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Technology and costs for decommissioning the Swedish nuclear power plants.

Swedish Nuclear Fuel and Waste Management Co
May 1986

SVENSK KÄRNBRÄNSLEHANTERING AB
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO

BOX 5864 S-102 48 STOCKHOLM
TEL 08-665 28 00 TELEX 13108-SKB

TECHNOLOGY AND COSTS FOR DECOMMISSIONING THE SWEDISH NUCLEAR POWER PLANTS

Prepared by a working group within the
Swedish power industry

May 1986

A list of other reports published in this series during 1986 is attached at the end of this report. Information on KBS 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) and 1985 (TR 85-20) is available through SKB.

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. The procedures and costs involved in decommissioning nuclear power plants are described in this study.

The study shows that, from the viewpoint of radiological safety, a nuclear power plant can be dismantled immediately after it has been shut down and the fuel has been removed, which is estimated to take about one year. Most of the equipment that will be used in decommissioning is already available and is used routinely in maintenance and rebuilding work at the nuclear power plants. Special equipment need only be developed for dismantlement of the reactor vessel and for demolishing of heavy concrete structures. Examples of existing equipment that can be used for this after minor modifications are given in the study.

The dismantling of a nuclear power plant can be accomplished in about five years, with an average labour force of about 200 men. The maximum labour force required for Ringhals 1 has been estimated at about 500 men during the first years, when active systems are being dismantled on a number of fronts in the plant. During the last years when the buildings are being demolished, approximately 50 men are required.

In order to limit the labour requirement and the dose burden 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 2-5 m and packed directly in refuse containers, and that certain items of equipment are taken out and transported intact.

The study has focused on immediate dismantling. By waiting ten years or so, certain advantages can be gained due to the fact that the radioactivity in the plant declines. In the case of immediate dismantling, the same effect can be achieved by system decontamination. A number of other factors also influence the choice of time of dismantling, for example availability of personnel, need for the site and the availability of a final repository. Non-technical factors will also be of importance. The choice of time of dismantling can therefore vary for different plants.

The cost of decommissioning a boiling water reactor (BWR) of the size of Ringhals 1 has been estimated to be about MSEK 540 in January 1986 prices, and for a pressurized water reactor (PWR,

Ringhals 2) about MSEK 460. The costs for the other Swedish nuclear power plants lie in the range of MSEK 410-760. These are the direct costs for the decommissioning work, to which must be added the costs of transportation and disposal of the decommissioning waste, about 100 000 m^3. These costs have been estimated to be about MSEK 600 for the 12 Swedish reactors. /1/.

Additional costs are incurred for the shutdown period from the time the nuclear power plant is finally taken out of operation until the dismantling work is begun. During this period, the fuel is transported away and some decontamination is carried out. The costs for the shutdown period are heavily dependent on the pace at which the plants are shut down and how long the shutdown period will last.

There are considerable quantities of spare parts, materials and equipment on the reactor sites that can be sold when the plants are closed down. The total value of these materials for all nuclear power plants is estimated to be MSEK 900. To this must be added the value of the land and the infrastructure.

The table below presents the costs of immediate dismantling of the Swedish nuclear power plants.

Table S-1: Costs for decommissioning etc of the Swedish nuclear power plants (MSEK).

	Oskarshamn 1-3	**Barsebäck 1-2**	**Ringhals 1-4**	**Forsmark 1-3**
Shutdown operation	190	110	310	190
Decommissioning	1630	950	1920	2090
Transport and final disposal of waste	150	90	190	170
Total	**1970**	**1150**	**2420**	**2450**
Residual value	**-230**	**-150**	**-300**	**-230**

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1 SEK = 0.14 USD (May 1986)

CONTENTS

1 BACKGROUND

The operation of a nuclear power plant leads to radioactive contamination of parts of the plant. This occurs firstly because the material in the reactor vessel and the surrounding concrete become activated due to neutron irradiation, and secondly because radioactive products are spread to different systems in the plant, mainly via the reactor water. These parts of the nuclear power plant must therefore be dismantled and handled in a radiologically safe manner.

According to earlier calculations, the costs of shutting down the nuclear power plants and subsequently dismantling and demolishing them constitute a large portion of the total costs for management and disposal of the waste products of nuclear power.

According to the Nuclear Activities Act (SFS 1984:3), the holder of a licence for nuclear activities is required to, among other things

> "ensure that the necessary measures are taken in order to decommission and dismantle in a safe manner plants in which the activity is no longer to be carried out"

According to the Financing Act (SFS 1981:669), a reactor owner is obligated to prepare an estimate 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 residual products of nuclear power, including decommissioning and dismantling of the nuclear power plants /1/.

The cost estimate for decommissioning has previously been based on a study carried out by SKB in 1979 /2/. In view of the additional experience that has been gained from maintenance and rebuilding work on the nuclear power plants, it has now been found warranted to update the study.

The Swedish nuclear power programme includes 12 reactor units (see Table 1-1), 9 BWRs of ASEA-ATOM design and 3 PWRs of Westinghouse design. The first unit, Oskarshamn 1, was commissioned in 1972, and the last two, Oskarshamn 3 and Forsmark 3, in 1985. The Swedish Parliament has decided that no further nuclear power plants are to be built in Sweden.

Table 1-1: Nuclear reactors in Sweden

Reactor	**Type**	**Capacity MW_e**	**Commercial service**
Oskarshamn 1	BWR	440	1972
Oskarshamn 2	BWR	595	1974
Oskarshamn 3	BWR	1050	1985
Ringhals 1	BWR	750	1976
Ringhals 2	PWR	800	1975
Ringhals 3	PWR	915	1981
Ringhals 4	PWR	915	1983
Barsebäck 1	BWR	595	1975
Barsebäck 2	BWR	595	1977
Forsmark 1	BWR	972	1980
Forsmark 2	BWR	972	1981
Forsmark 3	BWR	1050	1985

The parliamentary resolution also stipulates that no nuclear power plants shall be in operation after the year 2010 and that the order in which the reactors are to be shut down is to be determined on the basis of the safety of the plants. The Swedish nuclear power plants are estimated to have a technical life of at least 40 years. None of them will have reached this age in 2010. In other words, the phase-out rate is not based on the technical life of the facilities.

In this study, it is assumed that all nuclear power plants are taken out of service at the end of 2010. The direct cost for decommissioning a nuclear power unit is not affected by this assumption. But it is of importance for the costs of the period of shutdown operation, i e the period between final shutdown and the start of the dismantlement work. A calculation of these costs is therefore also carried out for the more realistic case where the final shutdown of the plants is spread out over a five-year period.

The cost calculations include all of the Swedish nuclear power plants. They have been carried out in detail for Ringhals 1 and 2. Ringhals 1 is representative of a BWR with external cooling pumps. Dismantlement of the reactor vessel has also been studied for Forsmark 3, which is representative of a BWR with internal pumps. Ringhals 2 is representative of the Swedish PWRs. For the other

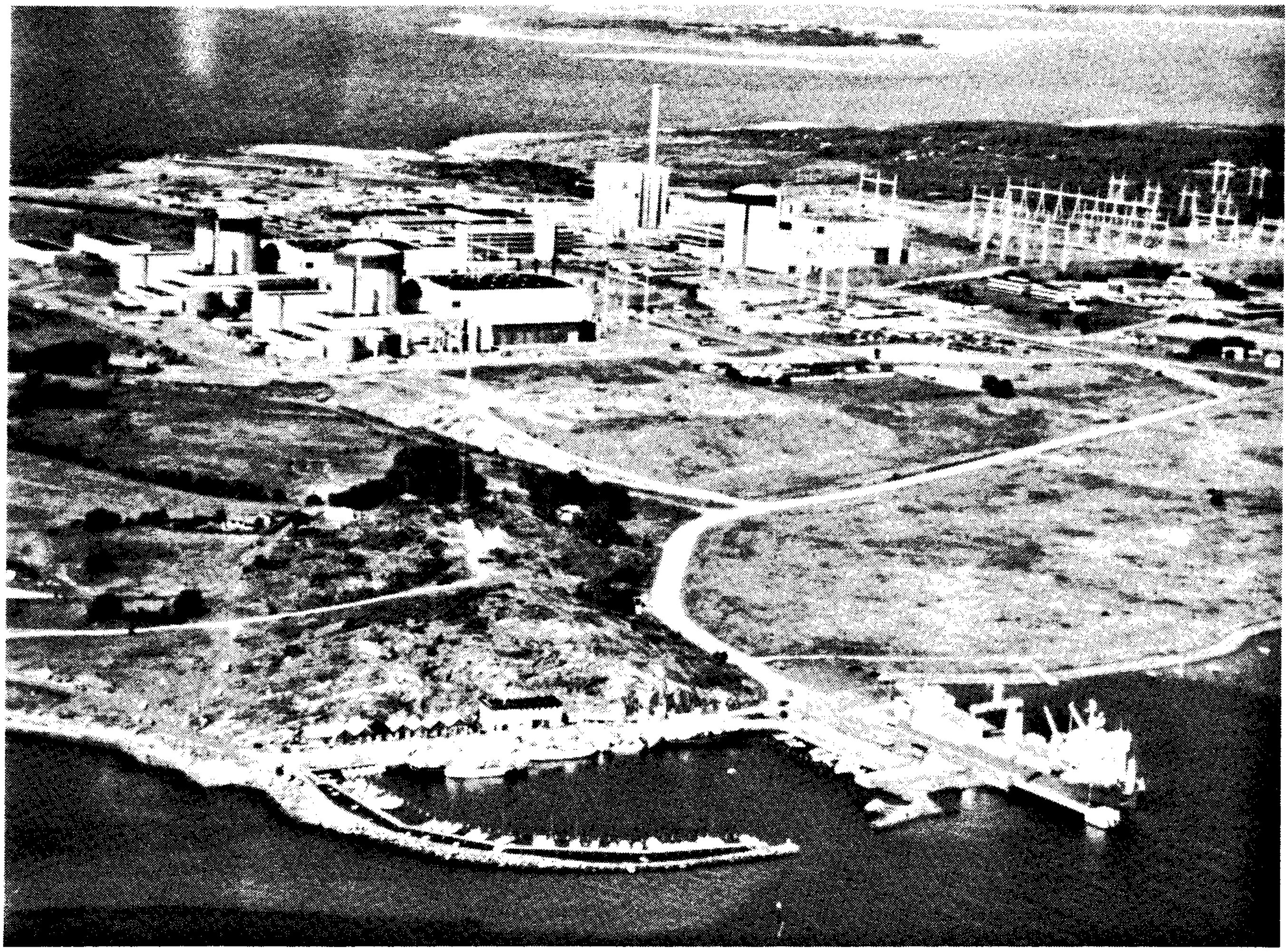


Figure 1-1. View of the Ringhals station, with M/S Sigyn in the foreground. (Photo Hallandsbild)

reactors, the decommissioning costs have been estimated by adjusting them in proportion to the quantities of material involved.

The study has been carried out in close cooperation with personnel at the nuclear power plants. The Swedish State Power Board (SV), South Sweden Power Supply (SK) and OKG AB have participated in the study.

The work has been divided as follows:

The Swedish State Power Board has studied the dismantlement of the reactor vessel and systems;

South Sweden Power Supply has studied the demolition of buildings;

OKG has studied the operation of the plant from the time electricity production ceases until dismantlement commences, as well as certain operational measures during the dismantlement period.

The work has been managed by a steering committee consisting of

Arnold Ambterntson	South Sweden Power Supply
Hans Forsström	SKB
Bertil Mandahl	OKG
Stig Pettersson	Swedish State Power Board

The subareas have been reported on in a number of work reports /3-8/. The steering committee has compiled this report based on the work reports.

2 TIME OF DISMANTLING

2.1 FACTORS INFLUENCING THE TIME OF DISMANTLING

2.1.1 General

When a nuclear power plant is taken out of operation, there is still fuel left in the reactor and the plant requires normal staffing. In order to reduce the personnel requirement, the first measure is therefore to transport the fuel as soon as possible to the central interim storage for spent fuel, CLAB. The factors that determine how fast this can be done are the decay power of the fuel and the available capacity for transporting and receiving at CLAB.

When all fuel is gone, there are two alternative ways to proceed:

- Dismantling is begun immediately, or
- The plant is "mothballed" and kept under surveillance for a certain period of time (20-100 years) before it is finally dismantled.

Table 2-1: Examples of factors that influence the time of dismantling.

The plant's activity content and radiation doses in different areas
The status of the plant in other respects
Reuse of land and facilities
Availability of personnel with knowledge of the plant
Availability of waste repository
Cost of surveillance
Availability of dismantling technology
Availability of funds
Political and social considerations

By postponing the dismantling, the natural process of decay of radioactivity can be taken advantage of, simplifying portions of the dismantling activities.

The alternative that is chosen depends on a number of different factors that can vary from country to country and even between nuclear power plants in a single country. The question has been discussed a great deal in different international contexts, but it has not been possible to formulate any general conclusion /11/. Some of the factors that can influence the choice are discussed in the following.

2.1.2 Activity content of the plant and radiation doses in different areas

The primary reason for postponing the dismantling of a nuclear power plant is to give the activity content an opportunity to decay. The radiation level in the plant is thereby reduced, simplifying the dismantling work. The radiation dose to the personnel can also be reduced.

Most of the activity in a shutdown nuclear power plant is located in the reactor vessel internals, which have been activated by neutron irradiation from the core. The reactor vessel and the concrete radiation shield nearest the reactor vessel, the biological shield, are also activated. It is mainly for these components that an extended storage period prior to start of dismantling is of importance.

The radioactivity in the reactor vessel and its internals is dominated by Co-60 and in the concrete also by Eu-152 and 154. Co-60 has a half-life of about 5 years, which means that the radiation dose decreases by a factor of 250 in 40 years. Eu-152 has a half-life of 13 years, which means that its radioactivity declines by a factor of 10 in the same period of time.

The radiation level in the reactor vessel internals will be so high even after 40 years of decay that these parts have to be cut up and handled behind radiation shielding by means of remote-controlled devices. Postponing the dismantling will therefore not affect the dismantling method used for these parts to any appreciable degree. In the case of the reactor vessel and the biological shield, however, a postponement can have positive effects.

The activity contents in other parts of the plant are much lower. The activity consists primarily of impurities, crud, which has spread from the reactor vessel via the reactor water to other primary systems. Here as well, Co-60 is the dominant nuclide from the viewpoint of radiation.

However, the radiation level will be so low in most areas that the dismantling work can be carried out in an acceptable manner from the viewpoint of radiological safety a short time after shutdown. By means of a thorough system decontamination before the actual dismantling work is commenced, it is judged to be possible to reduce the radiation level by a factor of 10-100, which is equivalent to 15-30 years of decay.

In summary, it is found that even though a postponement can have certain advantages from a dose viewpoint, there are no decisive differences compared to if dismantling is begun immediately.

2.1.3 The status of the plant in other respects

The condition of the plant's systems, components and building sections is of importance in the choice of time of dismantling. Thus, if dismantling is postponed, it must be able to reasonably show that the plant does not deteriorate, giving rise to a risk of leakage and radioactive release. With a modicum of building maintenance, mainly roof maintenance, and with suitably frequent inspections and surveillance, it is judged possible to keep the nuclear power plants in good condition for several decades.

2.1.4 Reuse of land and facilities

The site on which the nuclear power plant is situated should be suitable for industrial purposes in the future as well. A considerable infrastructure has been built up on the site, for example electricity and water supply, cooling water channels, good communications, workshops, housing and catering facilities. In view of the fact that good industrial land will be in limited supply in the future, there should be great demand for the nuclear power plant sites. The sites will probably primarily be used for electric power production, where the existing infrastructure will provide maximum advantage. But other industrial activities are also possible.

In our judgement, this factor will probably be the strongest one in the choice of time for dismantling. But the outcome may be different at different sites, depending on the availability of land at the nuclear power plants.

2.1.5 Availability of personnel with a knowledge of the plant

When the nuclear power plant is shut down, most of the personnel are still available. Some of the personnel are engaged during the final years of operation in planning for the forthcoming shutdown. Their knowledge of the plant is then of great importance.

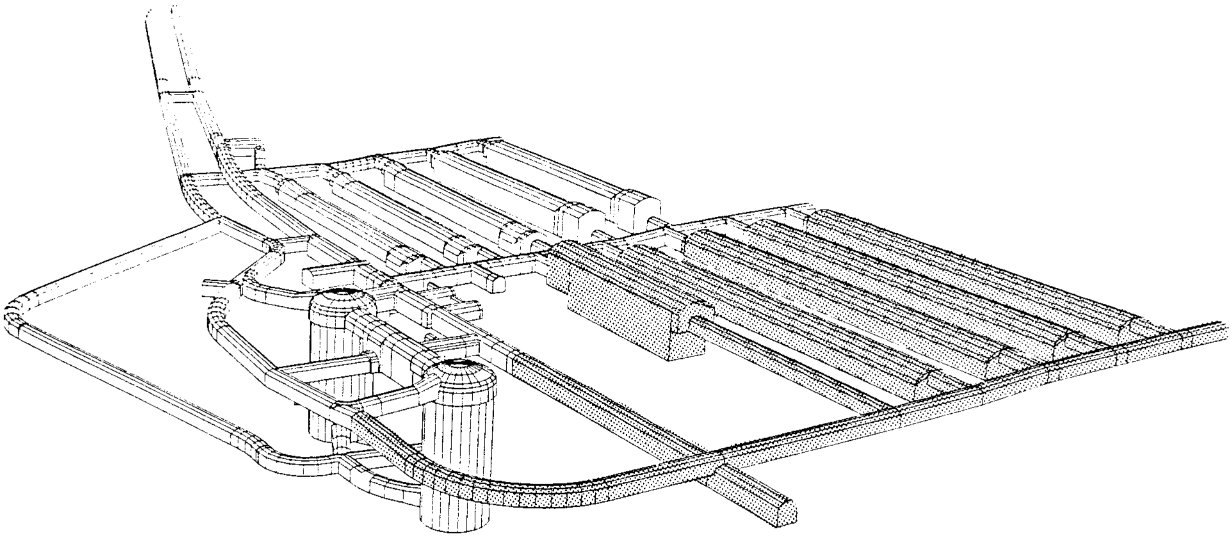


Figure 2-1. Final repository for reactor and decommissioning waste, SFR. The expansion for decommissioning waste has been marked.

Even during the actual dismantling work, it is an advantage to be able to make use of personnel with good knowledge of the plant and experience from solving working and handling problems in connection with maintenance and rebuilding work.

2.1.6 Waste repository

Large quantities of radioactive waste are generated by the decommissioning procedure and must be disposed of. It is therefore essential that a final repository is available when the dismantling work is commenced. In Sweden, most of the decommissioning waste is intended to be disposed of in an expansion (SFR 3) of the final repository for reactor waste, SFR, which is currently being constructed at Forsmark. SFR 3 can be built when the need arises and does therefore not comprise any constraint on the choice of time for start of dismantling.

Moreover, it will be possible to dispose of some waste at the plant site.

2.1.7 Cost of surveillance

If dismantling is postponed, the plant must be kept under surveillance during the intervening period. The demands on surveillance will depend, among other things, on how much activity is left in the plant and in what form the activity exists. The possibilities of safely sealing the plant will also be of great importance.

An appraisal of the surveillance requirement is carried out in section 9.1. It is found that the plants can be sealed in such a manner that no surveillance on the site is necessary. Surveillance can be performed by automatic alarms and regularly recurrent inspections. The cost of surveillance of this scope has been estimated to lie in the region of 0.5 MSEK/year and plant site. In cases where continuous surveillance on the site is required, the cost is about 2 MSEK/year and plant site /8/. If there are other industrial facilities on the site, the cost of surveillance is reduced.

2.1.8 Availability of dismantling technology

The equipment required to dismantle a nuclear power plant is already available. Most of the dismantling work will be carried out with equipment that is used in connection with the annual refuelling and maintenance outages. Special equipment will only have to be developed for dismantling the reactor vessel. Examples of existing equipment that can be used after minor modifications are given in this study.

If dismantling is postponed, developments within robotics in particular may lead to simplification of the dismantling work. However, this is not decisive in the choice of time for start of dismantling.

2.1.9 Availability of funding

This factor has been accorded great importance internationally. However, the Swedish system of setting aside funds in reserves for such purposes as decommissioning provides sufficient security that money will be available when the nuclear power plants are to be dismantled.

2.1.10 Conclusion

The analysis shows that there are no decisive differences from a technical point of view between whether a nuclear power plant is dismantled immediately after shutdown or after several decades. The working group therefore recommends an early start of dismantling, mainly with reference to the availability of personnel with good knowledge of the plant.

It is also found that non-technical factors will probably be decisive in determining when the dismantling is begun, mainly the fact that the land on the site is attractive. Political and social factors, which have not been dealt with here, will probably also be of importance.

This study focuses on early dismantling. The consequences of postponement are also discussed.

2.2 TIMETABLE FOR DECOMMISSIONING

The Swedish nuclear power programme includes 12 reactor units. It has been assumed in this study that these units are taken out of service almost simultaneously at the end of the year 2010. If it is then decided to dismantle the plants immediately, the actual dismantlement of the first unit can be commenced after just under one year. At that time, the fuel and control rods etc from the final core will have been removed.

A crucial factor in determining when the dismantling of the other units can be commenced will be the transport and receiving capacity of the central interim storage, CLAB. CLAB is designed to receive approximately 300 metric tons of fuel per year. It is judged possible to increase this capacity to 600 tons if the need arises. The quantity of fuel in the final cores is about 1140 tons. It will therefore take a total of two to four years to transfer all fuel from the final cores to CLAB.

In parallel with the fuel transports, reactor internals and core components will also be transported away from the reactors where dismantling has been commenced. In order to optimize the logistics, it is practical to postpone the starting time for dismantling so that dismantling of the first reactor unit on each site is begun one year after electricity production has ceased, and that dismantling of the other units on the same site is then commenced at two-year intervals. In this way, a rational utilization of the dismantling personnel is obtained. The personnel can be moved successively from plant to plant.

Figure 2-2 shows a possible timetable for decommissioning of the Swedish nuclear power plants. Since dismantling of one unit is estimated to take five years, this timetable means that the total decommissioning period will be about 12 years.

If the reactors are instead taken out of service successively over a five-year period, the actual dismantling work can be commenced one year after final shutdown for each individual unit. The timetable that is then obtained is shown in Figure 2-3.

If dismantling is postponed by 20-100 years, other considerations will determine the timetable. In this case, it may be economical to use a dismantling force that is moved from plant to plant. In order to take advantage of this possibility, the start of dismantling should be staggered two years between different units. Dismantling will then be spread out over a 25-year period.

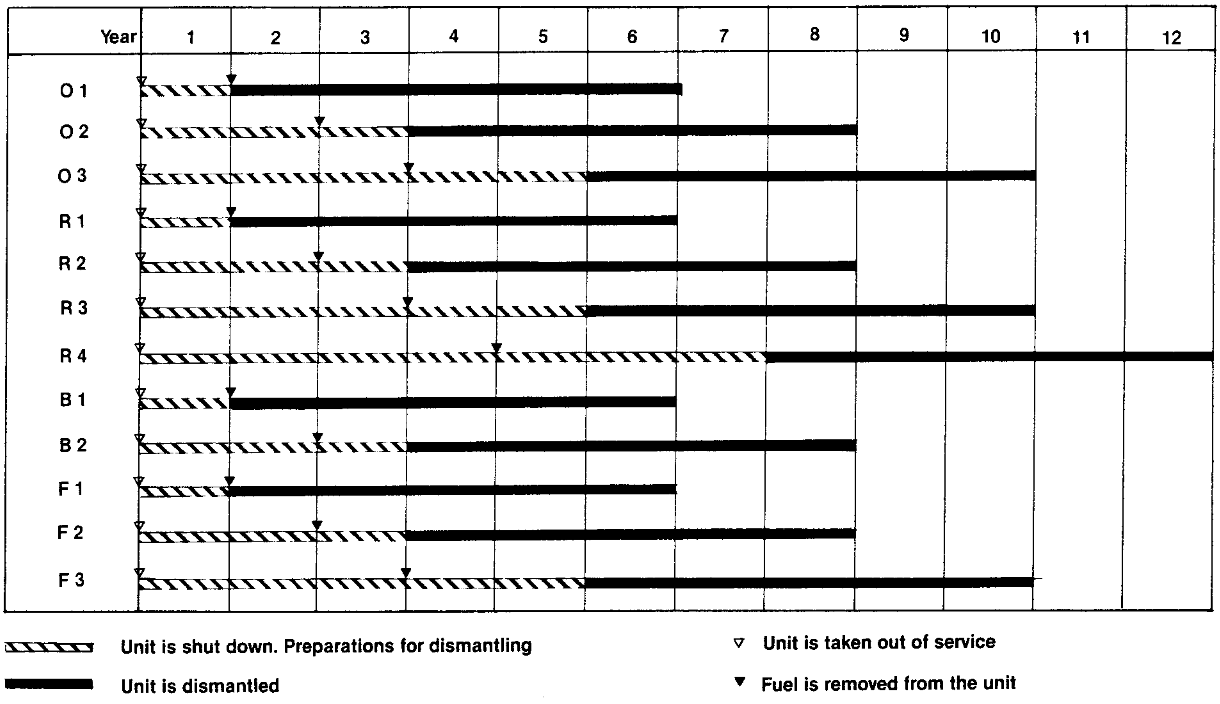


Figure 2-2. Example of timetable for decommissioning of the Swedish nuclear power plants if all units are shut down in the year 2010.

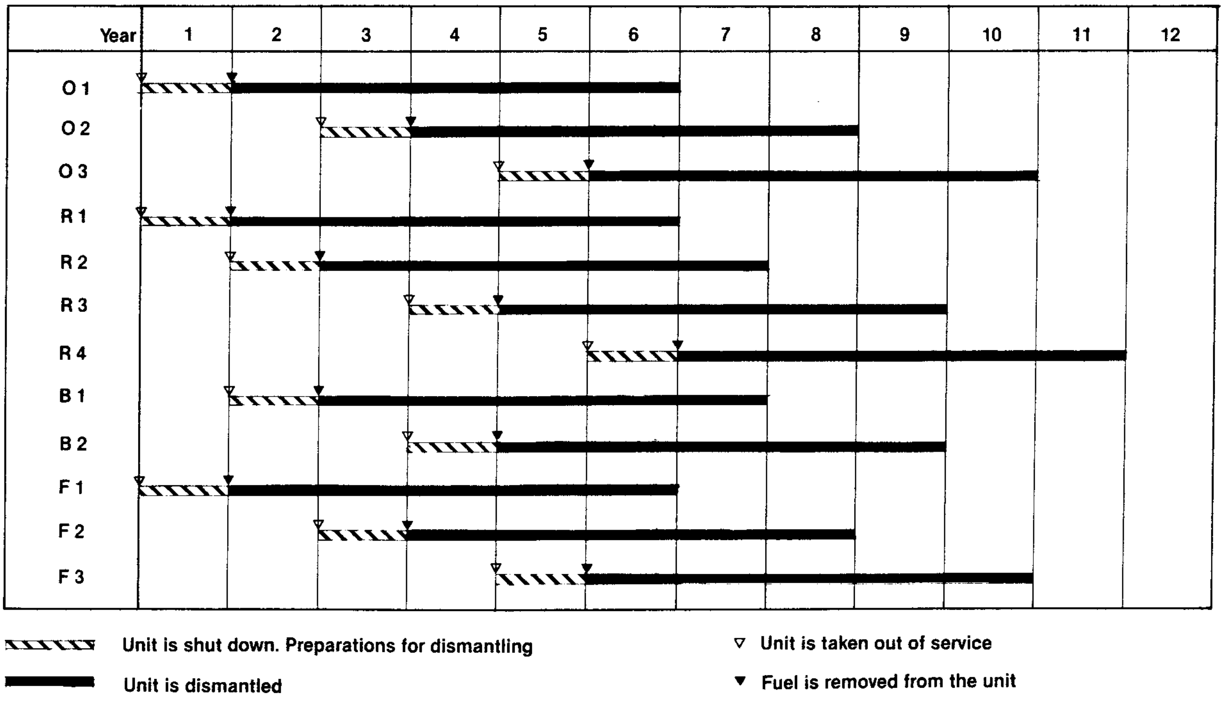


Figure 2-3. Example of timetable for decommissioning of the swedish nuclear power plants if final shutdown takes place over a five-year period.

3 PREMISES FOR THE DECOMMISSIONING STUDY

The premises that apply for this study are general and are not based on any attempt at optimization. Some of the premises can therefore be discussed from various viewpoints.

Reference plants: Ringhals 1 and Ringhals 2.

Operating life before final shutdown: 40 years.

The cost of decommissioning other plants will also be calculated, but in a simplified manner on the basis of the results obtained from the reference plants.

1 Dismantling starts as soon as possible after final shut-down and removal of spent fuel, control rods, neutron detectors and operating waste. This means that dismantling can be commenced one to four years after final shutdown.

The differences compared to dismantling after about 40 years are also studied as an alternative.

2 An estimate shall be made of the costs for "operation" of the plant from final shutdown until dismantling is commenced. This includes costs for keeping the plant systems going to the extent required in order to be able to store fuel and dispatch it for interim storage at CLAB.

For the case where dismantling is deferred, an estimate shall be made of the need for inspection and maintenance during the intervening period and of the costs of reactivating the plant to the extent required in order to be able to dismantle it in a satisfactory manner from the viewpoint of occupational safety.

3 Decommissioning shall be carried out using currently known technology.

4 The choice of working method shall be made with a view towards protecting personnel and preventing releases to the environment, as is normal in connection with maintenance and rebuilding work at nuclear power plants.

5 It is assumed that no other activities that disturb the decommissioning work will be allowed during the decommissioning period.

6 No incidents leading to a major release of radioactivity shall have occurred during the operating life of the plant. In other words, the release of radioactivity within the controlled area has been limited to normal leakage and minor releases.

7 An estimate of the inventory of radionuclides shall be made on the basis of previous studies, measurements and estimates.

8 The following is assumed considering contamination of concrete:

a) in large pools with stainless steel linings, leakage has led to a penetration of radioactivity to a depth of 5 cm over the entire surface behind the lining. In addition, cracks in the concrete have led to contamination of an additional 5 m^3 of concrete

b) in pump sumps, the concrete has been contaminated to a depth of 10 cm. Cracking has led to the contamination of an additional 1 m^3 of concrete

c) spillage in rooms with a limited amount of radioactive process equipment has led to contamination of 1% of the floor surface. In rooms with higher leakage risks, 10% of the floor area is contaminated.

These assumptions are rough and lead to an overestimate of the amount of radioactive waste. The floor surfaces are painted, so that no activity can normally penetrate into the concrete.

9 A system decontamination of reactor systems is performed before dismantlement is commenced. Decontamination agents that are suitable in terms of both effectiveness and waste handling are used.

Decontamination of turbines and turbine systems by means of simple decontamination methods, such as high-pressure spraying, is assumed. The spread of radioactivity to such systems is small, as a rule, and the activity is often easy to remove.

Scrap decontamination following disassembly shall be applied where this is deemed economically favourable. Electrochemical methods can thereby be used.

10 The waste is divided into three categories:

A. Waste that can be released;

B. Waste that can be disposed of on the site, for example in the underground parts of the buildings;

C. Waste that must be taken to a final repository.

11 Material is regarded as clean if it meets the requirements of the regulatory authorities on declassification. A limit of 300 Bq/kg is applied today in Sweden. This limit is purposely set very low and will probably be raised when more experience has been obtained from declassification. For example, the limit for material that does not require a licence for possession under the Radiation Protection Act, 70 kBq/kg, can be used as a guideline.

12 Transportation and final storage takes place in accordance with SKB's plans for other waste.

13 Inactive decommissioning waste is dealt with in the conventional manner. The possibility of using such waste as fill for restoring the nuclear power plant site will be considered.

The possibilities of reuse will be indicated.

14 The power plant site is restored so that it can freely be used for other activities.

15 The costs are calculated in the prices level of January 1986.

4 ACTIVITY CONTENTS

As a basis for determining the need for radiation shielding in connection with the decommissioning work and the quantity of material that must be treated as radioactive waste, the activity level in the different systems and building, components of the plant has been estimated. Both computer programs and recorded data from the operation of the Swedish nuclear power plants have been utilized for this purpose.

The radioactivity that is left in a nuclear power plant after it has been taken out of service and the spent fuel has been removed derives in part from material that has been activated by neutron irradiation from the reactor core and in part from radioactive corrosion products (crud) and fission products that have been transported out into systems and pools via reactor water, steam and fuel.

4.1 MATERIAL WITH INDUCED ACTIVITY

Most of the radioactivity is found in the reactor vessel and its internals. A calculation of the induced activity has previously been carried out for Oskarshamn 2 /2/. The activity level in different components is dependent partly on the composition of the constituent design materials and partly on what neutron flux the material has been exposed to.

The neutron flux and thereby the induced activity level declines very rapidly outside the reactor core. The crud activity dominates already at a distance of a few metres. Figure 4-1 schematically illustrates the parts of the reactor vessel and the surrounding concrete in the biological shield that have received an induced activity in excess of 70 kBq/kg. A detailed picture of the reactor vessel and its internals is shown in Figure 4-2. The activity contents are shown in Table 4-1.

The induced activity is dominated in terms of dose by Co-60. The specific activity in the most active portions, e g the core grid and the moderator tank, after 40 years of operation is estimated to be about 300 GBq/kg, which is equivalent to surface dose rates of more than 100 Sv/h.

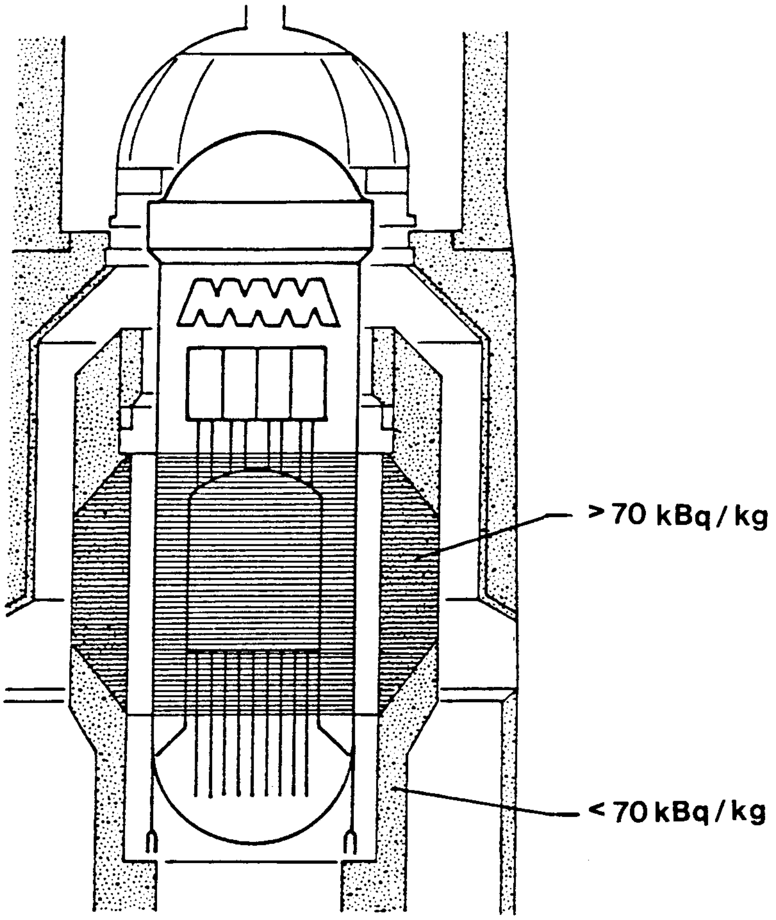
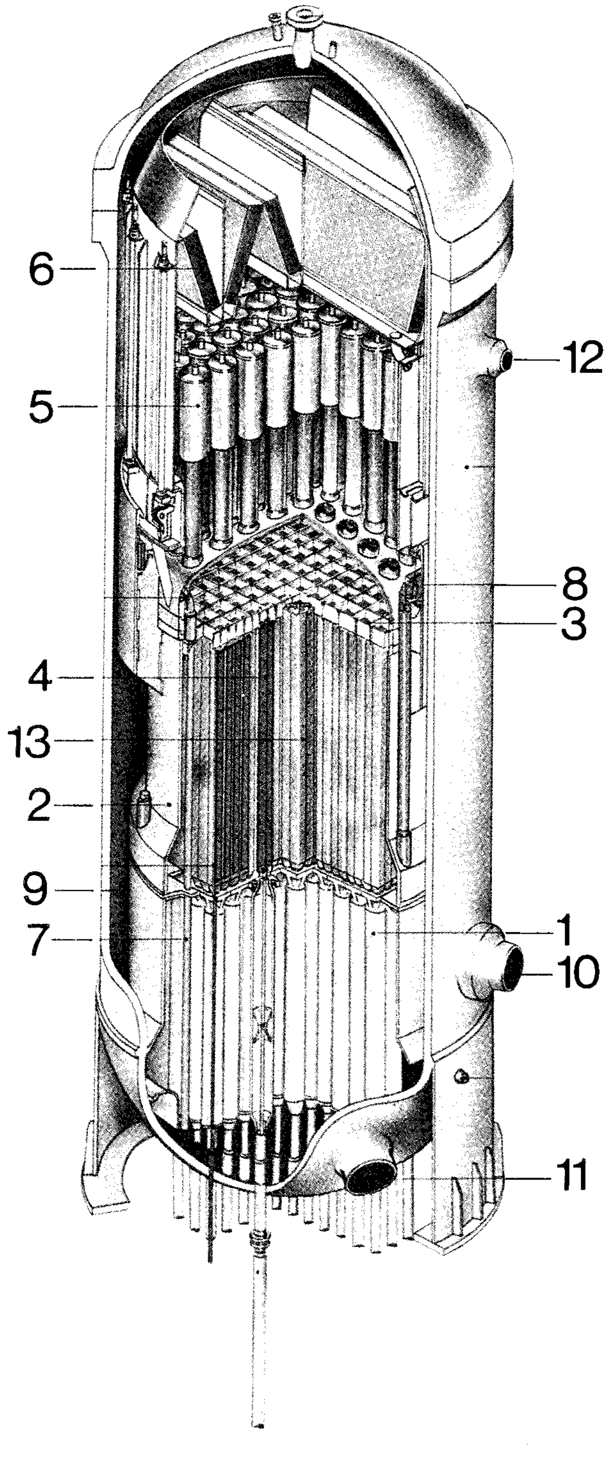


Figure 4-1. Induced activity in the reactor vessel and surrounding radiation shield (biological shield).

Table 4-1: Activity contents in reactor vessel and internals (Oskarshamn 2, 40 years of operation) /2/

Component	**Mass (tonnes)**	**Activity (GBq)** Co-60	Ni-63	Ni-59
Core grid	3	$1.0*10^6$	$1.5*10^6$	$1.0*10^4$
Moderator tank	23	$1.8*10^6$	$2.6*10^6$	$1.9*10^4$
Moderator tank cover	19	$1.0*10^4$	$1.3*10^4$	100
Moisture separator	24	$2.6*10^3$	150	10
Control rod guide tubes	25	$1.1*10^3$	$2.0*10^3$	20
Total internals	**130**	$\mathbf{4*10^6}$	$\mathbf{6*10^6}$	$\mathbf{4*10^4}$
Reactor vessel	**530**	$\mathbf{1.1*10^3}$	$\mathbf{1.3*10^3}$	**10**

Reactor vessel and internals



1. Control rod quide tube
2. Moderator tank
3. Core grid
4. Control rod
5. Steam separator
6. Moisture separator
7. Core spray pipe
8. Feedwater mainfold
9. Downcomer
10. Outlet spigot for cooling water to the circulation pump
11. Inlet spigot for cooling water from the circulation pump
12. Steam outlet
13. Reactor core

Figure 4-2. Reactor vessel with internals.

The Co-60 activity is much lower in the biological shield, 10 MBq/kg, which means that the dose rate on the inside surface of the shield is less than 1 mSv/h. One metre into the biological shield, the induced activity is negligible. The contribution from Eu-152 has not been analyzed here. Measurements in other power plants show that the Eu-152 content is of the same order of magnitude as Co-60 /10/.

4.2 MATERIAL WITH SURFACE CONTAMINATION (CRUD)

All system surfaces that come into contact with reactor water become more or less contaminated with radioactive particles known as crud. Data on crud buildup at different points in the reactor systems have been collected by means of measurements in connection with maintenance work.

On the basis of this material, a forecast has been made of how crud builds up during 40 years of operation /9/. This Figure 4-2 forecast has been based on a reactor system (the reactor water cleanup system) in Ringhals 1, after which an estimate has been made of how high the activity level is in other systems in relation to this system. Furthermore, a determination has been made of how much material comes into contact with reactor water and therefore can be contaminated. The results have also been compared with data from measurements on removed components.

Table 4-2 shows the estimated activity contents of several different systems. The table gives the values one year after shutdown. Only Co-60 is reported, since this nuclide is dominant.

Table 4-2: Activity content in several systems (Ringhals 1, 40 years of operation, one year of decay) /9/

System	**Activity (GBq)** **Co-60**
Main recirculation system (external pumps)	100
Shutdown cooling system	100
Reactor water cleanup system	200
Steamlines	150
Feedwater system (incl preheaters)	50
Total (all systems)	**2000**

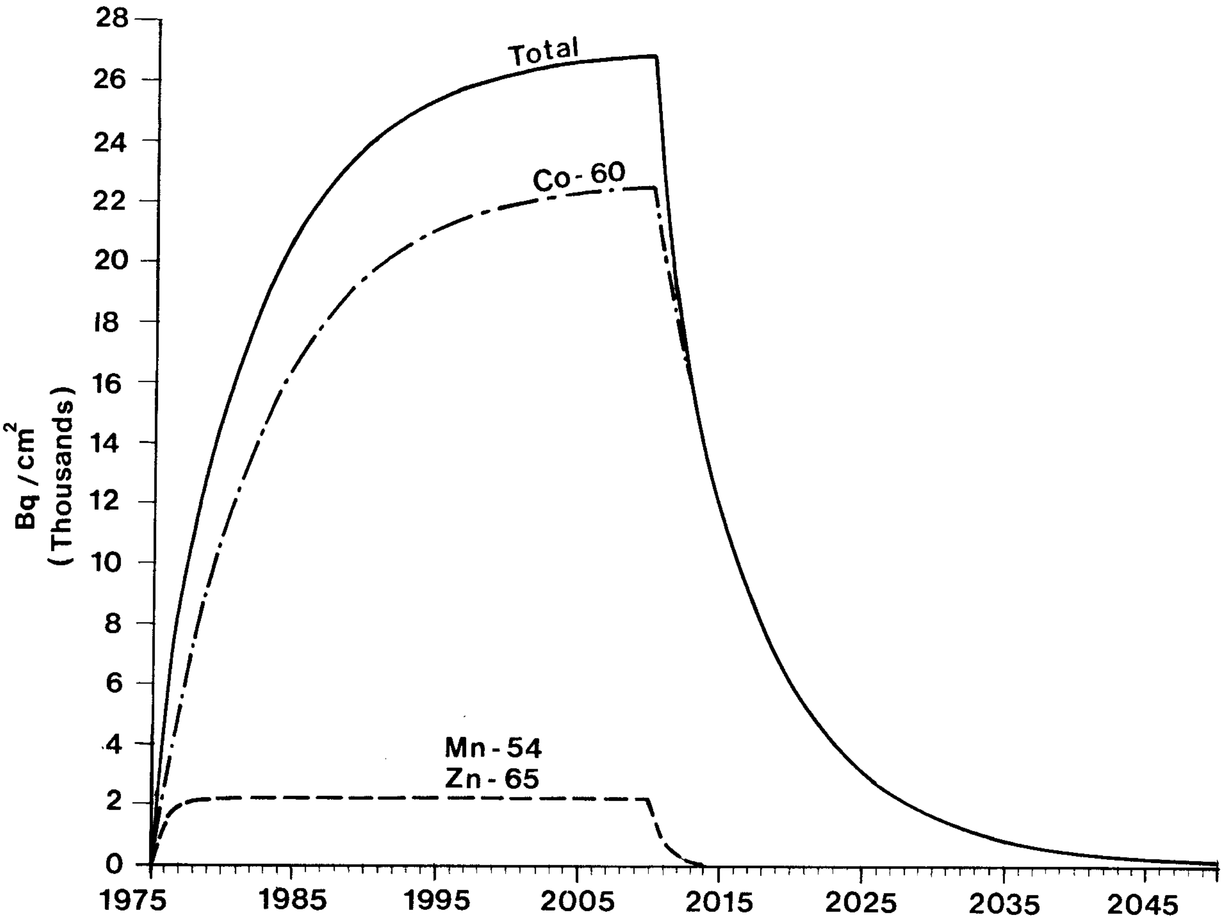


Figure 4-3. Measured and calculated activity buildup on a pipe in the reactor water cleanup system in Ringhals 1 /9/.

A small quantity of fission products, mainly Cs-137, may also be present (<10%). No allowance has been made in the table for the fact that the reactor systems will be decontaminated. This is expected to reduce the activity level by a factor of 10-100, depending on the type of component.

The reactor vessel and its internals will also have surface contamination. The total contribution to the activity contents from crud on these parts is estimated to be about 10^4 GBq /2/.

After the decontamination campaign, the dose level in most areas outside the reactor vessel is expected to be so low that the dismantling work can be carried out for the most part with normal radiation protection precautions.

A similar assessment of the activity contents and radiation levels has also been carried out for a PWR, Ringhals 2. The total activity contents agree well with that in Ringhals 1.

4.3 OTHER ACTIVITY

Some activity will also be present outside the reactor and turbine system as a result of leakage and spillage. The total quantity is small, however, in relation to what is present in the system.

Daughter products of radioactive noble gases, mainly Cs-137 and Sr-90, accumulate in the delay tank for radioactive off-gases. A total of about 500 GBq is estimated to be present there. Most of the activity will be in the bottom of the delay tank. In calculating the waste volume, it is assumed that 10% of the sand has to be sent to the SFR.

5 TECHNICAL DESCRIPTION OF THE DIFFERENT PHASES OF DECOMMISSIONING

5.1 GENERAL

The decommissioning of nuclear power plants has been divided in this study into three main phases as follows:

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

A project group for decommissioning is responsible for coordination during these phases. This group plans the decommissioning procedure in detail, prepares the necessary engineering documents and safety reports and maintains contacts with regulatory authorities etc. The project group is formed about three years prior to the start of the decommissioning work. The size of the group varies during the different phases. The project group belongs to the licensee's organization and is responsible for reporting and licensing matters in relation to authorities.

The following is a brief description of the activities that fall under the three phases. Detailed accounts are given in the supporting reports /3-8/.

5.2 SHUTDOWN OPERATION IN THE CASE OF IMMEDIATE DECOMMISSIONING

5.2.1 General

By "shutdown operation" is meant the operating activity that is required during the period from when the reactor has been taken out of operation until the actual work of dismantlement has begun. During this period, the spent fuel is removed and some system decontamination is carried out. Final plans are also drawn up for the dismantling procedure.

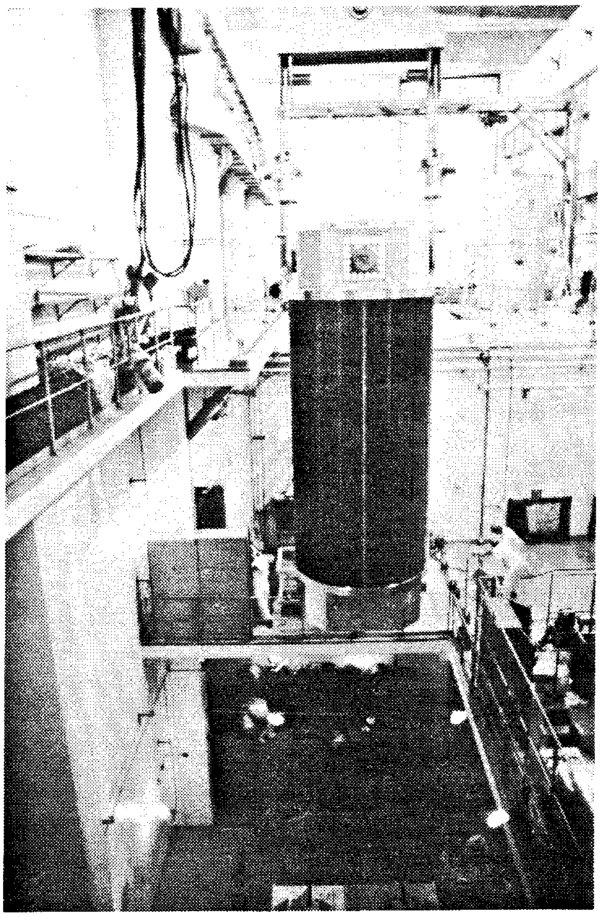


Figure 5-1. Removal of fuel shipping cask from a nuclear power plant.

5.2.2 Fuel handling

The shutdown procedure has been prepared for so that the fuel storage pools only contain fuel unloaded during the immediately preceding year. Fuel from previous years' unloadings has already been shipped.

The pools have been cleaned out as far as reactor internals and similar materials are concerned.

The fuel in the reactor core is immediately transferred to the fuel pools. The fuel unloaded during the preceding year has now been stored for one year, which simplifies handling and transport to CLAB. Shipment of the one-year-old fuel can therefore be commenced.

Removal of the fuel from the final cores will be planned so that the units that are to be decommissioned first also have their pools emptied first.

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

As long as fuel remains in the fuel storage pools of the unit, it is expected that the plant staff will work on continuous shift.

5.2.3 System decontamination

During the period the reactor fuel is being handled and removed, measures are taken to reduce the activity level within the unit. All active primary systems, including the reactor vessel, are subjected to this treatment.

The activity level is reduced by recirculation of decontamination solutions in the active primary systems. The decontamination agents are chosen with a view towards effectiveness and suitable waste management. Decontamination is expected to reduce the activity level by a factor of between 10 and 100 with a treatment time of about one month, even when mild decontamination solutions are used. These decontamination factors are based on experience, the lower value applying to apparatus such as tanks, while the upper value applies to piping, where higher flow rates can be obtained.

After completion of system decontamination, the systems are rinsed out with water and drained.

5.3 SYSTEM DISMANTLEMENT - BWR

5.3.1 Systems needed during decommissioning

Dismantlement of systems is begun when all fuel from the unit has been removed. All systems and all equipment not needed for decommissioning can be taken out of operation and their electricity supply disconnected.

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

- The waste station is needed for cleaning of water and treatment of filter and ion exchange media;
- Drainage systems will be kept in operable condition until dismantlement renders this impossible;
- The ventilation systems will be kept in normal operation as long as fuel remains in the plant. During the decommissioning

work, the risk of dispersal of airborne activity within the plant will be given due consideration. Stack 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 be reduced when the fuel is gone. Unnecessary busbars and equipment will be disconnected and separate supplies will be arranged to functions essential to decommissioning such as certain ventilation systems. The power will be supplied from existing switchgear;

- Monitoring equipment and alarm systems will be adapted to needs during decommissioning. Delimitations will be made in the control room so that only systems in operation are shown. In this way the operator can easily keep watch over the status of the plant;

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

- Surveillance and inspection rounds will be performed to the necessary extent. The operating area fence will be classified as an industrial fence after the fuel has been removed. Access control to active areas will be maintained until the active material has been removed;

- Service functions in the form of active laundry, personnel quarters, restaurants, housekeeping and occupational safety activities will be retained to the necessary extent during the decommissioning period.

A portion of the operating staff will be kept on during the decommissioning period. They will handle operation of systems, processing of work notices, service, maintenance, stores keeping, housekeeping etc as well as surveillance.

5.3.2 Principles of execution

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

Work methods and equipment for dismantlement and cutting up of piping systems and apparatus will be chosen so that the personnel are not exposed to unnecessary radiation doses. In order to avoid releases of airborne activity, large-diameter pipes in active systems will be cut with pipe lathes, while small-diameter pipes will be cut with hydraulic shears.

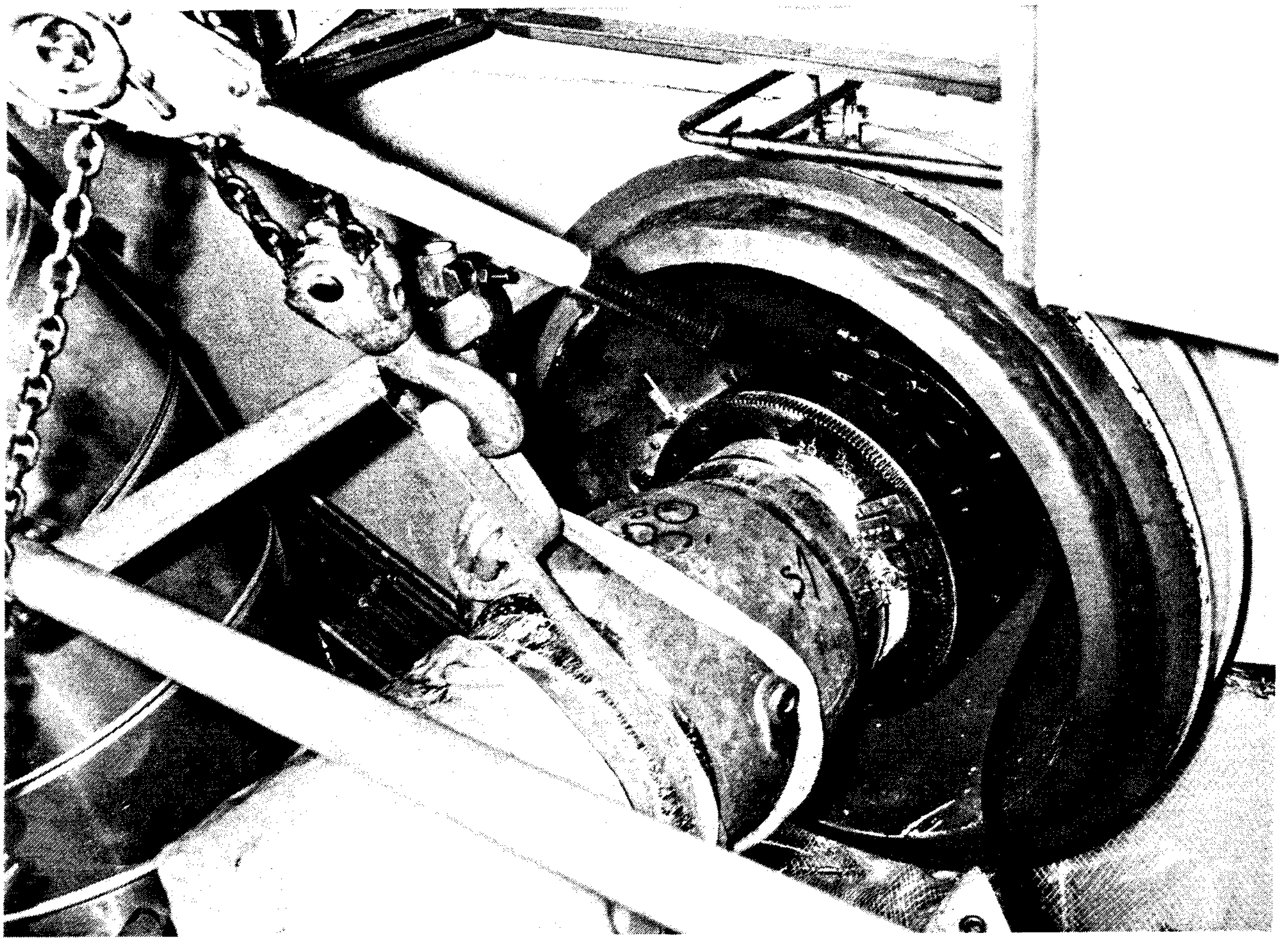


Figure 5-2. Cutting of pipe with pipe lathe.

All insulation material and any asbestos will be removed from piping systems and apparatus before active systems are opened. Most of the insulation material is inactive and can be declassified. A limited quantity may be contaminated due to leakage from stuffing boxes and flange joints in active systems. Only the contaminated insulating material has to be disposed of as active waste.

Normally, the rooms are also decontaminated before pipelines are cut. Where judged appropriate, extra protective painting/plastic coating of floors will be carried out if there is a risk of active water penetrating into the concrete during the decommissioning work.

Open pipe ends will immediately be covered with heavy plastic caps, which will immediately be secured with tape in order to prevent dispersal of activity. In exceptional cases, seal welding may have to be resorted to. This mainly applies to components that are intended to be transported without transport containers.

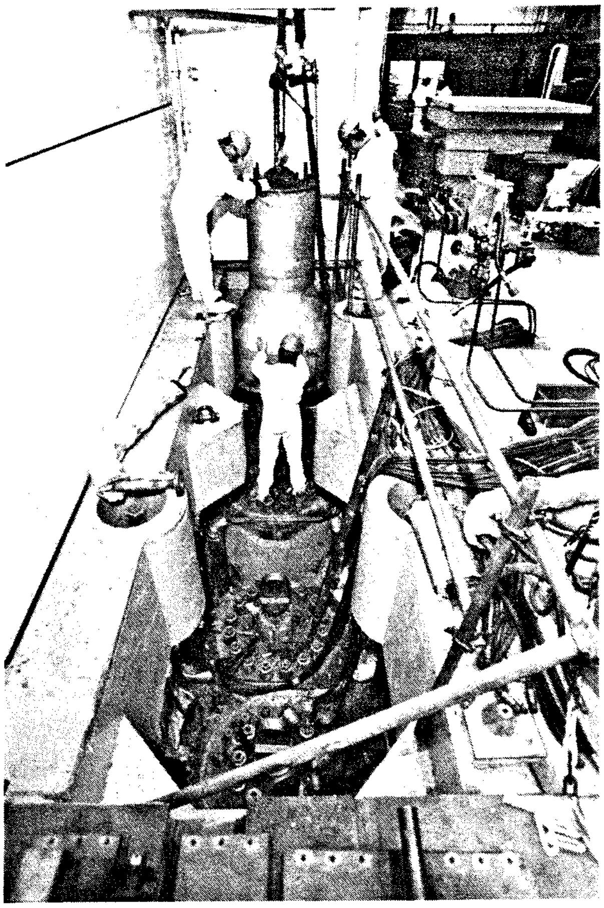


Figure 5-3. Removal of insulation around valves. (Photo Hallandsbild)

Pipes in active systems are cut into suitable lengths, 2-5 m, for handling in the process area and other handling up until disposal.

Pipe fittings and components are put in ISO containers, which are deposited in the final repository.

Segmenting of components shall be avoided wherever possible. This means that special transports of large components without transport containers will be necessary to some extent.

Extra boxes and containers shall also be avoided wherever possible in cases where the waste is transported in radiation-shielded reusable transport packagings.

Decommissioning shall be carried out with certain systems in operation. The electricity supply to ventilation fans and power take-offs may not be affected by the dismantlement of cabling in the plant. This may require the use of separate power feed paths to the equipment that has to remain in operation.

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

5.3.3 Communication and material transports

Control of personnel access to controlled areas takes place in the same manner as during normal operating and refuelling/maintenance work.

The flow of material out of the plant takes place primarily through existing doors, gates and passageways. In connection with detailed planning of the decommissioning procedure, it is important to provide sufficient space inside the plant for interim storage of material, placement of transport containers etc.

The decommissioning work should be divided into a number of subprojects so that the work can be pursued on several fronts, thereby reducing the total decommissioning time. Areas inside the plant that are emptied of equipment at an early stage, for example the generator section, can be utilized for buffer storage of materials and for decontamination as well as radiological survey.

Prior to the start of the dismantling work, a thorough radiological survey has been made of the different system parts of the plant. This radiological survey is assumed to be accepted by the licensing authorities so that no nuclide-specific measurement has to be performed on each individual waste package or transport container prior to shipment. However, each transport container is intended to be checked with regard to dose rate and presence of surface contamination prior to shipment from the plant in accordance with the IAEA's transport recommendations /13/. The surface dose rate on the transport container may not exceed 2 mSv/h and the dose rate at a distance of 2 m 0.1 mSv/h.

During the decommissioning work, the active material is sorted with regard to how it is to be handled from then on. The determining factors are thereby requirements on radiation shielding and whether or not the material can be declassified. The categories are roughly as follows:

- Some internal parts and reactor vessel materials have such high activity levels due to induced activity that they have to be transported in a type B container. A special transport cask is used for these components, the core component cask. It is similar in its design to a fuel transport cask;
- Other material that has to be transported to a final repository is placed, depending on the material's activity level, in radiation-shielded waste transport containers (ATB) or in ordinary ISO standard containers;
- Low-level material is placed, wherever possible, in shallow ground repositories adjacent to the plant;
- Declassification of material, possibly following decontamination, is carried out in accordance with limits stipulated by the licensing authorities.

5.3.4 Execution of system dismantlement

Reactor vessel and internals

The reactor vessel for an external pump reactor is shown in Figure 4-2. The total weight of the vessel with internals is about 650 tonnes. For internal pump reactors, this weight is about 760 tonnes.

The internal parts close to the reactor core have such high activity levels that the material must be transported in a type B package, the core components cask.

The work of segmenting the internals is commenced as soon as the fuel has been removed.

The internals are segmented by means of plasma-arc cutting under water. Pieces of suitable size are placed in boxes and canisters designed to fit into the core component cask.

Internal parts with lower activity levels, for example moisture separators and the lower parts of the control rod guide tubes, can be placed in boxes and then in a radiation-shielded transport container for transport to the SFR.

The insulating material on the outside of the reactor vessel will be removed in connection with segmentation of the reactor vessel. Some of this material has become active due to neutron irradiation.

The reactor vessel is segmented by being cut into rings. Cutting is done by remote control in air. The rings are then lifted up into a pool, where the sectioning into pieces of suitable size for transport to the final repository is performed under water.

Figure 5-4 illustrates the principle of the cutting equipment. Similar equipment has been used for segmentation of a research reactor vessel.

In plants with external pump reactors, the reactor vessel stands upright on a support. These tanks can therefore be segmented from the top down, with the uppermost ring first. In reactors with internal pumps, the reactor vessel is suspended from a flange at the top. Before segmentation is begun, a support must therefore be built up from below and from the sides. Cutting can then be carried out in the same manner. The time required for the work with the reactor vessel is four months longer in the latter case.

Alternative methods exist for segmenting the reactor vessel. Furthermore, an overview study has been carried out concerning handling and final storage of an intact reactor vessel. Disposal of an intact reactor vessel is a feasible alternative and is

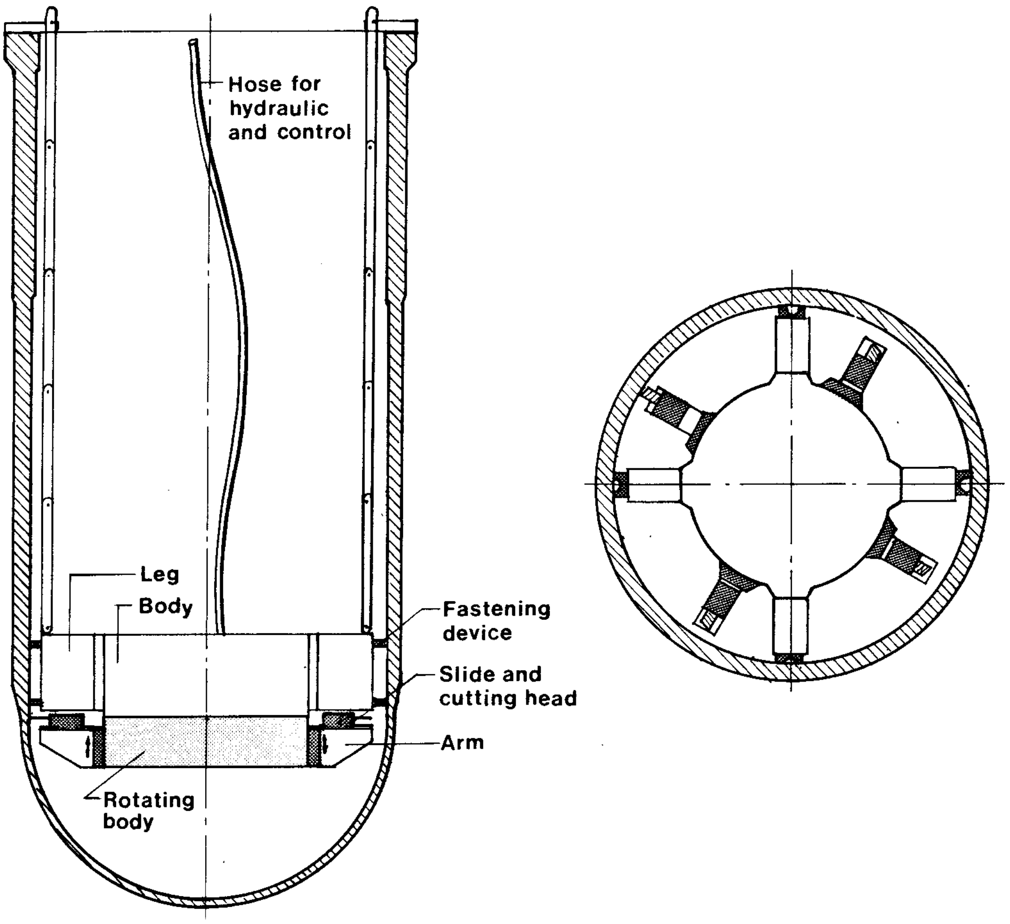


Figure 5-4. Schematic drawing of equipment for cutting of the reactor vessel.

especially recommended in the case of deferred decommissioning (see Section 9.2).

Active process systems

The dismantlement of active process systems is commenced with the removal of all insulating material and any loose contamination in the process areas.

Large-diameter pipes are cut with a pipe lathe in order to avoid as far as possible the generation of airborne activity. The use of a pipe lathe also enables the time spent by the personnel in direction connection with the process pipes to be limited. Smaller-diameter pipes are assumed to be cut with hydraulic shears.

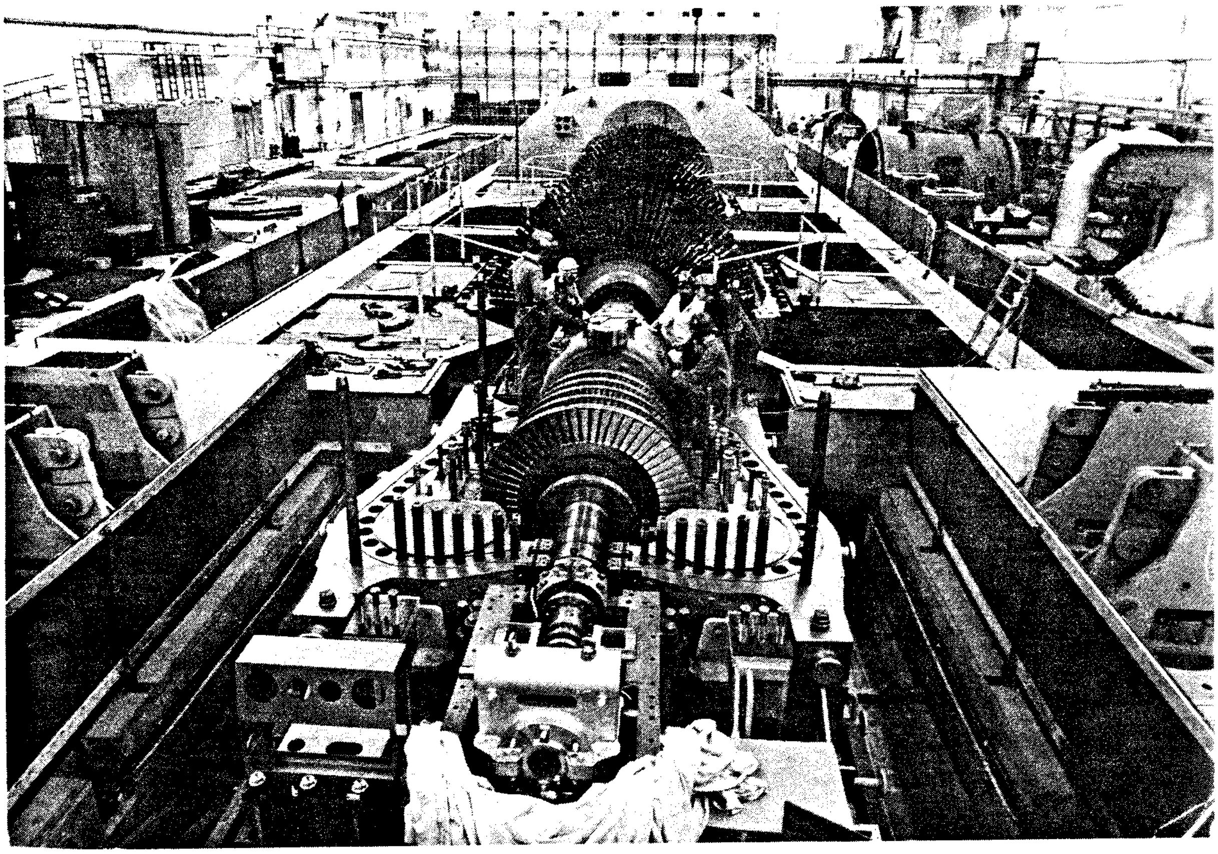


Figure 5-5. Installation of turbine in Ringhals 1.

In assessing the labour requirement for dismantling active process systems, experience from major modification and rebuilding work has been drawn on. This may entail some overestimate of resource requirements and time, since the dismantling work only involves disassembly, and no assembly inspection is required.

Turbine and generator

The estimate of the personnel and time requirements for dismantling the turbine and generator is based on experience from maintenance work performed on this equipment.

Most of the material in the turbine can be declassified, including the large turbine shafts. Some parts, for example the turbine blades, may have to be decontaminated. The generator has been assumed to be completely inactive.

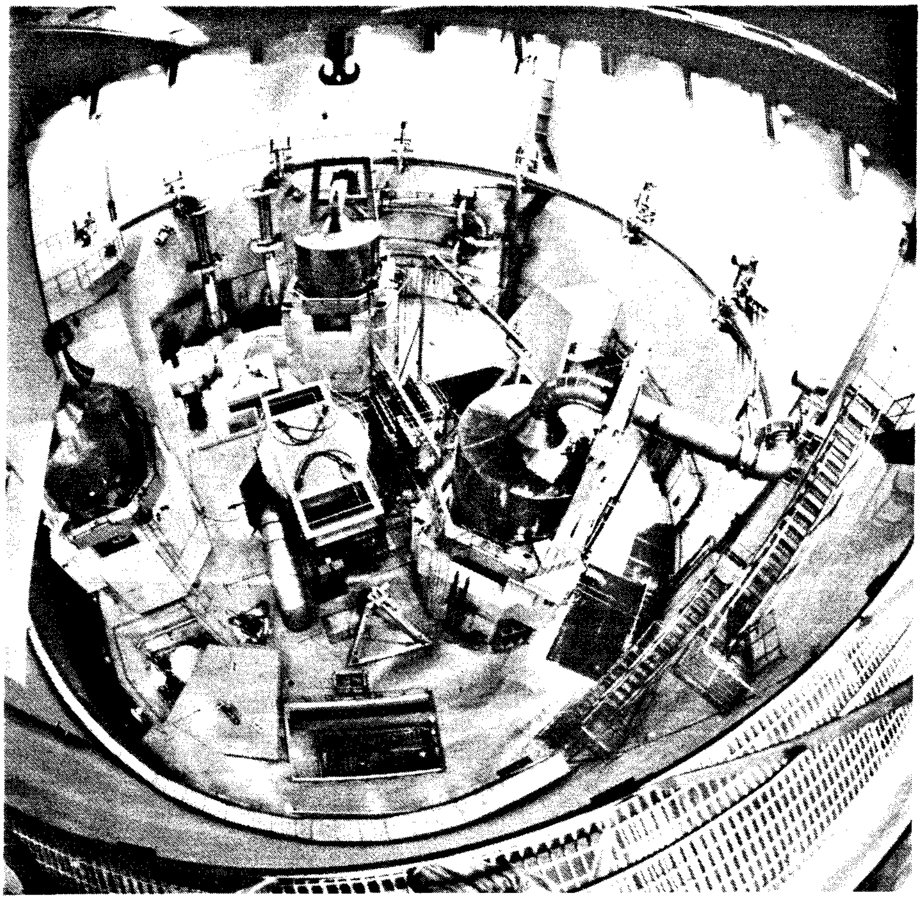


Figure 5-6. The reactor containment in Ringhals 2.

Inactive systems

No special study has been carried out for the dismantlement of inactive system parts. These are assumed either to have a residual value equivalent to the cost of dismantling, or to be included in the forthcoming building demolition.

5.4 SYSTEM DISMANTLEMENT - PWR

System dismantlement of a PWR does not differ in principle from dismantlement of a BWR plant.

The existing transport opening through the reactor containment wall must be enlarged in order to permit removal of internals, reactor vessel parts etc in core component casks and radiation-shielded waste transport containers.

It is also necessary to build a floor structure so that the terminal vehicle can place waste containers within the range of travel of the in-containment overhead crane.

A number of the large components inside the containment, such as pressurizer, accumulators, blowdown tanks etc are assumed to be transported intact to the final repository. The steam generators have to be cut between the tube bundle and the moisture separator in order to permit transport down into the final repository.

5.5 BUILDING DEMOLITION

When system dismantlement has been concluded, demolition of the buildings is begun. First all active material is removed. Then a thorough activity check is carried out, after which demolition of the inactive parts can be carried out without any special radiological safety control, but with observance of normal occupational safety.

5.5.1 Active building demolition

Active building demolition includes dismantlement, demolition and removal of those portions of the biological shield that contain induced activity, as well as of contaminated concrete behind pool linings, in pump sumps and on contaminated floors in the process areas. Removal of the stainless steel lining in pools and pump sumps is also included.

Demolition of active building parts is begun as soon as the active systems and the reactor vessel have been removed.

When the process equipment has been transported away and contaminated surfaces have been decontaminated, removal of the layer containing induced activity in the biological shield is begun. This layer is about 1 m thick.

The demolition work is carried out with the aid of, for example, an electrohydraulically powered and remotely controlled spalling machine, type BROKK. See Figure 5-7.

The machine operates from a vertically adjustable lifting table. The concrete rubble is collected in a hopper suspended next to the wall. From the hopper, the waste is dropped down into a box. When the box is full, it is lifted by the reactor hall crane and transported out.

Reinforcing bars are cut or sheared off with the same equipment.

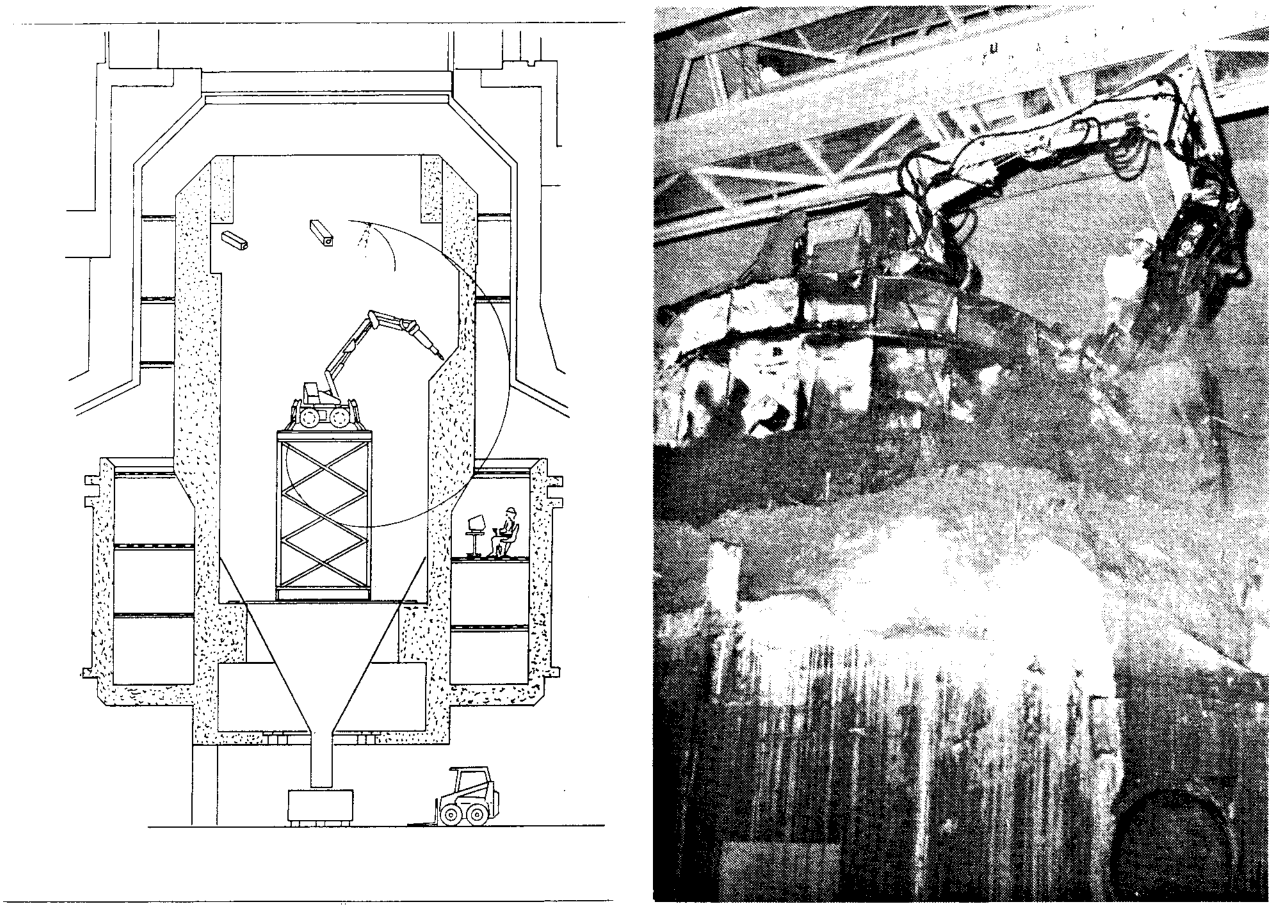


Figure 5-7. Demolition of the biological shield with the aid of the BROKK spalling machine. Schematic drawing (at left) and application in R1 reactor (at right). Work performed by Rivteknik AB.

Dust is controlled with a water spray from a nozzle attached to the hydraulic jib. The flow of water and the degree of atomization is adjusted so that the water is absorbed by the concrete dust with no excess water arising.

This method of spalling away concrete was used to demolish the biological shield in the R1 research reactor in Stockholm.

Prior to spalling, the open top part of the biological shield is covered with a dusttight structure with openings for control cables.

The bottom of the shield is covered so that an enclosure is obtained that permits controlled and filtered ventilation during spalling.

Concrete waste on the bottom of the enclosure is vacuumed up by a vacuum loader.

When the concrete layer with induced activity in the biological shield has been removed, the lining sheet in the wetwell and other pools is removed. Contaminated surface concrete in pools and on floors is spalled away by BROKK machines equipped with a breaking tool. The fragmented concrete is vacuumed up by a vacuum loader.

5.5.2 Inactive building demolition

After all contaminated concrete has been spalled off, packaged and transported out, conventional demolition takes over. This is begun in the top levels in the nuclear power unit.

The roof covering and roof beams as well as overhead cranes are removed first with the aid of lift cranes. Then concrete walls are spalled by means of, for example, BROKK machines in such a manner that sections sized about 2x3 m are cut out and lowered to the ground on the outside of the wall. The same procedure is used on the floor structure. Removal of 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 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 an embedded steel sealing sheet and is provided with pretensioned reinforcement and close-packed non-tensioned reinforcement. It is segmented by cutting with thermic lances to appropriately sized blocks, which are deposited in the reactor building underground.

The reactor containment on PWR units and certain BWR units contains pretensioned cables 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.

The concrete stacks are most easily demolished by spalling at the base and felling out towards the plant yard.

6 TIMETABLE AND PERSONNEL REQUIREMENTS

The time for start of the dismantling work depends on how fast all the reactor fuel can be removed. If the entire transport and receiving capacity at CLAB is reserved for one unit, it should be possible to commence dismantling approximately one year after electricity production has ceased.

In order for the timetable for removal of systems and process equipment to be short, dismantling work is pursued simultaneously in different parts of the unit. In a BWR plant, decommissioning can begin in the generator section, the reactor containment and the reactor hall level at the same time.

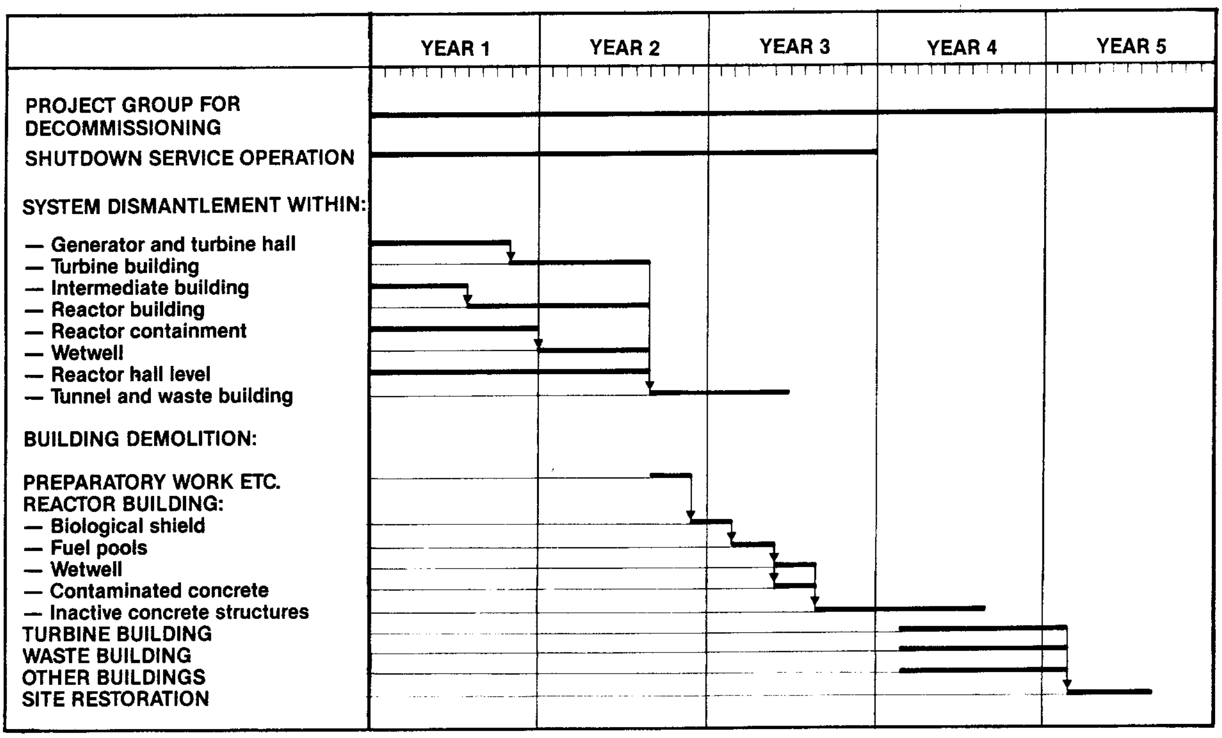


Figure 6-1. Total timetable for decommissioning of Ringhals 1.

The work on the reactor hall level mainly involves segmentation and packaging of the reactor vessel internals as well as the reactor vessel itself. This involves a great deal of work and is the determinant factor for the total time required for the decommissioning work.

For a PWR plant, the work inside the reactor containment is determinant for the timetable, and here as well, segmentation of the reactor vessel internals and the reactor vessel are determinant for the total time required for the dismantling work.

In drawing up a timetable and assessing personnel requirements, a total review has been carried out of both reference plants. The review includes a room-by-room analysis of systems and equipment, and the assessments have been based on experience from normal refuelling/maintenance work as well as major modifications and rebuilding work.

The total time for system dismantlement for Ringhals 1 has been estimated at 30 months. In the case of BWR units with internal pumps, segmentation of the reactor vessel entails an extension of the total time to 34 months. The resource requirement during the decommissioning period varies and amounts to a maximum of about 340 persons for system dismantlement.

Demolition of building structures has been studied by firms with many years of experience from industrial facilities.

The building demolition work begins with removal of concrete containing induced activity in the biological shield. This work can be commenced when all active process equipment, including the reactor vessel, has been removed, which occurs 20 months after the start of system dismantlement. For a BWR plant with internal pumps, an additional four months are required.

The time for building demolition, including site restoration, has been estimated at 36 months. During the first 12 months, building structures with induced activity, contaminated pool linings and contaminated concrete are demolished. When this work has been concluded and radiological measurements show that all activity has been removed, these buildings can be classified as inactive and the demolition work can proceed using conventional methods.

Building demolition will be carried out with the aid of large construction machines, so that the labour force can be kept down. The maximum labour force for building demolition will be about 40 persons.

A total personnel curve for decommissioning of Ringhals 1 is shown in Figure 6-2. The maximum personnel requirement is about 480 persons. This includes the project group, system dismantlement personnel and building demolition personnel with supervisors as well as personnel for service operation. For service operation,

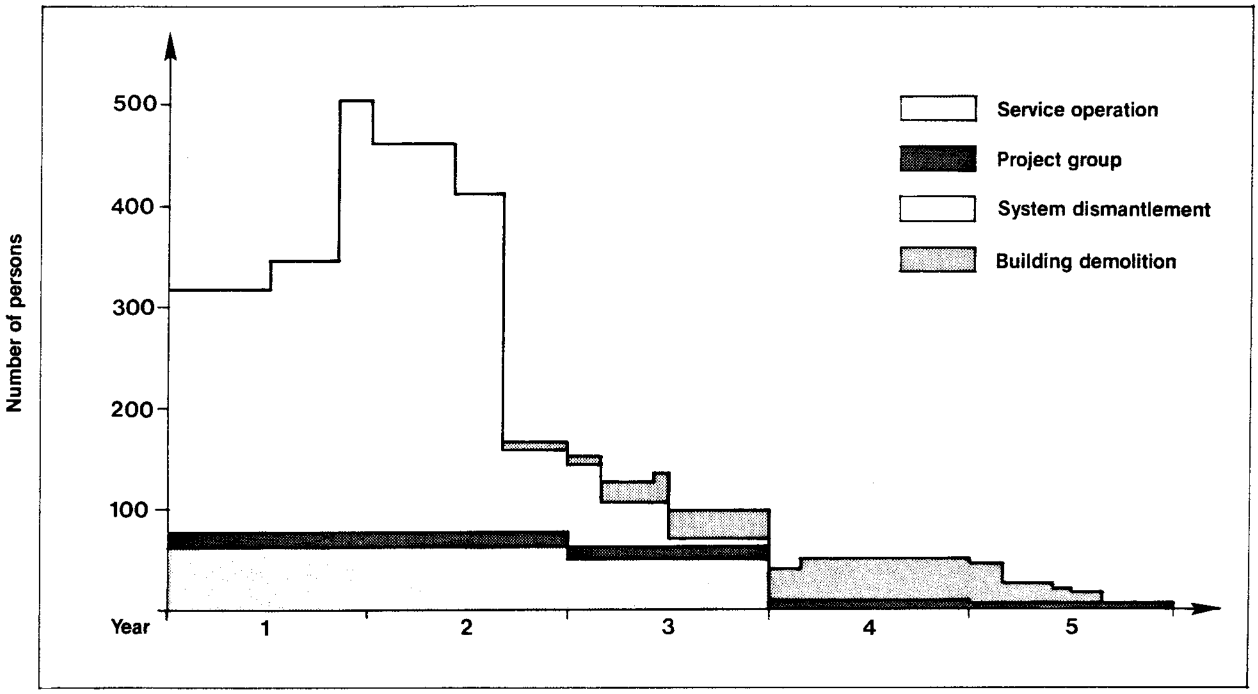


Figure 6-2. Total personnel requirement for decommissioning of Ringhals 1.

only Ringhals 1's share of the total operating personnel at the Ringhals plant has been included.

The same timetable as for Ringhals 1 has been assumed for other BWR units with external pumps, and for BWR units with internal pumps a 4-month-longer timetable has been used. It is possible to keep these timetables by varying the work force in accordance with the quantity of material to be removed.

The decommissioning plan for a PWR unit agrees in the main with that for a BWR unit. The extent of the active systems is smaller, however, since the turbine plant is completely inactive in a PWR unit. Here as well, the determining factor for the timetable for the execution of decommissioning is the dismantling of the reactor vessel internals as well as the reactor vessel itself. The total time for dismantling has therefore been judged to be the same as for a BWR unit (R1). It should be possible to shorten the time, however.

7 WASTE MANAGEMENT

7.1 MATERIAL QUANTITIES

In order to determine the quantity of waste that has to be managed in connection with decommissioning of the nuclear power plants, a detailed study has been carried out of the material quantities in Ringhals 1 (BWR) and Ringhals 2 (PWR) /6/. The results are presented in Table 7-1.

The material quantities in other BWR units have been estimated in relation to Ringhals 1. In determining the quantity of active material in system parts, the ratio between active and inactive material has been assumed to be the same in all BWRs.

Table 7-1: Waste quantities for Ringhals 1 and Ringhals 2 in tonnes.

	Ringhals 1		**Ringhals 2**	
	Active	**Inactive**	**Active**	**Inactive**
Reactor vessel and internals	650	-	330	-
Pipes and valves	1485	1435	465	appr. 1900
Apparatus	1780	4215	1935	appr. 5800
Insulation	60	90	60	150
Electric cables and trays	-	280	-	250
Sand	350	3150	-	-
Concrete	915	not est	975	not est
Process waste (immobilized)	300	-	300	-

Table 7-2: Decommissioning material from the units in tonnes.

	ACTIVE MATERIAL					INACTIVE MATERIAL
Unit	Reactor vessel	Other active systems	Sand	Con-crete	Total	(excl concrete)
01	650	1990	250	615	3505	6135
02	650	2475	250	900	4275	7480
03	760	4725	1050	1410	7945	13905
R1 (ref)	650	3325	350	915	5240	9170
R2 (ref)	330	2460	-	975	3765	8135
R3	330	2460	-	975	3765	8135
R4	330	2460	-	975	3765	8135
B1	650	2470	250	900	4275	7480
B2	650	2655	250	990	4550	7965
F1	760	4120	1050	1230	7165	12540
F2	760	3935	1050	1230	6980	12215
F3	760	4720	1050	1440	7975	13960
TOTAL TONNES					**63 205**	**115 225**

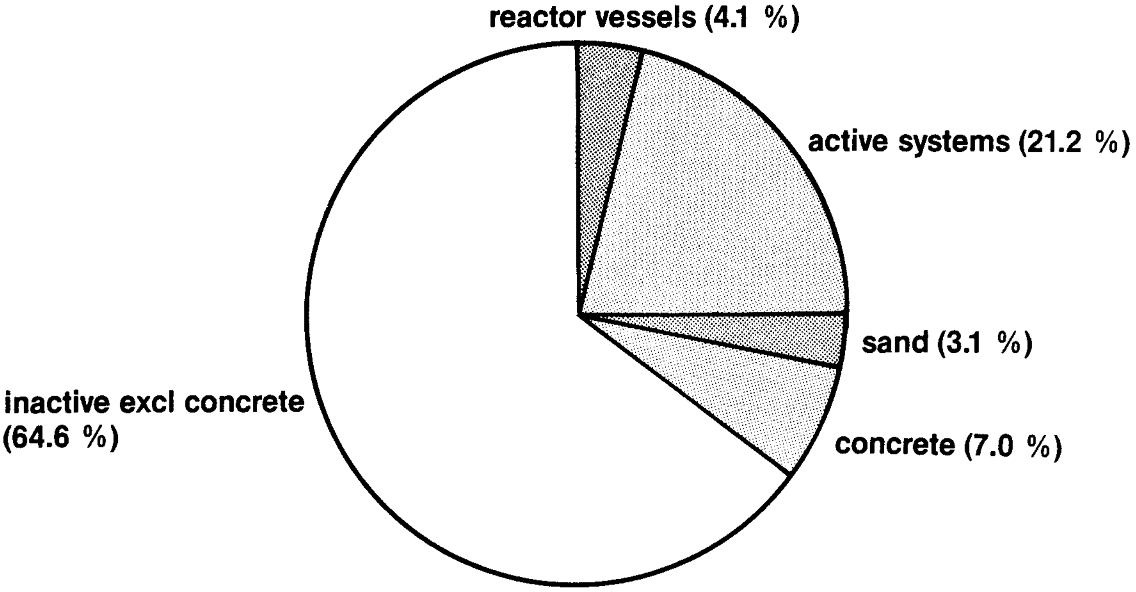


Figure 7-1. Waste quantities from decommissioning of the Swedish nuclear power plants.

The material quantities in Ringhals 3 and 4 are assumed to be equal to Ringhals 2. The total quantity of decommissioning material from all units is presented in Table 7-2 and Figure 7-1.

Some process waste, e g ion exchange resins and filters, is also obtained from decommissioning. Most of the ion exchange resins are obtained in connection with system decontamination /8/.

7.2 CLASSIFICATION OF WASTE

The waste products from decommissioning of the nuclear power plants have widely varying activity levels, everything from inactive building material to highly radioactive material from the reactor vessel internals. These waste products thereby put different demands on handling and final disposal.

With this in mind, the waste is divided into three categories:

- Waste that can be released without restrictions (declassified)
- Waste that can be disposed of on the site
- Waste that must be disposed in the final repository for reactor waste (SFR) or for long-lived waste (SFL).

Declassification

Some material is declassified, i e released for unrestricted use or for disposal. A limit of 300 Bq/kg is being applied on a trial basis in connection with declassification today. This limit has purposely been set very low and will probably be raised when more experience has been gained from declassification. For example, the limit for material that does not require a licence under the Radiation Protection Act, 70 kBq/kg, can be used as a guideline.

Disposal on the site

The licence of OKG for shallow ground burial at the Oskarshamn station states that the total amount of activity buried may not exceed 100 GBq at any time. Furthermore, the average activity concentration per package may not exceed 300 KBq/kg. The total activity limit for shallow ground burial will probably also be raised when experience has been gained. A guideline may be 10 TBq, which is the limit for SSI's (the National Institute of Radiation Protection) right to issue licences for shallow ground burial under the Nuclear Activities Act. Higher values may also be considered in accordance with the optimization principles being discussed within the ICRP /12/.

Final disposal in SFR or SFL

Most of the decommissioning waste that requires final disposal will be emplaced in SFR3. For practical reasons, some waste with a high activity level may also be emplaced in the SFL.

The activity contents of the decommissioning waste are dominated by Co-60, which has a half-life of about five years (see Chapter 4). The reactor vessel internals also contain a number of more longlived nuclides, for example Ni-63, Ni-59 and Nb-94. However, the activity level and radiological toxicity of these nuclides are so low that even the internals can be emplaced in the SFR.

Certain reactor vessel internals have such a high radiation level that they must be transported in a core component cask. It may also be deemed appropriate to store them in CLAB for several decades before they are disposed of, simplifying handling in connection with final disposal. There has not been scope within this study for any inquiry into which alternative is the most cost-effective.

7.3 TREATMENT OF WASTE

The waste can be divided into the following groups with respect to treatment:

- Direct dismantling waste
    - Scrap metal
    - Concrete and sand
    - Insulation
    - Other waste

- 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.

In the case of the direct dismantling waste, as little treatment as possible is presumed. Scrap metal is cut directly on dismantling into suitable pieces for transport to final disposal. Open pipe ends are sealed with heavy-duty plastic caps in order to

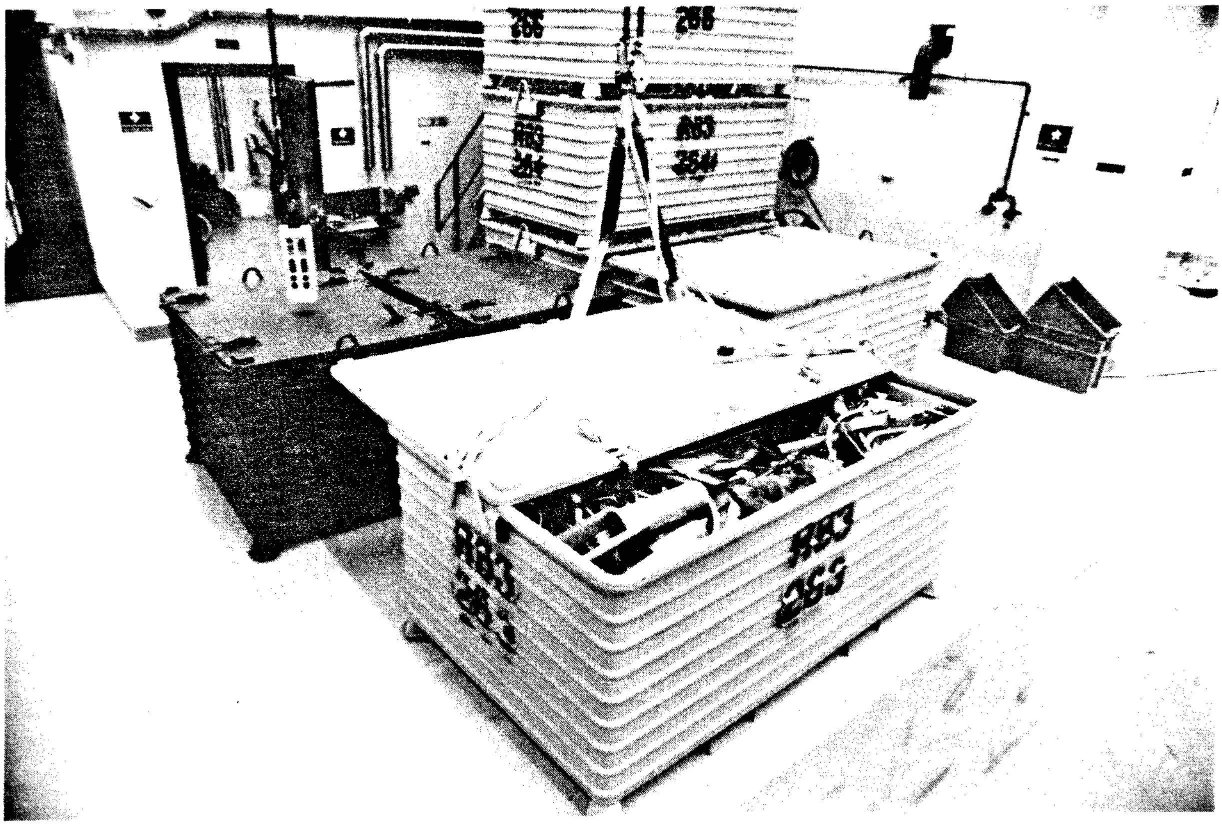


Figure 7-2. Boxes containing radioactive scrap.

prevent dispersal of loose activity. Low-level material is placed directly in transport containers, that can be deposited in the SFR. Material that requires radiation shielding is placed in radiation-shielded transport containers. In order to simplify handling in the SFR, they are provided with suitable lifting devices, e g net with lifting slings.

In some cases, the scrap is painted or plastic-coated in order to prevent dispersal of activity.

Concrete and sand are placed directly in suitable transport packages.

Scrap for which declassification or decontamination is judged to be appropriate is taken to the central decontamination workshop. This mainly applies to pipes and tanks from the turbine system. Good experience exists at the Swedish nuclear power plants from mechanical, chemical and electrochemical decontamination /8/. Decontamination can reduce the quantity of material that has to be placed in a final repository. Moreover, the decontaminated scrap has a residual value.

It is roughly estimated that about 500 tonnes of active material per BWR unit can be declassified after decontamination.

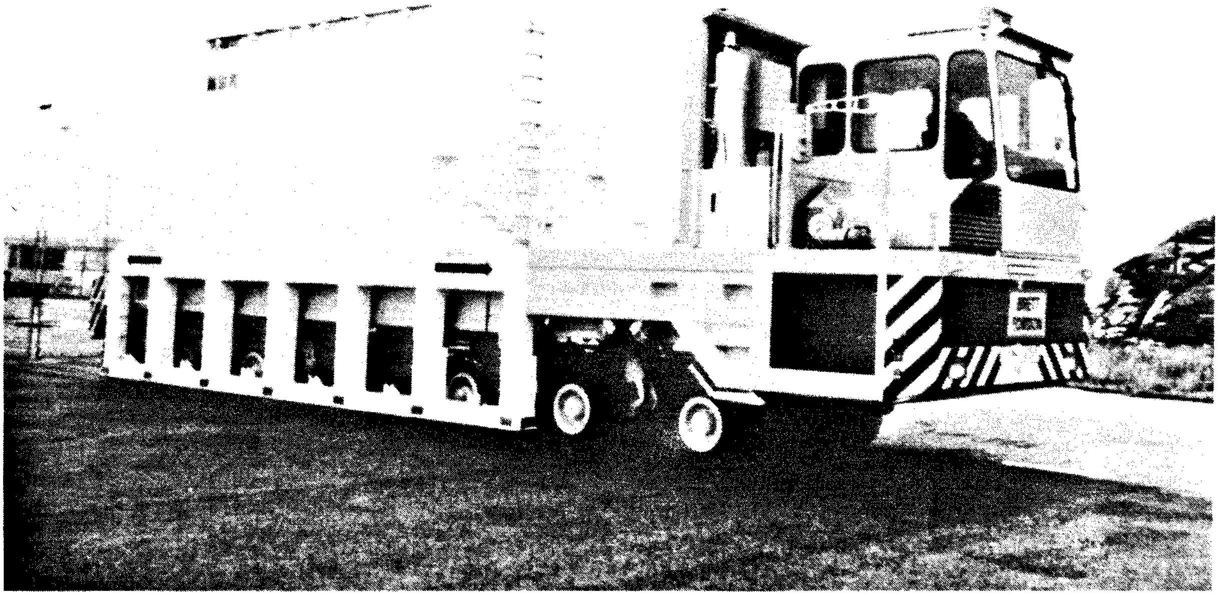


Figure 7-3. Radiation-shielded transport container, ATB, for reactor waste.

7.4 TRANSPORT OF DECOMMISSIONING WASTE

The Swedish transport system for spent fuel and radioactive waste will be used to transport decommissioning waste. The system consists of a ship, terminal vehicles and transport containers. Low-level material in ISO containers can also be transported by truck.

Transports of radioactive waste in Sweden must be approved by SSI. They must meet the requirements of the IAEA's transport recommendations /13/. Different types of transport containers will be used. In the main, the containers that are used for the transport of operating waste from the nuclear power plants can also be utilized for the transport of decommissioning waste, namely:

- Core component cask, which is approved as a type B package (BTB)
- Radiation-shielded ATB container (Figure 7-3)
- Standard ISO containers, whole- or half-height.

Special containers for certain types of decommissioning waste may also be developed.

Large components, such as heat exchangers and tanks, that do not fit in existing transport containers may be transported without any special packaging. These shipments will be of limited scope and adequate safety can be achieved.

In order to determine the need for radiation shielding in connection with shipments, radiation shielding calculations have been carried out /9/. The calculations have been performed for commonly occurring pipe sizes, 125 mm and 300 mm pipe diameter. They show that pipes with a surface activity of up to about 15 kBq/cm^2 can be transported in ordinary ISO standard containers without a radiation shield and still fulfil the requirements of the transport recommendations of IAEA.

On the basis of these calculations and estimated activity content in the plant (see chapter 4), the following rough classification has been made to determine transport and final disposal needs:

- In BWRs, the internals located nearest the core require transport in a core component cask. This applies from the top of the control rod guide tubes up to and including the steam separators (see Figure 4-2).

- In PWRs, some of the reactor vessel material also requires transport in a core component cask.

- Other internals, as well as the reactor vessel,can be transported to the SFR in an ATB container.

- It is assumed that most of the active parts in the primary cooling circuit, as well as from the waste plant, are transported to the SFR. Most material can be transported in ordinary ISO standard containers. However, some parts require radiation-shielded ATB containers.

- A large portion of the turbine systems should be able to be declassified after simple decontamination. For remaining portions, it is estimated that about 500 tonnes, mainly pipes and tanks, will be able to be declassified after e g electrochemical decontamination.

The estimated activity contents in the last two groups are a few hundred GBq per reactor unit after system decontamination. From the viewpoint of activity, this material should therefore be able to be disposed of on the site, for example in the underground portions of the plant.

If no on-site disposal of active waste is assumed, the total transport requirement for the different reactor units is as shown in Table 7-3 and Figure 7-4. If on-site disposal is carried out of parts from the reactor and turbine systems to a full extent, all

Table 7-3: **Shipments of decommissioning waste from the Swedish nuclear power stations broken down according to different types of transport containers.**

Unit	ISO-Cont (30 m^3)	ISO-Cont (15 m^3)	Spec transp	ATB (20 m^3)	BTB
Oskarshamn 1	60	115	29	37	40
Oskarshamn 2	75	168	29	38	40
Oskarshamn 3	143	337	29	45	40
Ringhals 1	100	196	29	38	40
Ringhals 2	50	118	11	63	65
Ringhals 3	50	118	11	63	65
Ringhals 4	50	118	11	63	65
Barsebäck 1	75	168	29	38	40
Barsebäck 2	80	175	29	38	40
Forsmark 1	124	300	29	44	40
Forsmark 2	119	300	29	44	40
Forsmark 3	143	340	29	44	40
Total (incl 10% for unforeseen)	1180	2700	294	610	555

Net storage volume in SFR (m^3)	Low-level	Medium-level
	88 000	12 000

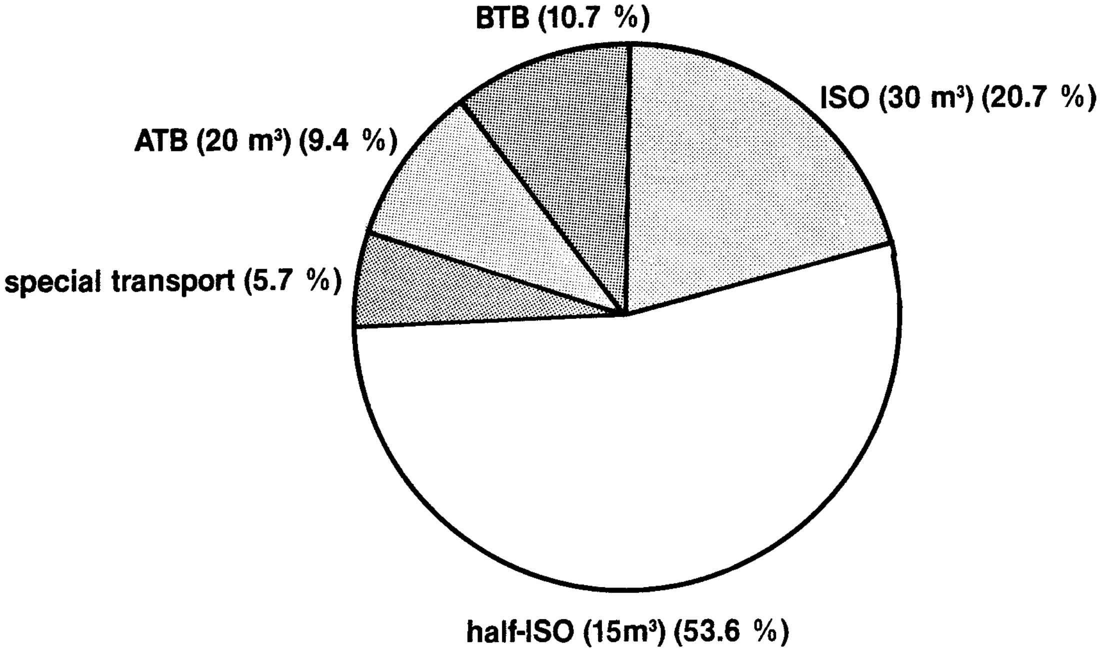


Figure 7-4. Total transport need for decommissioning waste from the Swedish nuclear power stations.

transports of ISO standard containers, and a large portion of the intact components, are eliminated. The total transport requirement is thereby reduced by about 75 000 m^3.

7.5 FINAL DISPOSAL OF DECOMMISSIONING WASTE

Most of the radioactive decommissioning waste is planned to be disposed of in the SFR, Final Repository for Reactor Waste, at the Forsmark nuclear power station. The SFR is built underground in rock at a depth of about 50 metres. It is located below the seabed approximately one kilometre offshore from the Forsmark station.

According to Table 7-3, the total quantity of waste from decommissioning of the Swedish nuclear power plants that is planned to be disposed of in the SFR is about 100 000 m^3, of which 88 000 m^3 is low-level and 12 000 m^3 medium-level waste.

For decommissioning waste, an addition will be built, SFR3, consisting of five rock caverns. See Figure 2-1. Four of the rock caverns are intended for the low-level decommissioning waste that is transported to the SFR in standard ISO containers or as large components without packaging. The containers will not be opened in the SFR, but like the large components will be emplaced as units. Emplacement of the containers in the final repository will be done by a fork-lift truck. See Figure 7-5.

The fifth rock cavern is intended for medium-level waste transported to the SFR in ATB containers. This rock cavern contains an unloading position where the containers are opened and a number of concrete pits in which the waste is placed. If necessary, the waste can be grouted with concrete in the pits.

The reactor vessel internals can also be emplaced in the 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 emplace them in the final repository for long-lived waste after several decades of interim storage in CLAB, is described in /1/.

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

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.

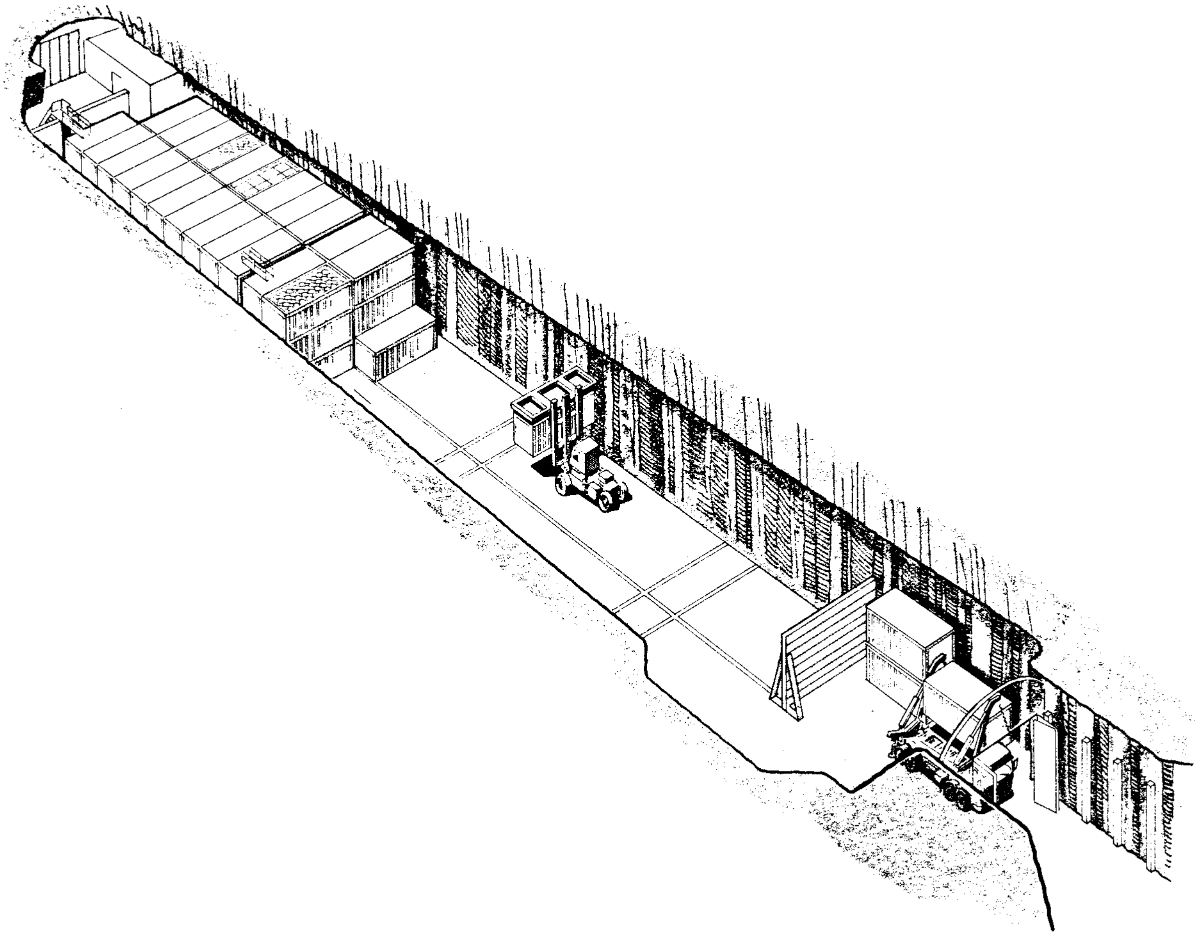


Figure 7-5. Emplacement of low-active waste in containers in SFR.

8 COST ESTIMATE

8.1 PREMISES AND METHODOLOGY

8.1.1 General

The costs have been estimated at the prices level of January 1986. The contingency allowance for unforeseen costs has been estimated from case to case at between 10 and 25%.

8.1.2 Shutdown operation

The costs of measures that have to be adopted from the time the plant is taken out of operation until the actual work of dismantling commences have been estimated for the Oskarshamn station. The point of departure has thereby been the estimated personnel requirement for the three units and for shared facilities, services etc, as well as an estimate of costs for materials and services /8/.

It has been assumed in the calculations that the labour force can be reduced so that the size of the labour force is determined by the need (Figure 8-1).

The costs of shutdown operation are plant-specific and dependent on what other activities are pursued on the site. In order to obtain costs that are also applicable to other stations, the fact that CLAB is located adjacent to the Oskarshamn station has been disregarded. The total costs for shutdown operation are also dependent on the timetable chosen for shutdown of the plants and start of dismantling of individual units.

8.1.3 Dismantlement of active systems

The resource requirement for dismantling of active systems, reactor vessel and internals has been calculated for Ringhals 1 and Ringhals 2 by the planning personnel at the Ringhals station. The calculation is based on experience from refuelling/maintenance /3,4,8/.

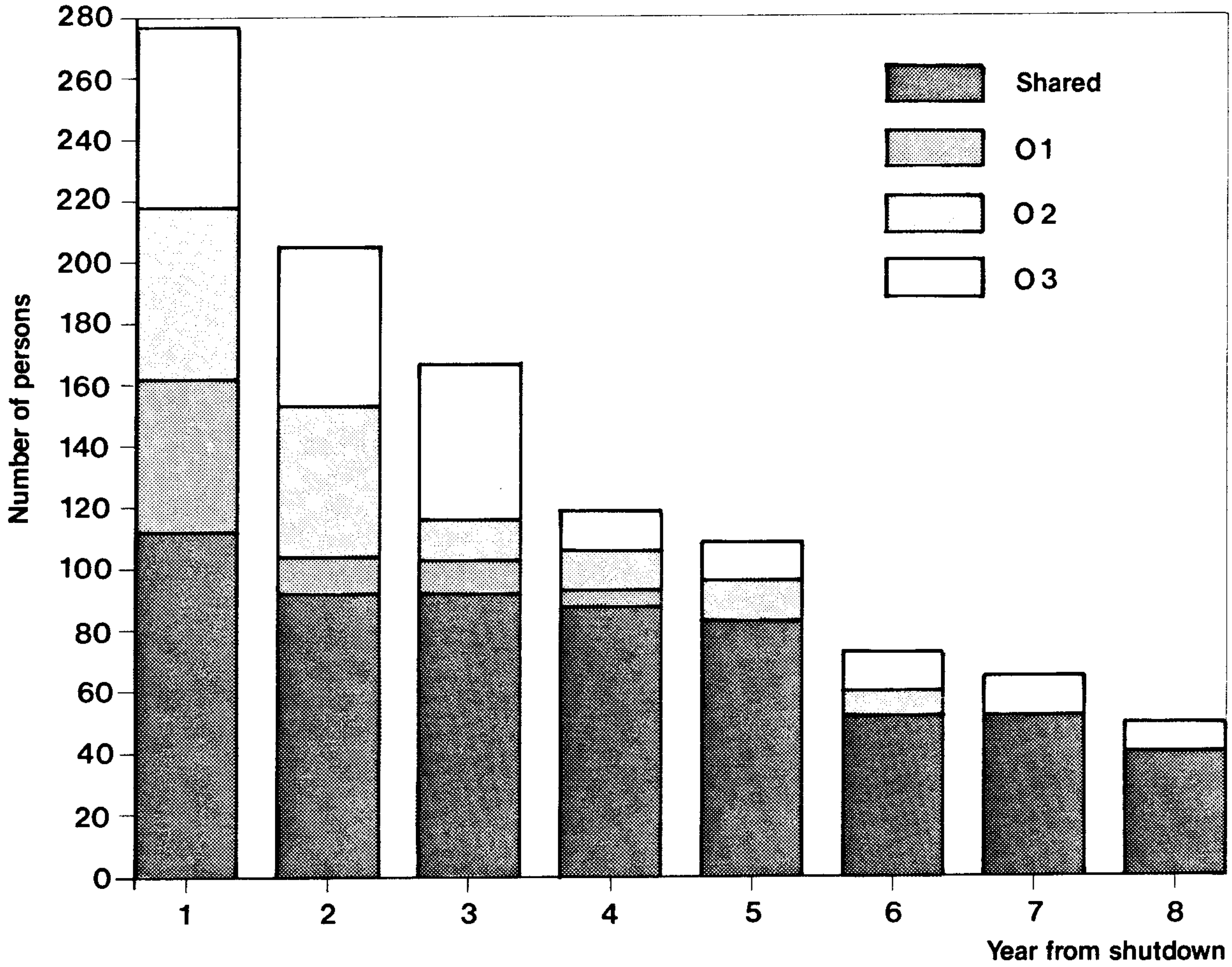


Figure 8-1. Personnel requirements for shutdown operation at the Oskarshamn station.

For active systems, the work has been estimated room by room, assuming normal working methods. For the reactor vessel, the estimate is based on a separate study. In addition to personnel involved directly with dismantling, the estimate also includes personnel for handling and removal of waste, decontamination and radiation protection personnel as well as some operating personnel for service. The resource requirement has been estimated with some conservatism. In calculating the costs, it has been assumed that the work is carried out by a contractor /5/.

8.1.4 Dismantlement of inactive systems

The above cost estimate also includes the cost of dismantling inactive systems. In some cases, the value of scrap material, for example cables, is so high that no extra dismantling cost has been taken up.

8.1.5 Building demolition

The costs of demolishing the building sections has similarly been calculated assuming that the work is contracted out. The cost data is based on the experience of contractors contacted and questioned and is expressed as unit prices. These prices include not only labour costs, but also costs for rental of equipment and machines and removal of demolition material (inactive) /7/.

8.2 COST ITEMIZATION - REFERENCE PLANTS

8.2.1 Shutdown operation

As mentioned above, the cost of shutdown operation is highly dependent on the on-site organization and the decommissioning timetable. A calculation has been carried out for the Oskarshamn station assuming that all reactors are shut down simultaneously, but that dismantling of the units is commenced at two-year intervals. (See Figure 2-2.) The total cost of shutdown operation according to this calculation is MSEK 190 (including 10% contingency allowance).

If it is instead assumed that the units are shut down successively over a five-year period, in accordance with Figure 2-3, the cost is MSEK 56 for the Oskarshamn station.

The total cost of shutdown operation for all reactors in Sweden is MSEK 795 assuming the timetable in Figure 2-2 and MSEK 225 assuming Figure 2-3.

8.2.2 Dismantling

The estimated costs of dismantling Ringhals 1 and Ringhals 2 are itemized in Table 8-1. The costs include a contingency allowance of 20% for system dismantlement and 25% for building demolition.

8.3 COSTS FOR OTHER SWEDISH NUCLEAR POWER PLANTS

8.3.1 Shutdown operation

The cost estimates for the Oskarshamn station have been adjusted so that they can also be applied to other plants /8/. The results are shown in Table 8-2.

Table 8-1: **Estimated costs for dismantling of Ringhals 1 and Ringhals 2, including contingency allowance (MSEK).**

	Ringhals 1	**Ringhals 2**
Dismantling of reactor vessel and internals	45	45
Dismantling of systems	277	185
Demolition of active building components	10	10
Demolition of inactive building components	90	100
Project management	43	43
Service operation	59	59
Insurances, taxes and fees	10	10
Waste containers	7	7
TOTAL	**541**	**456**

8.3.2 Dismantling costs

In assessing the dismantling costs for other units, a proportional adjustment has been made based on material quantities in buildings and system /5,7/. A separate calculation of dismantlement of the reactor vessel has also been carried out for reactors with internal pump. The results are presented in Table 8-2.

8.3.3 Transport and final disposal

The costs of transport and disposal have not been calculated in this study. These costs are reported separately /1/. The total transport costs for decommissioning waste are estimated to be about MSEK 200 and disposal costs about MSEK 400.

Table 8-2: Itemization of decommissioning costs for the Swedish nuclear power plants (MSEK).

	01	02	03	B1	B2	R1	R2	R3	R4	F1	F2	F3
Project management	43	43	43	43	43	43	43	43	43	43	43	43
Dismantling of reactor vessel and internals	45	45	67	45	45	45	45	45	45	67	67	67
Dismantling of systems	186	222	402	222	238	277	185	185	185	363	351	402
Demolition of buildings	70	90	160	86	100	100	110	110	110	125	123	170
Service operation	50	53	56	48	48	59	59	59	59	52	52	56
Waste containers	4	5	10	5	6	7	4	4	4	9	9	10
Insurances etc	10	10	10	10	10	10	10	10	10	10	10	10
Total decommissioning	**410**	**470**	**750**	**460**	**490**	**540**	**460**	**460**	**460**	**670**	**660**	**760**
Shutdown operation	**190**			**110**		**310**				**190**		

8.4 RESIDUAL VALUE IN THE REACTOR PLANT

Reactor plants contain considerable quantities of material and equipment that can be sold when the plants are decommissioned and dismantled. These include spare parts, piping materials, standard machine components etc in stores as well as workshop equipment, lifting equipment and electrical equipment (for example diesels) that have been used but are still in usable condition. A conservative estimate of the residual value of material at the Oskarshamn station is about MSEK 230 /8/, making the total for all nuclear power plants about MSEK 900.

The land as well as the infrastructure that has been built up on the site also has a large value for other industrial enterprises. This value has not been estimated here.

9 DISCUSSION CONCERNING POSSIBLE CHANGES

9.1 DEFERRED DISMANTLING

The effects of postponing the actual dismantling work were discussed in chapter 2. One of the main reasons for postponing dismantling is that the activity levels decline, which can simplify the work of decommissioning and reduce the dose burden on the decommissioning personnel. As an example, decommissioning after a shutdown period of about 40 years is considered here.

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. Control rods are also removed.

As long as fuel remains in the unit's fuel pools, it is assumed that the plant will be manned on a 24-hour basis.

Decontamination and cleaning

Most of the radioactive substances 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 for a system decontamination in this scenario.

In order to prevent dispersal of activity during the long surveillance period, shutdown is followed by thorough cleaning of all rooms as well as cleanup of pools, tanks and pump sumps. The reactor vessel internals are placed in the reactor vessel and the head is bolted on. Pool lining is treated 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 reactor vessel, which is sealed, and on inner surfaces in various system parts.

Surveillance period

A review has shown that a nuclear power plant can be sealed in such a reliable manner that continuous surveillance of the site is not necessary /6/.

A satisfactory surveillance of the plant can be obtained by means of automatic alarms as well as recurrent inspections at regular intervals. The alarm is transmitted via the Telecommunications Administration's alarm equipment to the County Alarm Centre. Examples of alarms are

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

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

Reactivation of the work site

In this scenario, it is assumed that all activities at the power station are suspended during the waiting period. The service premises of the plant in the form of workshops, stores, offices, dining rooms etc are not maintained and will not be able to be used in connection with the dismantling work without extensive refurbishing. After 40 years it will probably be necessary to build new facilities.

Before the dismantling work can start, the worksite must therefore be put in order with offices, workshops, stores, electricity, water, sewerage, restaurant, accommodations etc.

System requirements during decommissioning

Inside the units, systems required for the dismantling work must similarly be rendered operable, for example systems for water supply, drainage, ventilation, power supply and compressed air supply.

New overhead cranes, which are required for the dismantling work, are installed in the turbine hall, reactor hall etc.

Dismantling technology

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

Owing to the lower dose rate levels within the plant, the need for remote-controlled equipment will decrease. Remote control is still required for the reactor vessel and its internals, however.

The risk of airborne activity and contamination of premises and personnel in connection with segmentation of active systems and apparatus will also exist after 40 years. Routines for work with active process equipment must therefore be followed. The necessary protective equipment must be worn.

The waste quantities generated by deferred dismantling should be smaller, owing to the decay of radioactivity that has taken place. However, we have not taken credit for this reduction of the waste quantities in this alternative.

Costs

An estimate of the costs for deferred dismantling is naturally associated with great uncertainties. Only a rough estimate is therefore given here.

The costs of preparing the plant for an extended waiting period can be assumed to be roughly the same as the costs of preparing it for immediate dismantling.

The costs during the waiting period will depend greatly on the demands on surveillance. For the level of surveillance described above, the direct costs will be about 0.5 MSEK/year and reactor station. To this must be added fees to authorities, taxes and insurances, which cannot be estimated today.

If continuous surveillance, dehumidification of the plant etc are required, the annual costs increase to about 2-3 MSEK/year and reactor station.

Before dismantling commences, costs are incurred for reactivation of offices, changing rooms, service installations and systems required for dismantling, as well as for training of personnel. This is estimated to cost about MSEK 70 per reactor station plus about MSEK 25 per reactor unit /5/.

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

9.2 TRANSPORT AND DISPOSAL OF INTACT REACTOR VESSEL

As a main alternative, it has been assumed in this report that the reactor vessel is segmented before it is taken away. However, segmentation of the reactor vessel is very labourconsuming and expensive. The possibility of final disposal of an intact reactor vessel has therefore been explored.

When the reactor vessel was installed, the entire vessel was lifted into the reactor building, so the actual handling of the heavy vessel - 300-500 tonnes - does not constitute any obstacle. At Oskarshamn 1 and Ringhals 1 and in the PWR units, the reactor vessel was lifted in via an installation opening, which was later sealed. For these units, the opening must therefore be opened up again before the vessel can be lifted out. In other units, there are sufficiently large permanent lifting openings for lifting the reactor vessel in and out.

During the operating period, the reactor vessel has become contaminated and certain parts close to the reactor core have been the activated by neutron irradiation. Table 9-2 shows dose rates expected outside the reactor vessel (at core height) after 40 years of operation followed by shutdown for 5 or 40 years /14/. The difference in surface dose rate between the vessel in Oskarshamn 2 and Forsmark 3 - a factor of 10 - is mainly due to the difference in the width of the downcomer. The dose level from a PWR vessel is roughly the same as for Oskarshamn 2.

Table 9-2: Dose rate outside a reactor vessel after 40 years of operation and 5/40 years of decay. The fuel is gone. /14/

		Decay period	**Dose rate (mSv/h)** **Surface**	**1 m**	**10 m**
F3	Empty vessel	5 years	1	0.6	<0.1
	Vessel+internals	5 years	80	60	10
	Empty vessel	40 years	0.01		
	Vessel+internals	40 years	0.8	0.6	0.1
O2	Empty vessel	5 years	10	5	0.3
	Vessel+internals	5 years	200	160	20
	Empty vessel	40 years	0.1		
	Vessel+internals	40 years	2	1.6	0.2
R2	Empty vessel	5 years	10	5	0.3
	Vessel+internals	5 years	20		

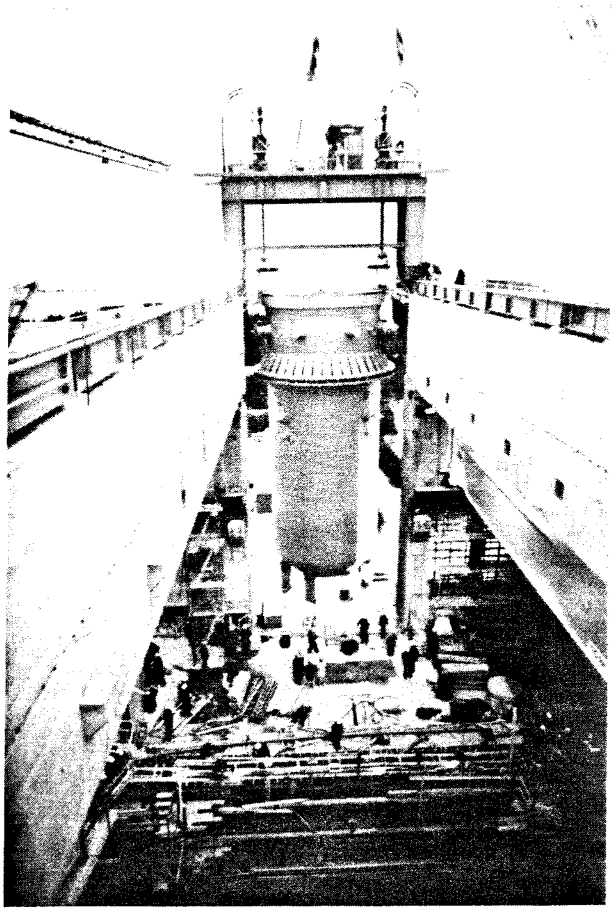


Figure 9-1. Lifting-in of the reactor vessel at Forsmark 3.

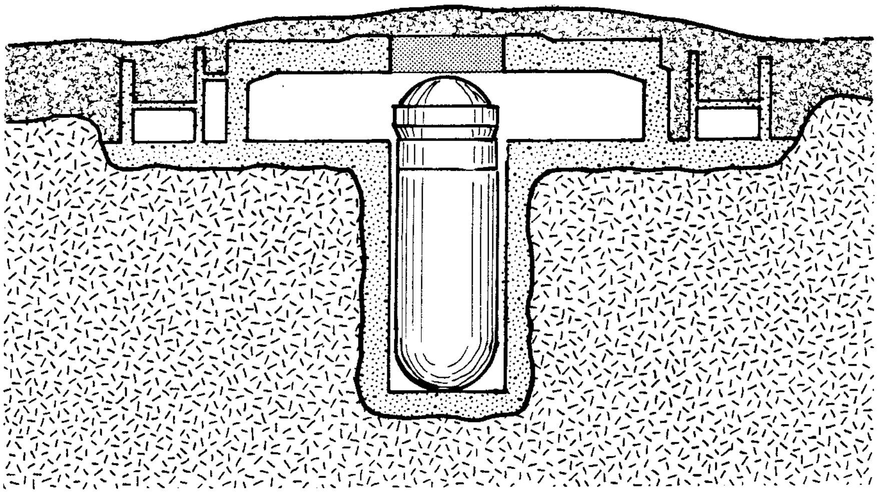


Figure 9-2. Reactor vessel buried under reactor site.

In the case of immediate dismantling, it should be possible to lift out and transport an intact reactor vessel, if suitable radiation protection measures are adopted. However, the vessel internals must be removed first.

After a waiting period of 40 years or more, the reactor internals can also be left in the vessel.

The reactor vessels can be placed in a common final repository of the same type as the SFR, but where the entrance tunnels are large enough to accommodate the vessel. Alternatively, the vessel could be disposed of on the site of each nuclear power plant. However, long-term safety in connection with such a procedure and the restrictions that would apply to the use of the site have not been studied.

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Department of water in environment and
society, Linköping university, Linköping
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Biosphere data base revision
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Site investigation—equipment for geological, geophysical, hydrogeological and hydrochemical charaterization
Karl-Erik Almén, SKB, Stockholm
Olle Andersson, IPA-Konsult AB, Oskarshamn
Bengt Fridh, Bengt-Erik Johansson,
Mikael Sehlstedt, Swedish Geological Co, Malå
Kenth Hansson, Olle Olsson, Swedish Geological Co, Uppsala
Göran Nilsson, Swedish Geological Co, Luleå
Peter Wikberg, Royal Institute of Technology,
Stockholm

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Analysis of groundwater from deep boreholes in Klipperås
S Laurent, Swedish Enviromental Research
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