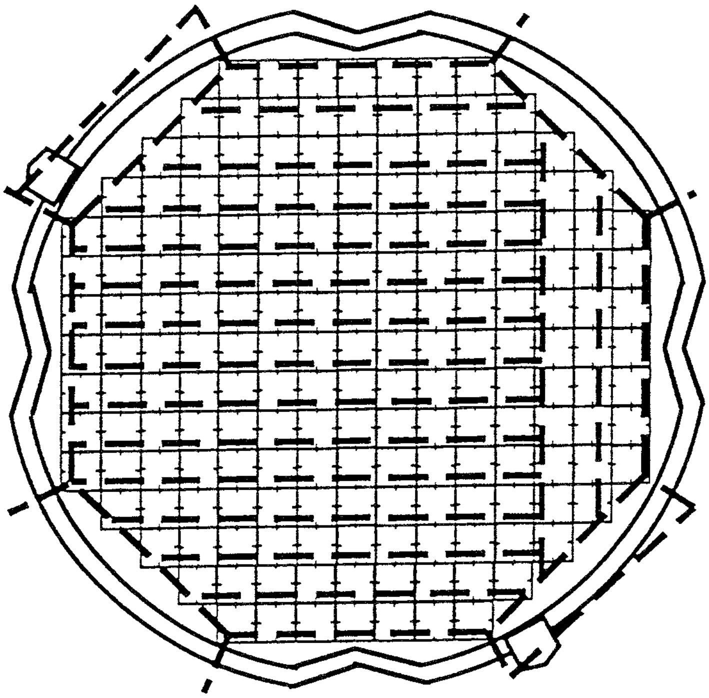


Figure 5.3 Oskarshamn 3 — Segmentation of core grid with ring

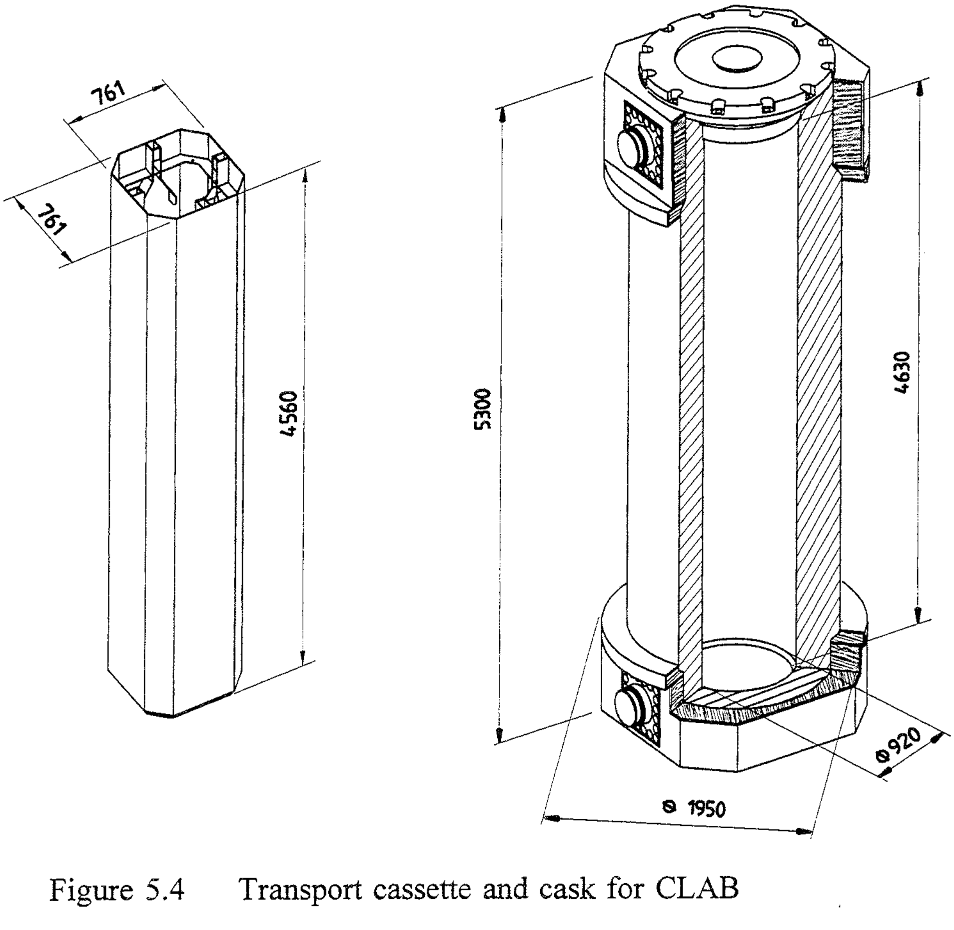


Figure 5.4 Transport cassette and cask for CLAB

5.3.7 Disposal of RPVs

5.3.7.1 General

Disposal of the reactor pressure vessels for both BWRs and PWRs is the area where extensive studies and testing of the technology must be done in order to choose the right principle and methodology for this very resource-demanding work operation.

Two main principles for disposal of RPVs are currently being pursued and examined in parallel within the planning for the Swedish NPP decommissioning, namely segmentation of the vessel and vessel head into pieces and the intact vessel alternative, where the RPV and RPV head are lifted out, transported and disposed of as a whole unit.

Studies have been carried out during 1990-1993 under the auspices of SKB for both of these alternatives to evaluate technology and costs. Forsmark 1 has been chosen as the reference plant for the intact-vessel alternative. Important differences from this reference plant have been studied, such as BWRs of an older type with external primary recirculation circuits and PWR vessels. Forsmark 1 was also chosen as a reference reactor for the segmentation study carried out by Siemens.

5.3.7.2 Intact RPV alternative

The feasibility of removal, transport and disposal of the RPVs as intact units was studied by SKB in the "Intact RPV study" (ref. 9). The results of the study were reported in August 1991 and Forsmark 1 was used as the reference plant. The results of a supplementary study for Ringhals 1 (external pump reactor) and Ringhals 3 (pressurized water reactor) were reported during 1993 (ref. 10).

The fundamental problem in the intact-vessel alternative has been to determine the feasibility and options for carrying out the actual lift of the RPV out of the existing building with available technology and then transporting it to the SFR. A requirement has been that the IAEA's transport recommendations regarding maximum permissible radiation dose rates from the package (the RPV) must be complied with from the start of the lift to final disposal. This necessitates the use of a radiation shield, which significantly affects the lifting and transport weight. The point of departure for determining the feasibility of the intact-vessel alternative has therefore been to determine the thickness and geometry of the radiation shield, based on the estimated activity inventory, and thereby obtain the total handling weight. The possibilities of disposing of the intact RPV with internals included have also been investigated in this context.

The activity in the reactor vessels occurs as both surface contamination and induced activity in the vessel material, especially in the inner stainless steel lining. The radiation-induced activity is completely dominant when it comes to determination of source strengths and dose rates. The estimated activity quantities are based on 40 years of operation followed by 5 years of decay. The inventory of the dominant nuclides in typical Swedish reactors of the BWR and PWR type are shown in Table 5.1.

Table 5.1 Radioactivity inventory (induced) in GBq

Nuclide	BWR Internals	BWR RPV	PWR Internals	PWR RPV
^{59}Fe	$5 \cdot 10^7$	$1 \cdot 10^4$	$1 \cdot 10^8$	$4 \cdot 10^4$
^{60}Co	$4 \cdot 10^6$	$1 \cdot 10^3$	$2 \cdot 10^7$	$5 \cdot 10^3$
^{63}Ni	$6 \cdot 10^6$	$1 \cdot 10^3$	$2 \cdot 10^7$	$3 \cdot 10^3$
Total	$1 \cdot 10^8$		$2 \cdot 10^8$	

Induced activity is completely concentrated to the area around the core, i.e. the length of the fuel assemblies plus a distance of no more than 1 metre above and below its ends.

The activity inventory has thus served as a basis for determining the necessary radiation shielding with and without reactor vessel internals. For the RPVs, the dose rate at 2 m has proved to be crucial when it comes to meeting the requirements in the transport regulations. When it comes to the Forsmark 1 RPV, the relationship between the dose rate at 2 m and the thickness of a steel radiation shield for an empty RPV (without internals) is shown in Figure 5.5.

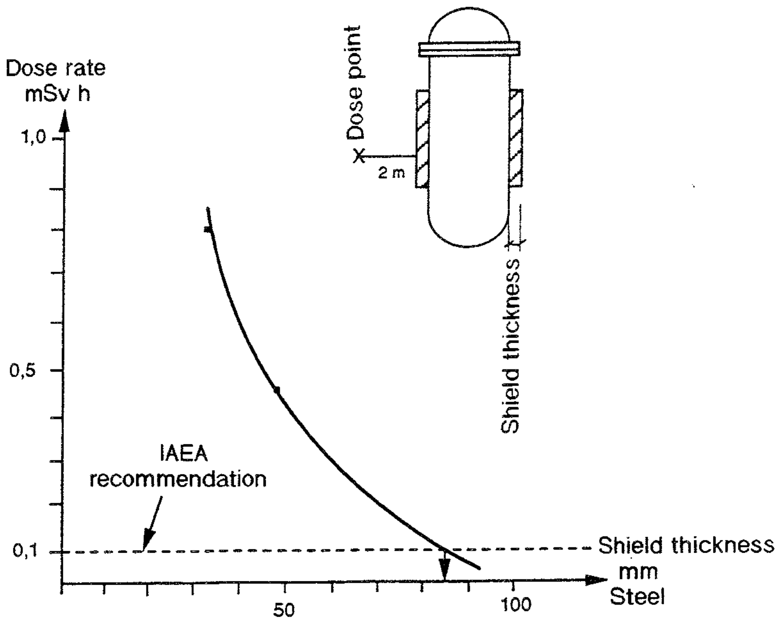


Figure 5.5 Dose rate at 2 m from empty RPV as a function of radiation shield thickness (Forsmark 1).

The result is thus a necessary radiation shield thickness of about 85 mm, corresponding to a weight of 90 tonnes in the case of Forsmark 1. The total lifting weight for an empty reactor vessel with head and radiation shield is then about 900 tonnes. Equivalent calculations for the case with internals included gives a radiation shield weight of nearly 400 tonnes and a total lifting weight of about 1500 tonnes.

Rough calculations of the building structure for Forsmark 1 have shown that loads equivalent to a lift of up to 1000 tonnes can be borne with an acceptable margin of safety. It is then assumed that the lift is performed in the same manner as when the RPV was put in place. A proposal for lift-out and shipment is shown in Figure 5.6.

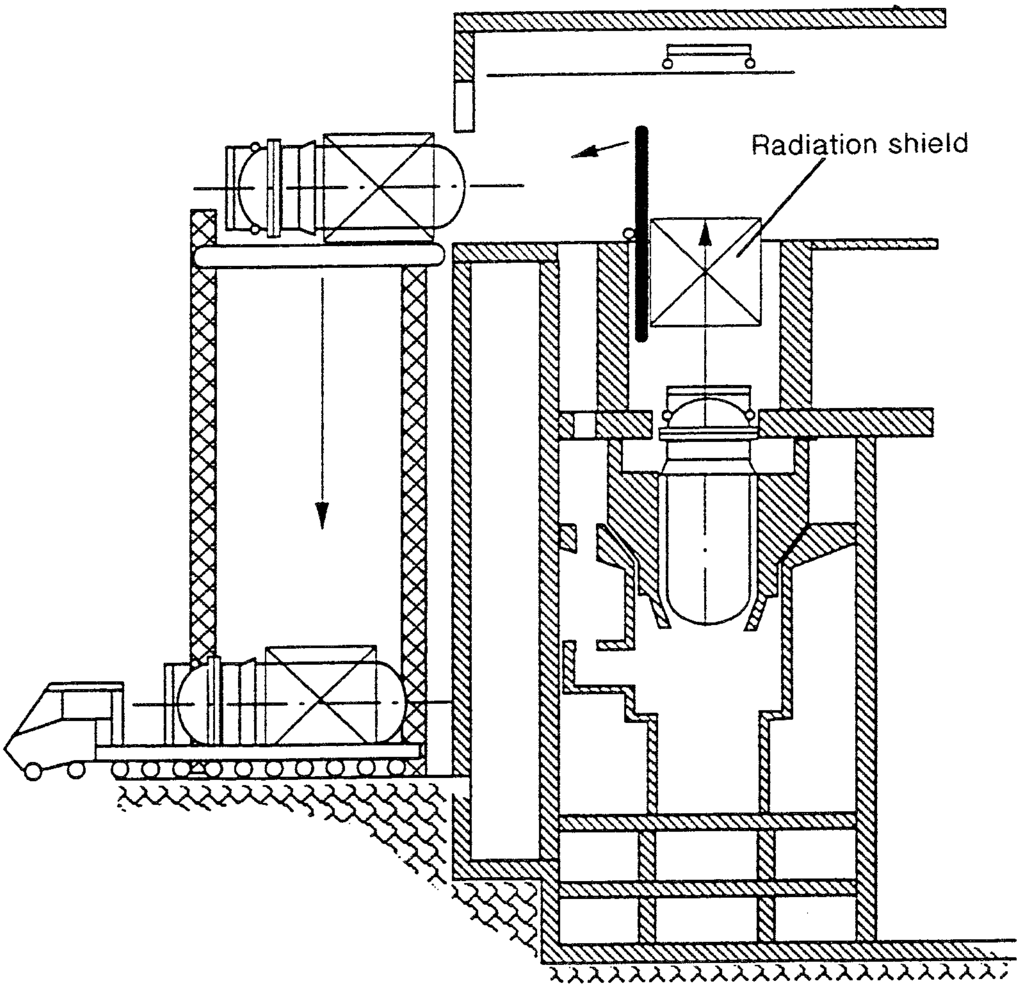


Figure 5.6 Lift and shipment of intact RPV (Forsmark 1)

The radiation shield, which is illustrated schematically in the figure, consists of two halves which are clamped around the RPV in conjunction with the vertical lift and then accompany it during lifting and shipment and are disposed of together with the vessel.

Planning for a total lift of up around 1500 tonnes, which is the case if the RPV internals are included, has been judged in the intact-vessel study to be unrealistic and has therefore not been further investigated. The practical work involved in removal and disposal of an intact RPV has therefore only been studied for a plundered RPV. The different aspects of the work that have been dealt with are as follows:

- Radiation protection measures
- Removal of insulation
- System and function requirements
- Work on buildings and site work
- Disconnection of RPV
- Lift and shipment
- Interim storage and disposal
- Scope of work, occupational doses and costs

When it comes to the other Swedish NPPs, fundamental differences from Forsmark 1 have been examined briefly. In the case of Ringhals 1, which is a boiling water reactor with external primary recirculation circuits, there is additional work with cutting of the twelve pipe connections. In contrast to the Forsmark 1 RPV, which is suspended in a skirt just underneath the head flange, the Ringhals 1 vessel rests in a cradle which is welded to the spherical bottom. The cradle is undergrouted with concrete and is attached by a bolt ring. Accessibility is poor and disconnection of the tank is judged to be a laborious operation.

The proven steam generator replacement technique can be used for removal and lift-out of the intact RPV at the three PWR reactors in Ringhals. Figure 5.7 shows lift-out of the steam generator in Ringhals 2. The PWR vessels have much smaller dimensions than the largest BWR vessels, and the total handling and lifting weight is only about half or 500 tonnes at most. The biggest problem with the PWR vessels is the higher activity inventory, which requires thicker radiation shields. Lift-out and shipment of the intact RPV in Ringhals 3 is illustrated in Figure 5.8.

The conclusion of the study is that it is fully feasible from both the safety and economic viewpoints to lift out the Forsmark 1 RPV and deposit it in SFR as an intact unit. The supplementary studies that have been conducted for other NPPs show that this conclusion applies to all Swedish NPPs of the BWR and PWR type.

The intact-vessel alternative is thus a very interesting strategy when it comes to planning of the Swedish NPP decommissioning programme.

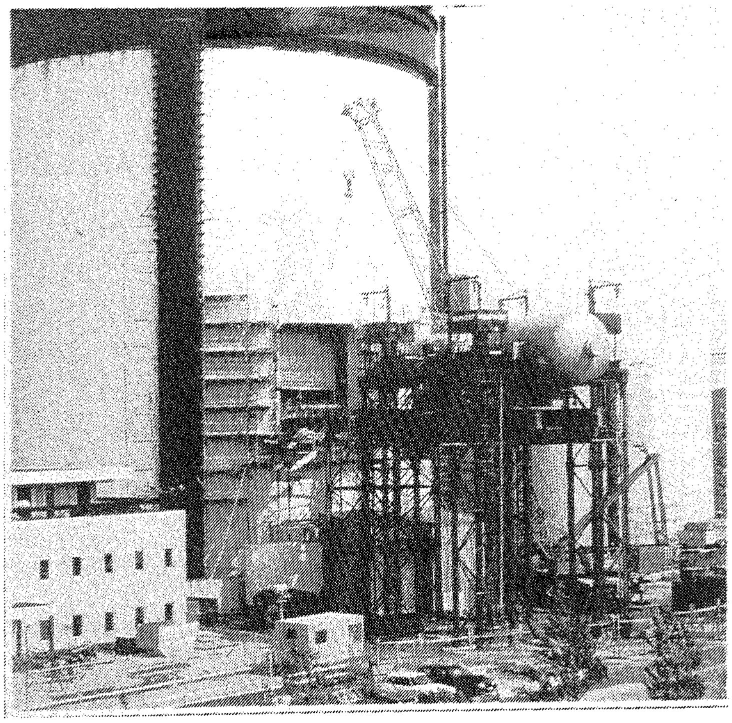


Figure 5.7 Lift-out of steam generator in Ringhals 2

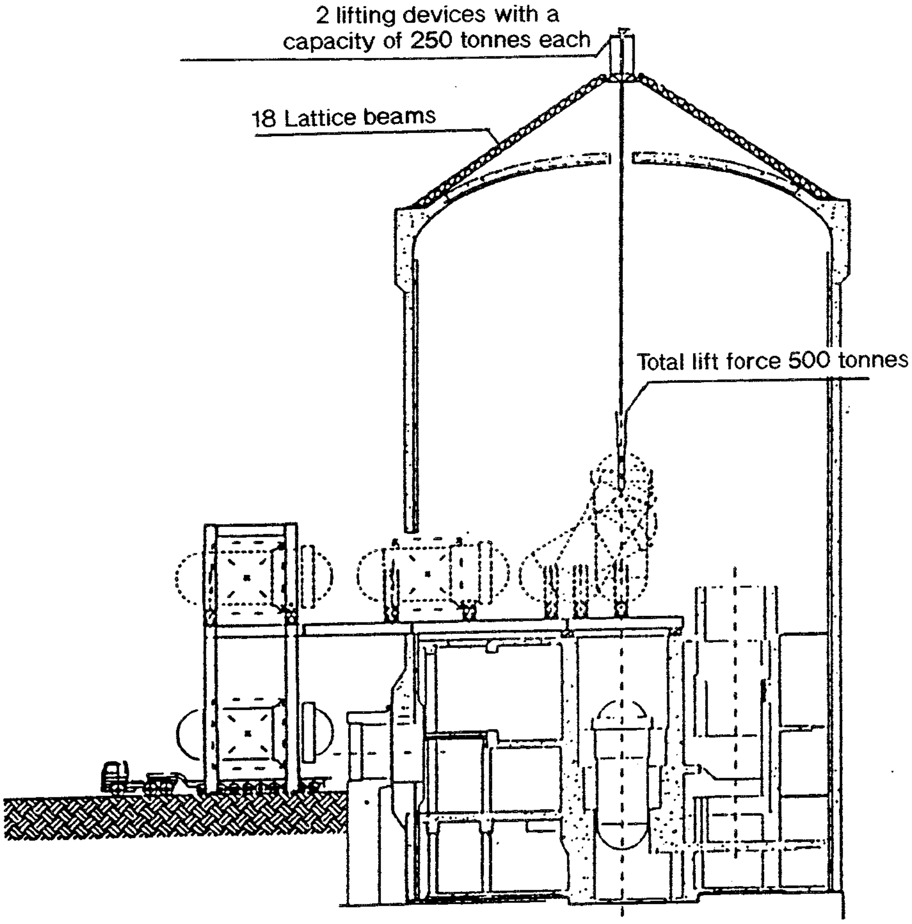


Figure 5.8 Lift-out and shipment of intact RPV (Ringhals 3)

5.3.7.3 Segmentation of RPVs

The alternative to removing and disposing of the reactor vessels as intact units is to segment them into pieces of suitable size. The pieces are then handled and transported in radiation-shielding containers to SFR for final disposal.

The so-called segmentation alternative has been studied separately and the results reported during 1993 (ref. 12). The purpose of this study has been to update technology and costs in order to obtain a good basis for comparison of the two alternatives intact vessel and segmentation. In the case of the segmentation alternative as well, Forsmark 1 has been used as a reference plant and design data such as the activity inventory and the dose rate are the same as those used in the intact-vessel study.

Segmentation of the reactor vessel is done after the vessel has been plundered of its internals. Segmentation is carried out using mechanical saw blades that are powered hydraulically and controlled and supervised from the reactor hall level. Cutting is done in air, but the water level in the vessel is kept as high as possible and lowered as segmenting progresses. In the study, which is based on the latest experience in the field, for example from the BR-3 reactor, it is assumed that a number of vertical cuts are made, after which a circular, horizontal cut is made to free the individual pieces. The size and shape of the pieces are chosen with a view towards handling, packaging in transport containers and disposal in SFR. The principle of the different work steps is illustrated in Figure 5.9. The same method has been used for segmentation of the thermal shield in BR-3 in Belgium, see Figure 5.10.

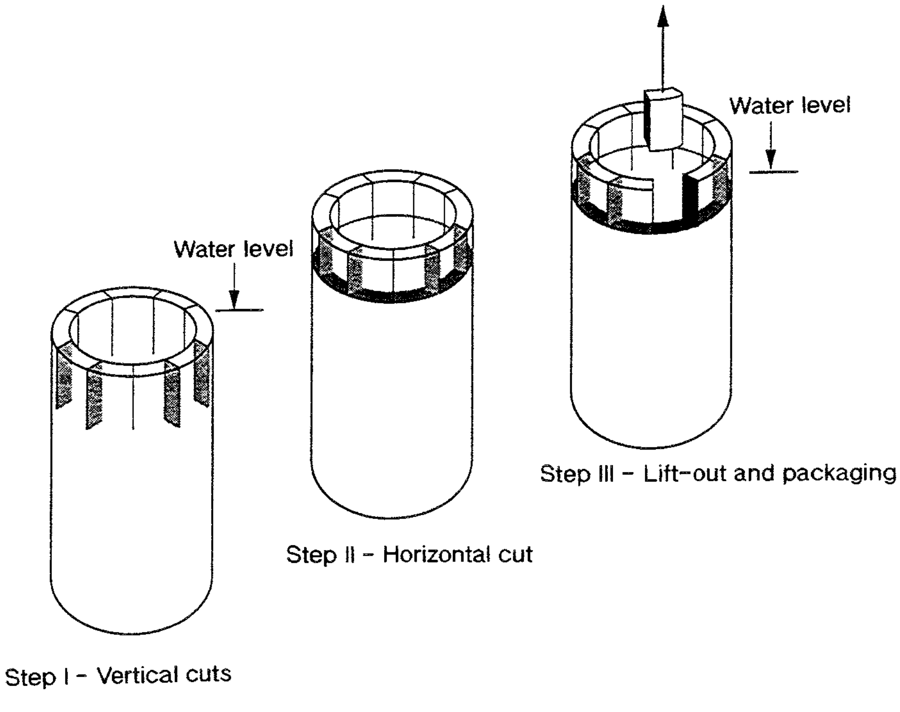


Figure 5.9 Work steps for segmentation of RPV

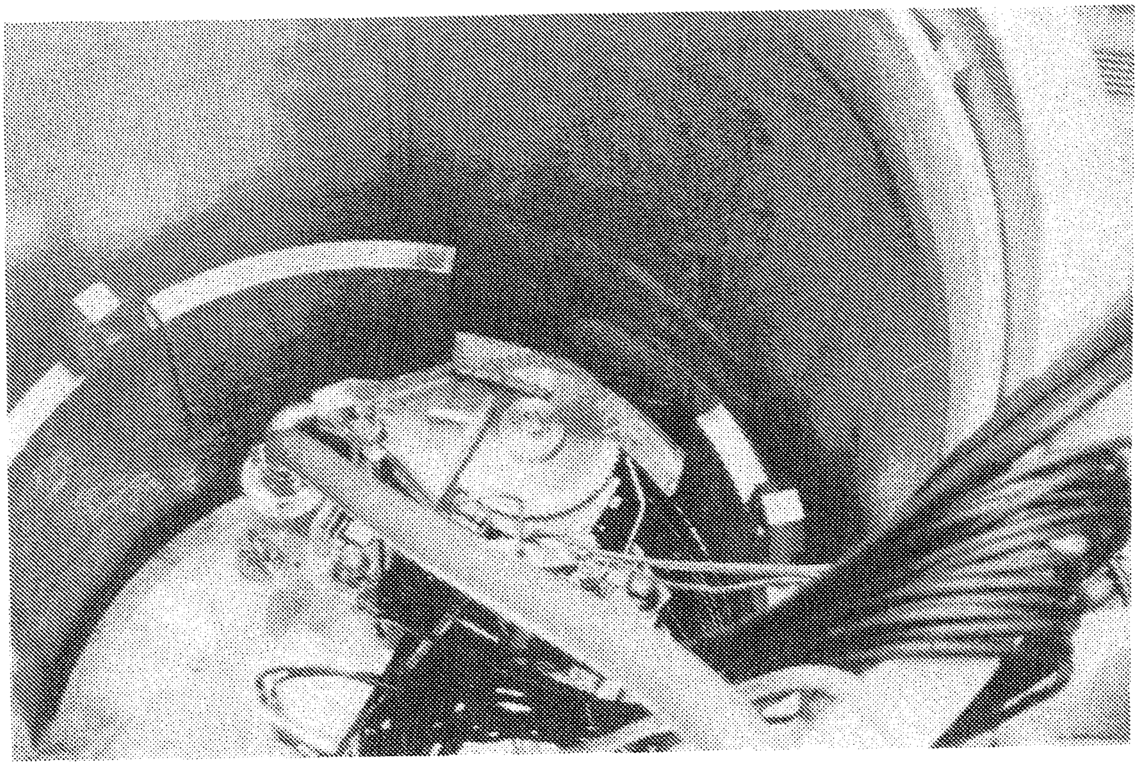


Figure 5.10 Segmentation of the thermal shield in BR 3. (Photo: Siemens)

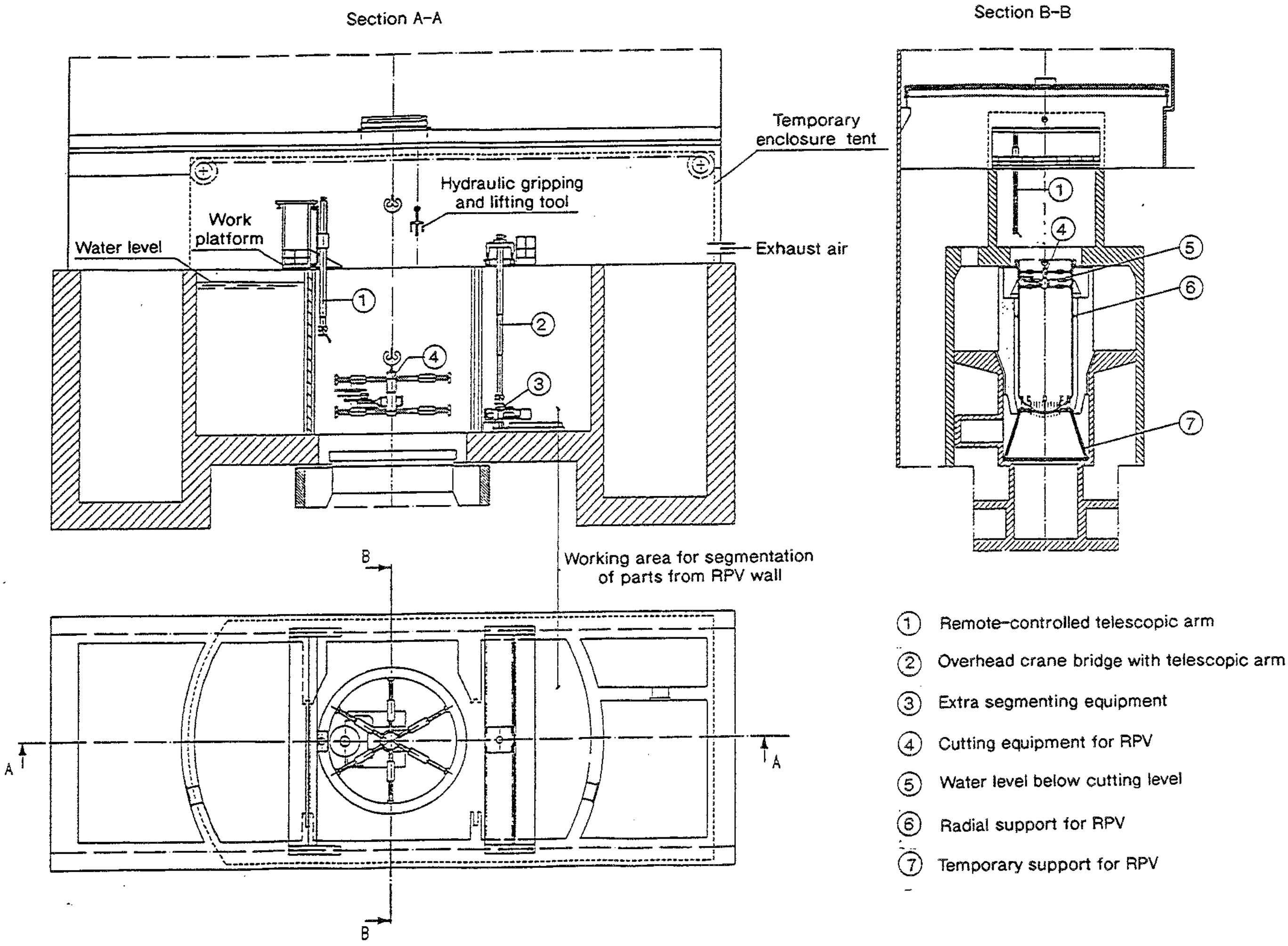


Figure 5.11 Segmentation of "suspended" RPV. Cutting equipment and support structure.

In older BWR plants with external primary recirculation circuits the RPVs rest on their bottoms inside the reactor containment, so no extra support is needed underneath the tank. The internal pump reactors such as Forsmark 1 are suspended in a flange just underneath the vessel head flange. Cutting below this level therefore requires a temporary support structure to hold up the RPV. The support structure and the cutting equipment for the RPV are shown in Figure 5.11.

5.4 BUILDING DEMOLITION AND SITE RESTORATION

When system dismantlement has been concluded and all spaces have been cleaned, demolition of the buildings is begun. First all active and contaminated concrete is demolished and hauled away. After a thorough activity check, the building is then released from radiological restrictions and conventional building demolition commences. In this study, the costs of demolishing inactive buildings, such as personnel and storage buildings, has also been included. However, it is probable that these buildings will be turned over to the subsequent enterprise on the site. Demolition is concluded with restoration of the site.

5.4.1 Active building demolition

After the process equipment has been dismantled and shipped away, and all contaminated surfaces have been decontaminated, active building demolition takes over. This includes all concrete that has become active, due to both neutron bombardment and activity spillage.

Induced activity is only present in the biological shield. Contaminated concrete is assumed to be present behind pool linings, in pump sumps and on floors in process rooms that have been contaminated. Removal of grouted-in parts of the stainless steel lining in pools and pump sumps is also included in active building demolition.

The work begins by removal of the layer of concrete with induced activity in the reactor containment. Here it is assumed that the layer is 1 metre thick. Removal of this layer is carried out e.g. with the aid of an electrohydraulically powered and remote-controlled pavement breaker.

The machine operates from a vertically adjustable lift table. The loosened concrete is collected in a hopper hung next to the wall. From the hopper the waste is dropped down into a concrete crusher and then vacuumed into a container for shipment and disposal in SFR.

The stirred-up dust is laid with a water spray from a nozzle attached to the hydraulic jib. The water flow rate is adjusted and the water atomized to a fine spray so that the water is absorbed by the concrete dust and water spillage is avoided.

This method of chipping off concrete with a pavement breaker was used for demolition of the biological shield in the R1 research reactor in Stockholm.

Prior to breaking, the open top part and the bottom of the biological shield are covered so that a tight enclosure is obtained. This enables controlled and filtered ventilation to be achieved during spalling. Concrete waste from the spalling work is vacuumed up by a vacuum loader.

At the same time as the concrete layer with induced activity in the biological shield is removed, remaining parts of the lining sheet in the wetwell and other pools can be removed. Since the lining sheet has already been flushed clean and removed during process dismantlement, all that remains is the grouted-in material, where the water-wetted surfaces are assumed to be radioactive. Contaminated surface concrete in the pool and on the floor is removed with an abrasive water jet. The water-jet nozzles are mounted on a special rig. The removed concrete is vacuumed up by a vacuum loader.

5.4.2 Inactive building demolition

After all contaminated concrete has been removed, packaged and shipped away, conventional demolition takes over. After scanning and free release of the building in question, demolition begins in the uppermost levels of the nuclear power unit.

The roofing and roof beams as well as overhead cranes are removed with the aid of lift cranes. Then the concrete walls are broken so that sections with a size of about 2x3 m are cut out by a pavement breaking machine and lowered to the ground on the outside of the wall. The same procedure is used on the floor structure. Transfer of material to the outer wall is carried out by a small mobile crane that operates from the floor structure in question.

Detailed demolition plans must be prepared for the fuel and component storage pools in the BWR plants, and demolition must be carried out in such a sequence as to guarantee the stability of the pool section that is supported on the containment and juts out with heavy loads.

The wall of the reactor containment, which is about 1.0 m thick, has a grouted-in steel lining and is provided with pretensioned steel reinforcement and dense non-tensioned reinforcement. It is segmented by cutting with thermic lances into blocks of appropriate size, which are disposed of under ground in the reactor building.

The containments in the Ringhals PWR plants have pretensioned cables running in oil-filled ducts. This pretensioned reinforcement must be removed before the demolition work is begun.

The concrete slabs in the turbine base are 2-3 m thick. These slabs can be demolished by drilling with thermic lances and hydraulic splitting in the drilled holes.

6 WASTE MANAGEMENT

6.1 CLASSIFICATION OF WASTES

The waste products from decommissioning of nuclear power plants have very different activity levels, ranging from inactive building materials to highly radioactive material from the RPV internals. These waste products thereby make different demands on handling and final disposal. In recognition of this, the waste is divided into four categories:

- Waste that can be released without restriction
- Waste that can be disposed of on the site
- Waste that can be disposed of in SFR
- Waste that must be disposed of in the deep repository

Free release

Material from NPPs is cleared for free release today in accordance with special regulations issued by the National Radiation Protection Institute (ref. 29). Free release material can be used freely without restrictions or disposed of as waste on an uncontrolled building tip or municipal sanitary landfill. The current maximum permissible mass activity concentration for free use of material that has been in controlled areas at NPPs is 100 Bq/kg. A raising of the limit to 1000 Bq/kg is being discussed. The corresponding limit for material that can be disposed of as non-radioactive waste is 5 kBq/kg for beta- or gamma-emitting nuclides. The total quantity of activity that is taken out for disposal from all reactors on a site is limited to 1 GBq/y.

Besides free release in accordance with the aforementioned regulations, material can be released from case to case after testing by the National Radiation Protection Institute, SSI. The latter practice is applied in many countries. Attention has been given to the potential problems with free release limits in different countries for several years. A great deal of work is being done internationally today on harmonization of the limit values for free release of material. The results of this work may well affect the quantity of waste that has to be disposed of on decommissioning. Melting technology has also undergone considerable development in recent years, which may also lead to a substantial reduction of the quantity of waste that needs to be disposed of.

On-site disposal

Today permits exist for shallow land disposal at Oskarshamn, Ringhals and Forsmark. The permits stipulate that the total amount of activity buried on the site may not exceed 100 GBq. Furthermore, the average activity concentration per package may not exceed 300 kBq/kg for radionuclides with a half-life longer than five years.

It is assumed that the existing shallow land repositories will be full at the time of decommissioning and will therefore not be available for disposal of decommissioning waste. New permits will be required to dispose of decommissioning waste in shallow land repositories similar to those that exist today.

Disposal in SFR

Most of the decommissioning waste that requires final disposal will be emplaced in SFR 3. The activity content of the waste is dominated by ^{60}Co, which has a half-life of 5 years.

Disposal in the deep repository

Some of the RPV internals contain long-lived nuclides such as ^{63}Ni, ^{59}Ni and ^{54}Nb with such high activity levels that they cannot be disposed of at SFR. These components must therefore be disposed of in the deep repository after interim storage at CLAB for several decades.

6.2 WASTE QUANTITIES

The quantity of waste that has to be managed in conjunction with the decommissioning of the NPPs has been determined in detailed studies of the material quantities in Oskarshamn 3 (ref. 8) and Ringhals 2 (ref. 6). The concrete quantities are based on an updated study of building demolition at the Swedish NPPs (ref. 5). The results have been summarized in Tables 6.1 and 6.2.

The material quantities for other BWRs have been estimated based on the results for O3. The results have been weighted with regard to size and design differences. The material quantities for Ringhals 3 and 4, which are PWRs like Ringhals 2, have been assumed to be identical to those for Ringhals 2. Some process wastes, e.g. ion exchange resins and filters, are also obtained from decommissioning.

Table 6.1 Waste quantities for Oskarshamn 3 BWR, in tonnes

		Active	Inactive
1.	Reactor tank (incl. internals)	760	
2.	Handling equipment	136	122
3.	Valves > 65 ND and actuators	130	116
4.	Sundry components	97	50
5.	Cables and racks		704
6.	Instruments	4	2
7.	Steel structures		1,032
8.	Air treatment	10	1,076
9.	Large heat exchangers	77	47
10.	Lining sheet		106
11.	Containment dome	35	
12.	Pumps	35	14
13.	Overhead cranes		485
14.	Tanks	268	247
15.	Turbine components	4,573	1,261
16.	Electrical components		482
17.	Electrical cubicles		1,042
18.	Process piping	659	532
19.	Insulation	13	244
20.	Heating/Plumbing		263
21.	Operational waste during decom. period	400	
22.	Sand from delay tank	1,050	
23.	Concrete with induced activity	555	
24.	Other concrete	855	318,570
	Total: (excl. inactive concrete)	**9,660**	**7,830**

Comments on Table 6.1:

- In item 1, the RPV internals consist of 132 t in transport cassettes for CLAB and 101 t in ISO freight containers

- Item 15 includes 3,000 t for low-pressure turbine under "Active" waste and certain other components

- For items 22 and 23, 2.4 has been assumed for the specific gravity of the concrete

Table 6.2 Waste quantities for Ringhals 2 PWR, in tonnes

		Active	Inactive
1.	Generator section		
2.	Turbine level		2,168
3.	Turbine systems		3,100
4.	Intermediate building		230
5.	Active auxiliary systems building	1,370	
6.	Inactive auxiliary systems building	90	
7.	Filter building	50	
8.	Fuel building	71	
9.	Containment	1,959	
10.	RPV with internals	330	
11.	Concrete with induced activity	450	
12.	Operational waste during decommissioning	400	
13.	Other concrete	525	
	Total:	**5,245**	

Table 6.3 shows the quantity of decommissioning materials from all units in tonnes.

Table 6.3 Waste quantities from all units in tonnes.

	Active material						Inactive material		
Unit	**RPV (incl. internals)**	**Other active systems**	**Oper. waste**	**Sand**	**Concrete**	**Total**	**Concrete**	**Other**	**Total**
B1	650	3,170	400	250	900	5,370	172,350	4,960	177,310
B2	650	3,170	400	250	990	5,460	196,350	4,960	201,310
F1	760	5,950	400	1,050	1,230	9,390	229,500	7,700	237,200
F2	760	5,950	400	1,050	1,230	9,390	200,200	7,700	227,900
F3	760	6,040	400	1,050	1,440	9,690	322,920	7,830	330,750
O1	650	2,820	400	250	615	4,735	135,150	4,420	139,570
O2	650	3,170	400	250	900	5,370	175,500	4,960	180,460
O3	760	6,040	400	1,050	1,410	9,660	173,850	7,830	181,680
R1	650	4,700	400	350	915	7,015	190,200	5,910	196,110
R2	330	3,540	400		975	5,245	267,300	8,140	275,440
R3	330	3,540	400		975	5,245	198,600	8,140	206,740
R4	330	3,540	400		975	5,245	219,300	8,140	227,440
Total (t) incl. 10% allowance	8,010	56,790	5,280	6,110	13,810	90,000	2,751,340	88,760	2,840,100

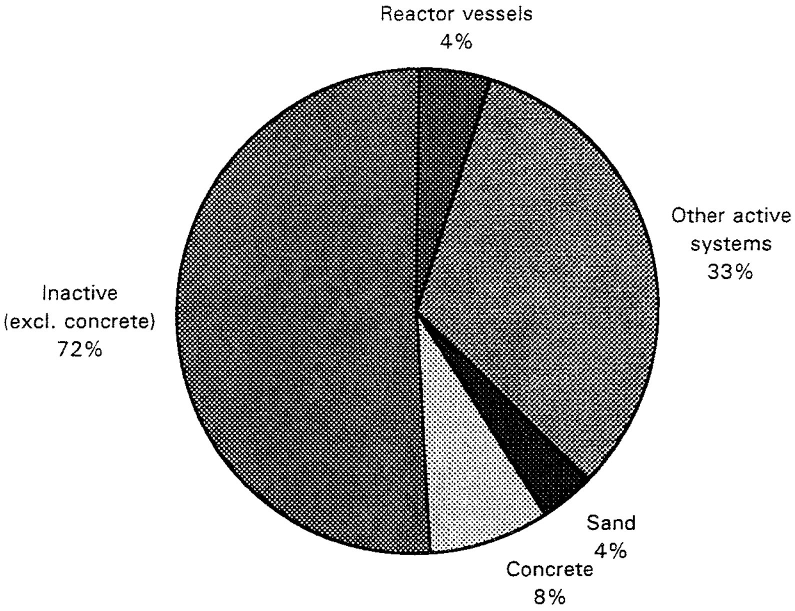


Figure 6.1 Waste quantities from decommissioning of the Swedish NPPs

6.3 TREATMENT OF WASTES

With regard to treatment, the wastes can be divided into the following groups:

- Direct decommissioning waste
  - Scrap metal
  - Concrete and sand
  - Insulation
  - Other
- Process waste
  - Ion exchange resins
  - Filters
  - Protective clothing etc.

The process waste is treated in a similar manner as during the operating period, i.e. ion exchange resins are solidified or dewatered and filters are compacted.

Concrete and sand are placed directly in suitable transport packages.

Components that are not placed in containers or packages are painted or plasticized to prevent radioactivity from spreading.

The least possible treatment is foreseen for the direct decommissioning waste. Scrap metal is cut directly on dismantlement into suitably sized pieces for transport to final disposal. Open pipe ends are sealed with rugged plastic caps in order to prevent the spread of loose activity. Low-level materials are placed directly in transport containers, which can be deposited in SFR. Materials that require radiation shielding are transported with an extra outer radiation shield over the container.

The above describes the main alternative for treatment and handling of the decommissioning waste. In recent years, various technologies have also been developed to reduce the quantity and volume of waste (particularly scrap metal) that has to be emplaced in a final repository. A possible scenario for such treatment is described in brief below.

6.3.1 Melting of contaminated scrap

The technologies that can be considered for free release of scrap metal include:

- monitoring
- decontamination
- melting

Materials must always be monitored (i.e. their activity must be measured) prior to free release. Owing to the fact that it is often difficult to determine surface contamination and activity content solely by means of monitoring, melting has emerged as an economical alternative. Then the specific activity of the material can easily be determined (measured) with good accuracy and its volume reduced. The quantity of scrap that can be released from restrictions is expected to be greater than for the monitoring alternative. In some cases it can be meaningful and economical to decontaminate the material before melting.

A special study (ref. 11) has been carried out for the purpose of investigating how melting could be employed in connection with the decommissioning of Swedish NPPs. Today there are four plants where contaminated scrap is melted:

- The Carla plant, Siempelkamp, Germany
- The Studsvik melting plant, Sweden
- The INFANTE plant, Marcoule, France
- The SEG plant, Oak Ridge, USA

Table 6.4 shows some data on the plants:

Table 6.4 Data on melting plants

Plant	Start year	Capacity (tonnes)	Quantity melted through June 1993 (tonnes)
Carla	1989	3.2	7,000
Studsvik	1987	3	1,500
INFANTEA	1992	12	3,600
SEG	1992	20	2,000

Foreign melters of contaminated scrap metal focus on reuse of the material within the nuclear field, for example in the manufacture of cast-metal waste containers or radiation protection blocks, partly due to the fact that set activity limits for free release are lacking. Studsvik focuses on free release of material from components with a suitably low contamination level for the purpose.

Free release of the ingots from melting takes place in batches on receipt of a permit from the National Radiation Protection Institute from case to case. So far the highest permissible activity concentration for free release in ingots from Swedish scrap has been 0.8 Bq/g. If the ingots have higher activity levels after melting, they are stored until the ^{60}Co (the largest activity component) has decayed to an acceptable level.

Two alternatives for melting in Sweden are described in the study: A large central furnace to which all waste is shipped, and a furnace on each site. The latter alternative is deemed to be the most likely.

Assuming a reasonable storage period of 20-25 years, components with up to 20-25 Bq/g can be melted for free release. If this philosophy is applied to the scrap metal from decommissioning of Oskarshamn 3, it is judged that the waste quantity for final disposal can be reduced from 6,200 to 2,600 tonnes. The estimate is based on a calculation of the material quantities assuming a change of the free release limit from 1 to 20 Bq/g.

The cost of melting is estimated at about SEK 10/kg with a furnace on each site. Melting capacity is 2,500 t/y. The marginal cost for SFR 3 is estimated to be roughly the same amount per kg.

6.4 TRANSPORT OF DECOMMISSIONING WASTES

SKB's transportation system will be used for shipments of decommissioning waste. This system consists of a ship, terminal vehicles and transport containers.

For the most part, the containers used for transport of operational waste from the NPPs can also be used for transport of decommissioning waste, namely:

- Core component casks, which are type B approved
- Radiation-shielding containers
- Standard ISO freight containers, full- or half-height

Most of the material that cannot be released from radiological restrictions is placed in ISO freight containers. This study has assumed the use of ISO freight containers with a volume of 15 m^3. The maximum content has been limited so that the total weight does not exceed 20 tonnes.

Shipments of radioactive waste within Sweden must be approved by SSI (the National Radiation Protection Institute). The shipment shall meet the requirements of the IAEA's transport recommendations (ref. 28). This means that the dose rate may not exceed 2 mSv/h on the surface or 0.1 mSv/h at a distance of 2 m. The ISO freight container may, however, contain more, since a radiation shield can be placed on the container during transport. In this study it has been assumed that the direct decommissioning waste is transported with a radiation shield on the ISO freight container at high dose rates. The alternative is the ATB container.

Some types of equipment are not placed in freight containers. These includes high-level RPV internals and large unique components. In BWRs, the internals that have been installed closest to the core must be transported in core component casks. In PWRs, some of the RPV material requires this type of transport. Large unique components such as heat exchangers and tanks are deemed unsuitable to be cut up, due to the risk of activity spreading. These components therefore do not fit in existing transport containers and can be transported without any special packaging.

It is believed that a large portion of the turbine systems, about 3,000 tonnes for O3, can be released without restriction after simple decontamination. This has not been taken into account in this study.

It is assumed that process waste arising in conjunction with decommissioning will be embedded in moulds of the same type as those used for operational waste. Approximately 100 moulds per unit are projected to arise. They are shipped to SFR in ATB containers.

Assuming that no active waste is disposed of locally, the total transport requirement for the various units is estimated as per Table 6.5.

Table 6.5 Shipments of decommissioning waste from the Swedish NPPs in different types of transport containers (ISO freight containers have an inside volume of 15 m^3)

Unit	**ISO container**	**ATB**	**Special transp.**	**Core component casks**
Barsebäck 1	298	6	38	56
Barsebäck 2	307	6	38	56
Forsmark 1	487	6	115	56
Forsmark 2	487	6	115	56
Forsmark 3	519	6	75	56
Oskarshamn 1	255	6	34	56
Oskarshamn 2	298	6	38	56
Oskarshamn 3	516	6	75	56
Ringhals 1	348	6	111	56
Ringhals 2	372	6	26	71
Ringhals 3	372	6	26	71
Ringhals 4	372	6	26	71
Number of units incl. 10% contingency	5,095	83	789	717

6.5 DISPOSAL OF DECOMMISSIONING WASTES

Most of the radioactive decommissioning waste is planned to be disposed of in SFR, Final Repository for Radioactive Operational Waste, at the Forsmark Nuclear Power Station. SFR is built underground in rock at a depth of about 50 metres. It is situated beneath the seabed, approximately one kilometre offshore from the harbour in Forsmark.

An addition is planned to SFR, SFR 3, to accommodate the decommissioning waste. It is planned to consist of five rock vaults, see Figure 2.2. Four of the rock vaults are intended for the low-level decommissioning waste that is transported to SFR in standard ISO freight containers or as large components without packaging. The freight containers will not be opened in SFR, but will be emplaced as units. Emplacement of the containers in the final repository is done by fork-lift truck, see Figure 6.2.

The fifth rock vault is intended for intermediate-level waste transported to SFR in ISO freight containers with a radiation shield. This rock vault contains an unloading position where the transport containers are opened and a number of concrete pits into which the waste is placed. If necessary, the waste can be grouted with concrete in the pits.

The total quantity of Swedish NPP decommissioning waste that is planned to be deposited in SFR is about 144,000 m^3.

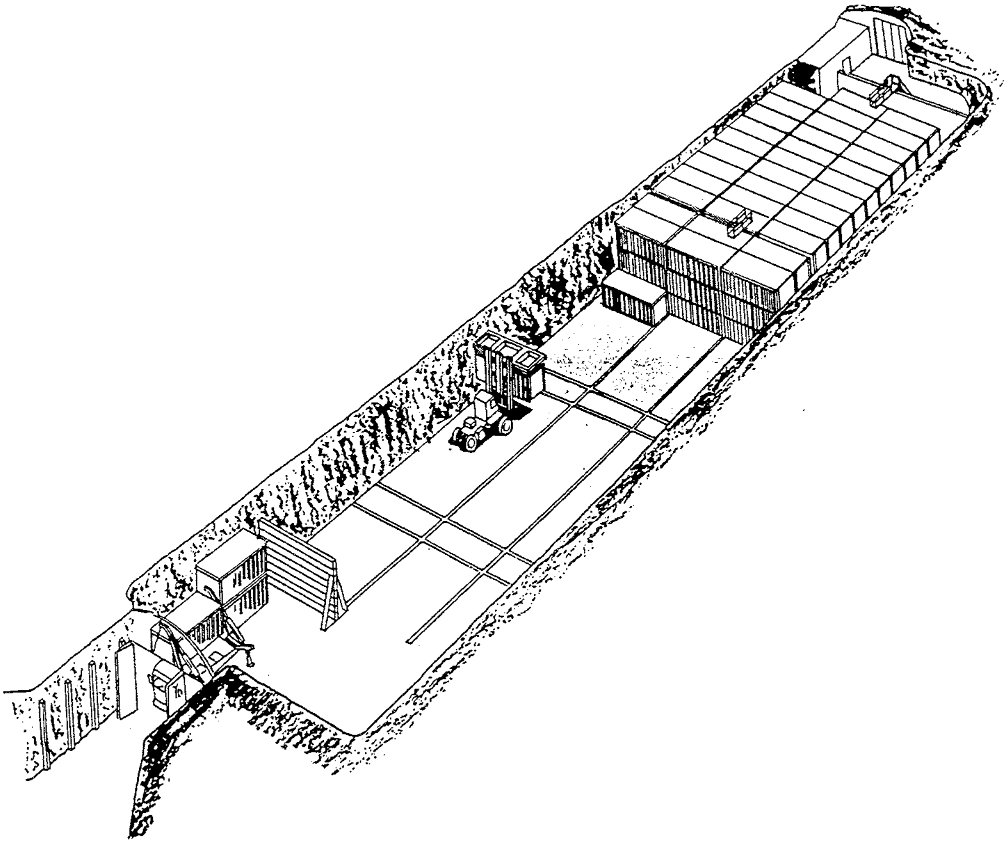


Figure 6.2 Emplacement of low-level waste in freight containers in SFR 3

The RPV internals can also be emplaced in SFR. This requires a special area for unloading in view of the high radiation level. This area has not been studied here. The alternative, to dispose of them in connection with the deep repository after several decades of interim storage in CLAB, is assumed in this study. This alternative is described in ref. 2.

Alternatively, a large portion of the low-level waste can, as has been mentioned above, be disposed of on the site, for example in those portions of the reactor facility that are located under ground. After emplacement, the material is covered with a layer of soil about one metre thick.

Inactive waste that cannot be reused is primarily used as filler material for restoring the power plant site. Excess material can be dumped on an ordinary building tip.

7 METHODOLOGY FOR COST ESTIMATION

7.1 GENERAL

In the cost estimation, the decommissioning work has been divided into a number of sub-areas as follows:

- Shutdown and service operation
- System dismantlement of BWR/PWR
- Building demolition and site restoration

This chapter provides a description of the methodology for the calculations for the different sub-areas.

7.2 SHUTDOWN AND SERVICE OPERATION

The costs of shutdown and service operation include the power plant owner's personnel from the time the reactor is taken out of service until the active dismantlement is completed. As a basis for the cost calculation, manpower estimates have been made based on the present-day organization. The estimates have been made using a simplified model, since it is difficult today to go into detail and describe the organization after shutdown. Other activities on the site, which would reduce common costs, have not been credited in the calculation.

Three main cases have been distinguished as far as manpower requirements are concerned:

1. The period from when the reactor has been taken out of service until all fuel has been shipped off site.

   As long as fuel remains in the unit's fuel pools, continuous shift personnel are required. Safe decay heat removal is maintained, with the same requirements as during normal refuelling outages for redundant cooling systems, electricity feeds and activity and process monitoring. System decontaminations, radiological surveys of the plant, waste management and decontamination planning are also carried out during this period.

2. The period from when the fuel has been shipped off site until system dismantlement is concluded.

   Here personnel are on hand for operation and maintenance of the necessary equipment and buildings, waste management, and planning and coordination of the decommissioning work.

3. The dismantlement of active building sections.

It is assumed that the manpower requirement will further decline during this period.

Two personnel estimates, for cases 1 and 2 above, have been carried out for Ringhals based on an examination of the present-day organization (ref. 4). A slightly rougher estimate has been made for case 3, i.e. during active building demolition. The personnel requirement for other nuclear power stations has been estimated on the basis of the Ringhals station. Figure 7.1 shows the manpower requirement for the three cases above for Ringhals 2.

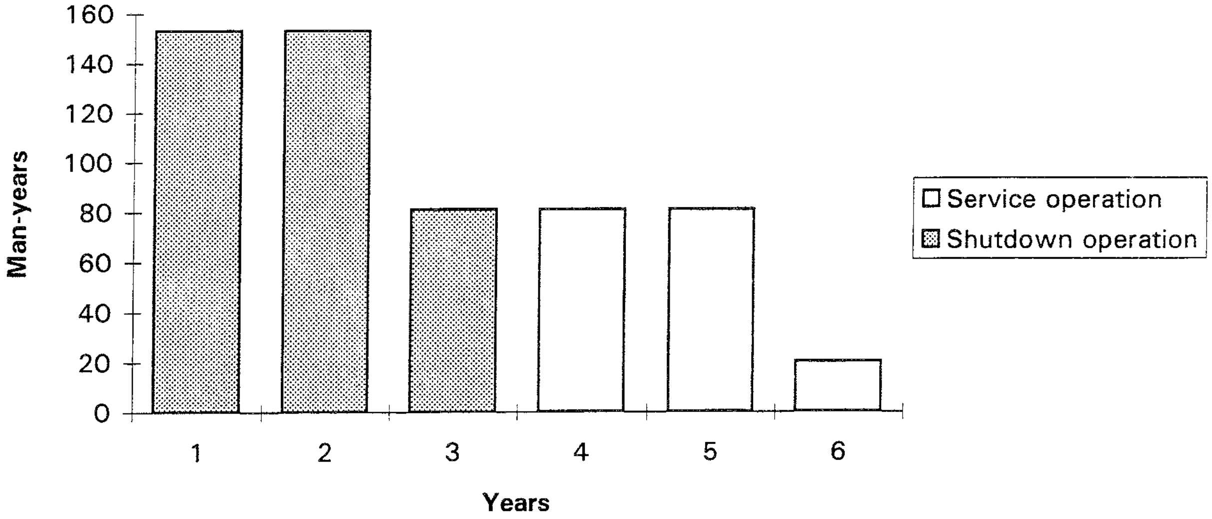


Figure 7.1 Manpower requirement during shutdown and service operation for Ringhals 2.

Shutdown operation

The costs of shutdown operation have been determined for two alternatives: first a successive shutdown of the reactors, and secondly a simultaneous shutdown. The alternative with simultaneous shutdown, see Figure 2.3, gives a considerably longer shutdown period. The successive shutdown, see Figure 2.4, is based on a case with an equally long operating period for all reactors. In the case of reactors that are situated near each other and that may also have certain systems in common, it has been assumed that dismantling is not begun in the first unit until the fuel has been removed from the "twin unit". This is true, for example, in the case of Oskarshamn 1 and 2.

Since there is still fuel left in the unit, the costs have been estimated in accordance with case 1 above. For the period after removal of the fuel until system dismantlement is begun, the costs are based on case 2 with a lower manpower requirement.

The station's common costs have been apportioned equally between the units. The share of the common costs that is attributable to a shutdown unit has been assigned to shutdown operation even when other units at the station are still in operation. The principle has been that starting with shutdown, all costs for the unit shall be defrayed by the waste disposal reserve.

Service operation

The costs of service operation have been calculated based on cases 2 and 3 above. To avoid counting functions twice or omitting them, the items have been checked off against system dismantlement.

7.3 SYSTEM DISMANTLEMENT

Two studies have been conducted for system dismantlement, one for Oskarshamn 3, the BWR reference plant, and one for Ringhals 2, the PWR reference plant. The premises for the two studies have been the same, but different methods have been used.

The reactor pressure vessel has not been included in these studies, but has instead been dealt with in a separate study.

7.3.1 BWRs

An extensive study has been carried out by ABB Atom for system dismantlement of Oskarshamn 3 (ref. 8). The study's calculations of labour input, material quantities and activities are based on two foundation stones:

- a database of the unit's systems and components
- 16 work procedures

Most of the data for the study's database have been obtained from existing databases. Different databases at ABB Atom and STAL have been used. One of the reasons O3 was chosen as a reference plant was access to these databases. Manual data collection has been used when information has not been available in computerized form, for example regarding ventilation and the RPV internals.

For calculation of activities and dose rates, every system included in the study has been classified as active or inactive. The active systems have then been assigned different activity codes, which in turn represent different activity levels.

The entire dismantling process, from preparation of the work site until the site can be turned over to building demolition, has been divided into work procedures. A total of 16 different procedures have been identified:

1. Preparation of work sites
2. Insulation removal

3. Pipe removal
4. Transport of dismantled material within the station
5. Scanning of inactive material
6. Packaging of active dismantled material
7. Dismantling and transport of large components and tanks
8. Steel removal
9. Handling of dismantled material outside controlled areas
10. Removal of cables and cable racks
11. Removal of ventilation
12. Handling of core components
13. Removal of lining sheet
14. Removal of overhead cranes
15. Removal of electrical components
16. Removal of turbine string

Each procedure includes a work description, requisite workforce, tools and time required.

Material quantities from the database are used as input data in the calculation of time required. For example, the input data for pipe removal, procedure 3, are pipe thickness and length. Estimates of time required are based on laboratory tests and estimates. To compensate for the difficult conditions that will prevail in reality, a difficulty factor has been added to the ideal time. This factor is intended to compensate for difficulties in the form of confined spaces, waiting times, walking times and changes of clothes.

To calibrate the procedures, they were checked with the planning and maintenance personnel at Oskarshamn with application to a room in O3.

Using an established dismantling logic, where the sequence of dismantlement of the plant's systems and the times required for the dismantling procedures are determined, a dismantling schedule has then been set up.

To calculate the costs of system dismantlement, these have then been divided into three categories: project management, dismantling personnel, and tools and consumables.

The project management consists of a group of seven persons:

- project manager
- project engineer
- planner
- accountant
- purchaser
- method study man
- administrator/payroll/time-keeping

It is estimated that they will have to start their work of planning the dismantling work during the year prior to the start of dismantlement. During dismantlement they direct the work during the three years the process dismantlement is expected to take. The activities then have to be wound up, for example termination of subcontracts, final accounting and coordination with building demolition, which is estimated to take another couple of months.

The cost for the dismantling personnel is calculated based on the times calculated in the procedures. The personnel are divided into different personnel categories with different hourly costs. The net times that have been obtained from the computer processing are adjusted in the planning study so that an even work load is obtained. This leads to slightly longer times than those obtained from the computer.

The use of consumables and tools and their wear has been calculated for each procedure. For machines we have assumed that a residual value of 70% remains after decommissioning, i.e. 30% of the value is borne by each unit that is decommissioned. The total cost for consumables during dismantlement is obtained with the aid of the procedure times obtained from the computer processing.

Additional costs not included in the process study consist mainly of:

- Costs of project organization and operation of remaining systems are reported under service operation.
- Costs of containers for the dismantled material have been calculated separately.

7.3.2 PWRs

System dismantlement for PWRs has been studied for Ringhals 2 (ref. 6). The study has been carried out by planning and maintenance personnel at the Ringhals NPP. The dismantling work has been divided into nine sub-projects as follows:

1 Generator section
2 Turbine level
3 Turbine systems
4 Intermediate building
5 Active auxiliary systems building
6 inactive auxiliary systems building
7 Filter building (PMR)
8 Fuel building
9 Containment

The sub-projects have been assessed individually. Constituent components have been listed for each sub-project. Resource consumption for the dismantling work has then been estimated for each component. Resources for erection of provisional arrangements, decontamination, radiation protection, insulation removal, building of scaffolding and transport have then been added. The time for radiological safety permits, changing of clothes and long walking distances is included in the manpower requirement.

Based on these sub-schedules and limitations with respect to personal safety and shipment of materials, an overall schedule and resource specification for the implementation of system dismantlement has been drawn up.

7.3.3 Dismantling of RPV

For the option of segmentation of the reactor pressure vessel and RPV internals, a separate study has been carried out by Siemens for Forsmark 1. Experience from dismantling of internals in the Belgian BR-3 reactor has been drawn upon. The work has been divided into a number of work steps:

- Development, testing and planning of method and equipment for segmentation

- Installations of equipment

- Removal and segmenting of the RPV internals

- Modification of the work site for segmentation of the RPV

- Segmentation of RPV

- Concluding work such as decontamination and disassembly of equipment

For each work step, estimates have been made of labour input, occupational exposure, required tools and waste quantities.

7.4 BUILDING DEMOLITION AND SITE RESTORATION

An updating has been done of a previous study on building demolition and site restoration. The study was conducted by Rivteknik AB and is based on experience from decommissioning of the R1 reactor in Stockholm and a detailed study for the Barsebäck NPP. Costs for personnel and machines have been calculated for demolition of buildings and restoration of the station site at Barsebäck. The costs have then been converted to SEK/m^3 of concrete with different prices for concrete with induced activity, other contaminated concrete and inactive concrete. These unit prices have then been used to calculate the costs of building demolition for the other NPPs.

8 SCHEDULE AND MANPOWER REQUIREMENTS

8.1 GENERAL

Dismantlement is commenced as soon as all fuel has been shipped away from the reactor site. This means that the starting time is dependent on how fast the fuel can be shipped to CLAB. If the entire transport and receiving capacity at CLAB were to be reserved for one unit, dismantlement could be initiated about one year after shutdown.

In order that the schedule for decommissioning should be as short as possible, the dismantling work is carried out in parallel in different parts of the unit. Table 8.1 describes the overall schedule for decommissioning of Oskarshamn 3.

Table 8.1 Overall schedule for decommissioning of Oskarshamn 3

Phase	**Tasks**	**Time period**
Shutdown operation	Removal of fuel Decontamination Preparation for dismantling work	1 — 2 years
Service operation	Overall planning of operation of systems	3 years
System dismantlement	Dismantling of: - RPV internals - RPV - process systems	
Building demolition 1	Demolition of active concrete	
Building demolition 2	Demolition of inactive concrete and site restoration	2 years

8.2 SHUTDOWN OPERATION

For the period after shutdown when there is still fuel left in the plant, the personnel requirement is estimated to be about 50% of normal operation. Continuous manning of the plant with shift personnel is assumed during this period. The personnel requirement declines further, to about 25% of normal operation, when the fuel has been transferred away from the plant. Shutdown operation continues until dismantlement of the plant begins.

Activities during shutdown operation are dominated by fuel handling and system decontamination. A radiological survey of systems and buildings is done during this period, along with routine maintenance. The project group that has responsibility for the overall planning of the decommissioning work is also included in shutdown operation. The project group consists of about 10 persons.

8.3 SERVICE OPERATION

Personnel from the NPP's organization take part in the service operation during the period for system dismantlement and active building demolition. Service operation includes overall planning, control of access to the plant, operation of the plant's systems prior to successive shutdown, treatment of waste material from dismantlement, process waste during dismantlement and radiation protection.

The manpower requirement is estimated to be about 25% of normal operation at the beginning of the period. The workforce can be further reduced during demolition of active concrete.

8.4 SYSTEM DISMANTLEMENT

The sequence in which the station's systems are to be dismantled is determined by different factors. The main principle is that radioactive systems are dismantled first.

The most active systems are the reactor internals and the reactor vessel (RPV), which constitute the first part in the dismantling schedule. Other systems can also be dismantled at the same time, however, for example in the turbine building.

In assessing schedules and manpower requirements, a thorough survey of the two reference plants, O3 and R2, has been carried out. The survey includes a room-by-room analysis of systems and equipment. Assessments have been based on experience from normal refuelling and maintenance outage work as well as major modifications and alterations.

BWRs

Below follows a summary description of the sequence of activities for system dismantlement of a BWR.

1 System dismantlement begins with segmentation of the RPV internals. Segmentation takes place under water in the pools, minimizing the personnel dose. The work with the reactor internals is completed in about four months. The internals are then transferred to CLAB.

Dismantlement of other parts of the station begins at the same time, for example systems in the turbine, generator and auxiliary system sections. Installations in the wetwell can also begin to be dismantled. Scaffoldings and flushing and dismantlement of the pool linings take about six months.

2 Fuel pools and RPV are emptied and cleaned.

3 Cooling and cleanup systems for fuel pools are drained and the lining sheet in the pools is removed when this is appropriate with reference to other activities.

4 All pipe connections on the RPV are cut. The RPV is now free for lifting. If it is to be segmented instead, this should wait until the reactor containment has been emptied of other equipment.

5 The containment's equipment is dismantled. The most radioactive parts are the piping systems for the reactor's cleanup loops. These parts are removed first, reducing the activity level in the containment to a level that facilitates the work with other equipment.

After the reactor vessel has been removed, its insulation and the concrete's thermal shield can be removed. The arrangement with reactor vessel insulation differs between the BWR units.

6 Continued dismantlement in areas with radioactive systems. The regular ventilation is kept as long as possible so that regular air flow through the plant is sustained and the exhaust air is monitored via the normal operating system. The original equipment is also used to a great extent for auxiliary power and lighting. These auxiliary functions are gradually replaced by temporary systems. This means that the group for preparation of the rooms returns several times to areas for rebuilding of scaffoldings and for supply work.

7 Supply air systems in ventilation from radioactive areas and chimney monitoring are shut off and dismantled.

8 All other equipment is dismantled. To a large extent, this dismantling can be commenced in parallel with earlier measures.

9 The waste treatment station is kept in operation as long as there is radioactive material in the plant. During process dismantlement, all rinse liquids and floor drainage from controlled areas and filter resins are sent to the waste plant for treatment in the same way as during operation of the NPP. The waste treatment station shall be in operation for collection and treatment of floor drainage and rinse liquids during the first part of building demolition as well, when contaminated or activated material is dismantled. This station is thus dismantled as the last part of the process, which means that operating personnel are needed throughout process dismantlement and for a few more months.

The total time for system dismantlement for O3 has been estimated at about 3 years. The manpower requirement varies during the system dismantlement period and amounts to about 280 persons from the contractor during a couple of months. Beyond this there are personnel for service operation during this period, estimated at about 90 persons per unit.

PWRs

The dismantling plan for a PWR unit agrees for the most part with the plan for a BWR unit. However, the scope of the active systems is smaller, since the turbine plant is completely inactive for a PWR unit. The work inside the reactor containment is the limiting factor for the schedule.

The total time for dismantlement has been estimated at about 3 years, i.e. the same as for O3. But it should be possible to shorten the time.

8.5 BUILDING DEMOLITION

Building demolition can be commenced when most of the active process equipment, including the RPV, has been removed.

The time for building demolition, including site restoration, has been estimated at 3 years. Building structures with induced activity, contaminated pool linings and contaminated concrete are demolished during the first year. When this work is finished and radiological monitoring show that all activity has been removed, these buildings can be classified as inactive and demolition can proceed using conventional methods.

Building demolition will be carried out with large construction machines, enabling the workforce to be kept to a minimum. The labour requirement reaches a peak of about 40 men, which occurs during the latter part of the demolishing process.

During the first year of demolishing, in conjunction with demolishing of active concrete, the workforce for service operation is estimated to be about 20 persons per unit. During conventional building demolition and site restoration, no service operation personnel are expected to be needed.

8.6 DOSE TO PERSONNEL

ABB carried out calculations of the personnel dose for the different work operations during dismantling of process equipment in the O3 study. The total dose during three years has been estimated to be about 12 manSv with start of dismantlement one year after shutdown. Preparation of rooms and dismantling of process piping accounts for a large portion of the total dose exposure of the dismantling personnel. It is possible to reduce the dose exposure by proper planning of the work and by the use of shielding. Siemens has estimated the total occupational dose for segmentation of the RPV and internals to be about 2 manSv. The occupational dose rate at the Swedish NPPs during the period 1988-93 has varied between about 1 and 6 manSv per unit and year.

8.7 TABLE OF MANPOWER REQUIREMENTS

Table 8.2 shows the manpower requirements for decommissioning of Oskarshamn 3 and Ringhals 2 for the different decommissioning phases.

Table 8.2 Resource requirements for decommissioning of Oskarshamn 3 and Ringhals 2 for the different decommissioning phases.

Phase	**Tasks**	**No. of man-years**	
		O3	**R2**
Shutdown operation	Removal of fuel Decontamination Preparation for dismantling work	420	490
Service operation	Overall planning of operation of systems	200	180
System dismantlement	Dismantling of: - RPV internals - RPV - process systems	640	410
Building demolition 1	Demolition of active concrete		
Building demolition 2	Demolition of inactive concrete and site restoration	80	60
Total man-years		**1,340**	**1,140**

The total manpower requirement for decommissioning of Oskarshamn 3, according to the schedule for simultaneous shutdown shown in Figure 2.3, is presented in Figure 8.1. The peak manpower requirement at the whole Oskarshamn NPP during the decommissioning period amounts to about 500 persons. This includes the project group, personnel for shutdown and service operation and personnel for system dismantlement and building demolition with supervisors.

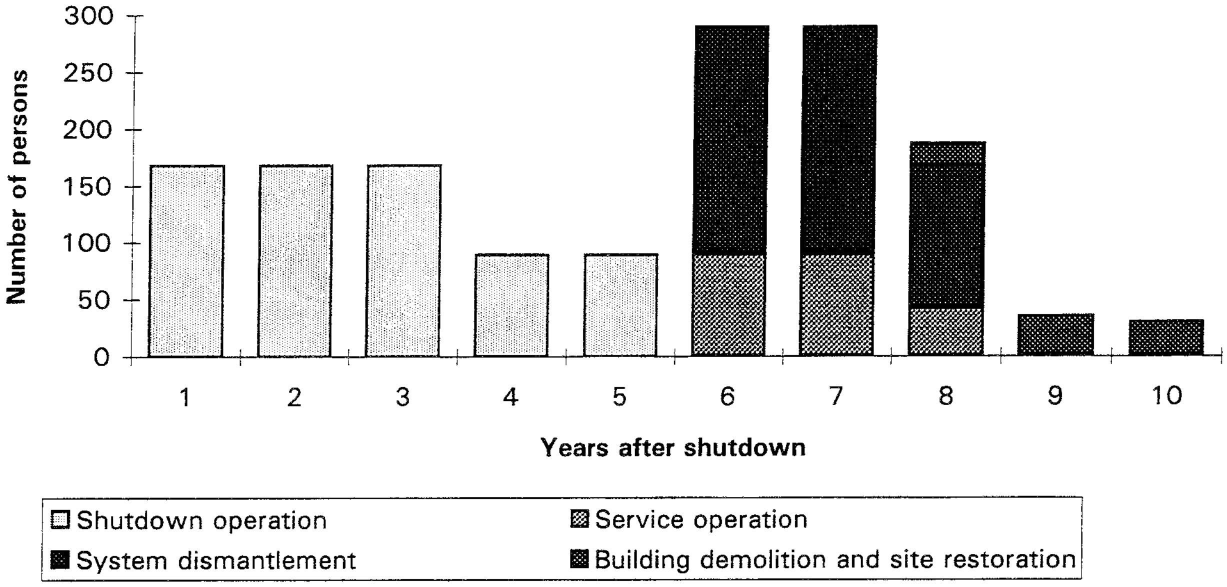


Figure 8.1 Manpower requirements during decommissioning of Oskarshamn 3

9 COSTS

9.1 GENERAL

The total decommissioning costs for the Swedish NPPs are presented in Table 9.3. The costs are given in January 1994 prices. A contingency allowance for unforeseen expenses is included at 25% for the costs of building demolition and 20% for other costs. The costs consist mainly of labour costs (man-hours). An annual cost of SEK 450,000 per man-year is used in the calculation, which includes an extra charge for some material consumption.

The overall planning of plant shutdown is carried out by a project group selected by the station personnel a few years before shutdown. This preparatory work is not included in the decommissioning costs, but is assumed to be included in the station's operating costs. The costs for the project group after shutdown are included in shutdown and service operation.

9.2 SHUTDOWN OPERATION

The costs of shutdown operation include measures that need to be taken from the time the plant is taken out of service until the actual dismantling work commences. The manpower requirement for this period is based on function-by-function estimates based on the operating organization.

The costs of shutdown operation are plant-specific and dependent on what other activities are being pursued on the site. The total costs for shutdown operation are also dependent on the schedule chosen for the shutdown of the station and the start of dismantlement of individual units.

Cost calculations have been carried out for the case when all reactors are shut down at the same time (see Figure 2.3) and for a successive shutdown during a five-year period (see Figure 2.4). For the case with simultaneous shutdown, it is assumed that dismantling of the units at a station is begun at two-year intervals. The estimated costs per plant for the two cases are presented in Table 9.1. Since the costs for different units are related, it is not fruitful to report the costs by unit.

Table 9.1 Costs of shutdown operation for simultaneous and successive shutdown

Shutdown operation	Simultaneous shutdown	Successive shutdown
Barsebäck	344	350
Forsmark	751	410
Oskarshamn	751	529
Ringhals	1,170	640
Total	3,015	1,929

9.3 SERVICE OPERATION

Costs for service operation include costs for the NPP's personnel during the period for system dismantlement and active building demolition. Their work includes overall planning, control of access to the plant, operation of the plant's systems prior to successive shutdown, treatment of waste material from dismantlement, process waste during dismantlement and radiation protection. Costs for service operation are presented in Table 9.2.

9.4 SYSTEM DISMANTLEMENT

Costs for dismantling of systems, not including the reactor vessel and its internals, have been estimated for Oskarshamn 3 by ABB Atom and for Ringhals 2 by the Ringhals NPP. It has been assumed that the work is carried out by a contractor.

The labour costs for Oskarshamn 3 have been estimated to be MSEK 475. To this must be added tool consumption and rental of special machines. The cost of machine procurement has been estimated at MSEK 53. The machines can be used for more than one unit. A residual value after decommissioning of MSEK 37 is therefore assumed. The net cost per unit for machine procurement is then MSEK 16. Tool consumption has been estimated at MSEK 7. This gives a total of MSEK 500 for system dismantlement of Oskarshamn 3.

The system dismantlement cost for Ringhals 2 has been estimated at about MSEK 280.

Siemens has made a study of dismantlement and segmentation of the RPV and RPV internals in Forsmark 1. The cost of segmenting the internals has been estimated to be MSEK 23 per unit. Dismantlement and segmentation of the RPVs has been estimated to cost about MSEK 50 per unit.

Removal and lift-out of the intact RPV has also been studied. The costs of this alternative have been estimated to be about MSEK 15-20 for Forsmark 1 and MSEK 20 for Ringhals 1 and Ringhals 3.

The alternative of segmentation of the RPV has been included in the cost estimations.

9.5 BUILDING DEMOLITION

The costs for demolition of the building components have, as in the case of system dismantlement, been calculated as a contract job. Cost data have been based on values reported by questioned contractors and have been expressed in unit prices. Besides personnel costs, these prices include costs for rental of equipment and machines. The cost of building demolition has been estimated at MSEK 223 for O3 and MSEK 153 for R2. This cost also includes demolition of inactive buildings that may not have to be demolished. Table 9.3 shows the costs for other reactor units.

9.6 TABLE OF DECOMMISSIONING COSTS

Table 9.2 shows the costs for dismantling and shutdown operation of the two reference plants, O3 and R2. The cost of system dismantlement in Oskarshamn 3 has been translated to other BWR units with the aid of a weighting based on the estimated resource requirement for each type of equipment. The weighting has been done taking into account differences in size and design of the different plants. The same costs have been used for Ringhals 3 and 4 as for the reference plant, Ringhals 2.

Table 9.2 Costs for dismantlement and shutdown operation at Oskarshamn 3 and Ringhals 2. Shutdown operation costs are calculated assuming simultaneous shutdown of the NPPs.

	Oskarshamn 3	**Ringhals 2**
Service operation	121	113
Dismantling of RPV	52	51
Dismantling of internals	23	23
Dismantling of systems	498	279
Building demolition	223	153
Waste containers	14	11
Transport and disposal of inactive waste	6	7
Total decommissioning	937	637

Table 9.3 shows the total decommissioning costs for the Swedish NPPs broken down by block.

Table 9.3 Total decommissioning costs for the Swedish NPPs.

	B1	**B2**	**F1**	**F2**	**F3**	**O1**	**O2**	**O3**	**R1**	**R2**	**R3**	**R4**	**Total**
Service operation	108	108	121	114	121	117	117	**121**	115	**113**	103	101	1,359
Dismantling of RPV	51	51	52	52	52	51	51	**52**	51	**51**	51	51	616
Dismantling of internals	23	23	23	23	23	23	23	**23**	23	**23**	23	23	280
Dismantling of systems	316	316	483	483	498	289	316	**498**	387	**279**	279	279	4,424
Building demolition	124	147	179	170	242	103	129	**223**	146	**153**	158	169	1,942
Waste containers	7	8	13	13	14	6	7	**14**	9	**11**	11	11	121
Transport and disposal of inactive waste	4	4	6	6	6	4	4	**6**	5	**7**	7	7	66
Total decommissioning	634	657	877	861	956	593	648	**937**	736	**637**	631	641	8,808
Shutdown operation	344		751			751			1,170				3,015

The table contains costs for waste containers. The ISO freight containers with active waste are disposed of in SFR 3. A cost for transport and disposal of inactive waste from system dismantlement has been taken up. It is assumed that this waste is dumped on a nearby landfill.

9.7 TRANSPORT AND DISPOSAL

The costs of transport and disposal have not been estimated in this study. These costs are reported separately in ref. 2. Altogether for Sweden, transport costs for decommissioning waste, not including RPV internals, are estimated to be about MSEK 250 and final disposal costs about MSEK 730. That amounts to between MSEK 60 (for R2) and MSEK 100 (for O3) per unit.

9.8 RESIDUAL VALUE IN REACTORS

At the plants there are considerable quantities of material and equipment that can be sold in conjunction with decommissioning. There are spare parts, piping materials, standard machine parts in stores, workshop equipment, lifting equipment and electrical machinery (e.g. diesel generators) that have been used but are still in usable condition. The land, as well as the infrastructure built up on the site, also has great value for other industrial establishment. No residual values have been taken into account in this study.

10 DEFERRED DISMANTLING

The effects of postponing the actual dismantling work were discussed in chapter 2. One of the main reasons for postponing dismantlement is that the activity levels decline, which can simplify the dismantling work and reduce the dose to the personnel. The nuclide that makes the greatest contribution to the occupational dose burden is ^{60}Co, with a half-life of about 5 years. Waiting 40 years would reduce the dose rate to about 0.5% compared to the case with commencement of dismantlement immediately after shutdown and no decontamination of the most contaminated systems. It has been conservatively estimated that decontamination can reduce the dose rates by a factor of 10-100.

Deferred or delayed dismantling entails a number of disadvantages that must be weighed into a decision on when to dismantle. Besides the fact that personnel with knowledge of the plant will not be on hand, infrastructure on the NPP site cannot be utilized for other electricity-generating units. Furthermore, surveillance and limited maintenance must be carried out during the waiting period, and certain equipment must be restored to operable condition prior to the start of dismantlement. In some cases it may even be necessary to carry out a whole new establishment within the area.

The principles of deferred dismantling can be summarized as follows:

Fuel handling

Removal of the fuel takes place in the same manner as in the case of immediate dismantling. Any control rods and RPV internals stored in pools will also be shipped away. Removal of the fuel from the plant is necessary to be able to reduce the operating personnel at the plant.

Decontamination and cleaning

Most of the radioactive materials that give rise to external doses will have decayed to a very low level when the dismantling work is commenced. There is therefore no reason to carry out system decontamination with this scenario.

To prevent dispersal of activity during the long surveillance period, a thorough cleaning of all rooms and vacuum desludging and decontamination of pools, tanks and sumps is carried out after shutdown. The RPV internals are placed in the RPV, and the RPV head is bolted on. The pool lining sheets are coated where necessary with a suitable paint or plastic in order to prevent activity release.

Radioactivity remaining from the operating period is then mainly present in the RPV, which is sealed, and on inner surfaces in different system parts.

Surveillance period

A satisfactory surveillance of the plant can be obtained via automatic alarms as well as periodic inspections at regular intervals. It is assumed that the alarm can be transmitted to a central alarm station. Examples of alarms are:

- high level in pump sumps
- unauthorized opening of exterior doors
- fire

The need for maintenance is determined in connection with the periodic inspections.

Preparation of the site before dismantling

In this scenario, it is assumed that all activities at the power station are suspended during the waiting period. The plant's service premises in the form of workshops, stores, offices, canteens etc. are not maintained and will not be able to be used during the dismantling work without extensive renovation. After 40 years it is likely that new facilities will have to be built.

Before the dismantling work can begin, the work site must therefore be provided with functioning offices, stores, restaurant, accommodations, electric power, water supply and drainage, etc.

Dismantling technology

The same methods and the technology that are used for immediate dismantling will also be used for dismantling after 40 years.

Owing to the lower radiation doses inside the plant, the need for remote-controlled equipment will decrease. Remote control is still needed for the RPV and its internals during the dismantling work, however.

The risk of airborne activity and contamination of premises and personnel in connection with cutting-up of active systems and apparatus will still exist even after 40 years. Routines for work with active process equipment must therefore be followed. The necessary protective equipment must be used.

The waste quantities in the case of deferred dismantling should be smaller, considering the decay of activity that has taken place. However, no estimate of how great this decrease will be has been made in this study.

Costs

No estimation of the costs for this alternative has been carried out, in view of the uncertainties regarding the premises. Among other things, the cost of the waiting period will be heavily dependent on the requirements on surveillance and maintenance as well as service of the plant.

Before dismantling is begun, offices, service facilities and different types of supply systems must be restored. This cost is dependent on the length of the waiting period, and on whether the nuclear power site has been completely abandoned during the waiting period or not.

The cost of the actual dismantling work is not expected to decrease to any appreciable extent, since the same work methods must be employed even after a waiting period of 40 years.

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[1] Department of Geology, Chalmers University of Technology/Göteborg University
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