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Cost Calculations for Decommissioning and Dismantling of Nuclear Research Facilities Phase 1

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Abstract

Today, it is recommended that planning of decommission should form an integral part of the activities over the life cycle of a nuclear facility. However, no actual international guideline on cost calculations exists at present.
Intuitively, it might be tempting to regard costs for decommissioning of a nuclear facility as similar to those of any other plant. However, the presence of radionuclide contamination may imply that the cost is one or more orders of magnitude higher as compared to a corresponding inactive situation, the actual ratio being highly dependent on the level of contamination as well as design features and use of the facility in question. Moreover, the variations in such prerequisites are much larger than for nuclear power plants.
This implies that cost calculations cannot be performed with any accuracy or credibility without a relatively detailed consideration of the radiological and other prerequisites. Application of inadequate methodologies – especially at early stages – has often lead to large underestimations.
The goals of the project and the achievements described in the report are as follows:

1	Advice on good practice with regard to
1a	Strategy and planning
1b	Methodology selection
1c	Radiological surveying
1d	Uncertainty analysis
2	Techniques for assessment of costs
2a	Cost structuring
2b	Cost estimation methodologies
3	Compilation of data for plants, state of planning, organisations, e t c.
3a	General descriptions of relevant features of the nuclear research facilities
3b	General plant specific data
3c	Example of the decommissioning of the R1 research reactor in Sweden
3d	Example of the decommissioning of the DR1 research reactor in Denmark

In addition, but not described in the present report, is the establishment of a Nordic network in the area including an internet based expert system.
It should be noted that the project is planned to exist for at least three years and that the present report is an interim one covering the work for approximately the first 16 months.

Key words

decommissioning, radiological survey, technical planning, methodology selection, nuclear research facility, cost calculation, early stage, cost estimation, Nordic, dismantling

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COST CALCULATIONS FOR DECOMMISSIONING AND DISMANTLING OF NUCLEAR RESEARCH FACILITIES, PHASE 1

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Perspektiv

Bakgrund

Detta uppdrag har finansierats gemensamt av Dansk Dekommissionering, Institutt for energiteknikk (IFE, Norge), Nordisk Kärnsäkerhetsforskning, Statens Kärnkraftinspektion (SKI, Sverige), Tekniska Forskningscentralen (VTT, Finland). Projektet är initierat av SKI som också bidrar med perspektivet nedan.

SKI presenterar den 1 september varje år ett förslag till regeringen om avgifter för det kommande året inom ramen för den s.k. Studsvikslagen . En viktig del i detta arbete är att avgöra om det finns en jämvikt mellan vad som är fonderat i kärnavfallsfonden och de framtida åtagandena för dekontaminering och nedläggning av vissa kärnteknisk verksamhet som bedrivits vid Studsvik.

I arbetat med att analysera och värdera fondens utveckling är de framtida kostnaderna den väsentligaste variabeln. För de flesta objekt rör det sig om belopp på 10-tals miljoner kronor eller mer och dessa belopp kräver att detaljerade kostnadsberäkningar skapas, analyseras och evalueras. I föreliggande projekt görs ett försökt till att utveckla mera ändamålsenliga metoder för att verifiera att en korrekt skattning ligger till grund för beräkning av de totala framtida kostnaderna, och den därpå följande fonderingen, av äldre kärntekniska anläggningar.

Syfte

Detta forskningsprojekt har haft till syfte att utveckla en metod för en värdeneutral och tydlig beräkning av kostnaderna för dekontaminering och nedläggning av äldre kärntekniska anläggningar kan göras i ett tidigt skede. Uttrycket tidigt skede refererar till att beräkningar skall göras idag för kostnader som infaller i en avlägsen framtid. Det kan till och med vara så att kalkylen omfattar en tidsrymd på upp emot ett halvt sekel.

Då flera av de nordiska länderna har, eller har haft, forskningsreaktorer som endera har rivits eller kommer att rivas så finns det fördelar till ett aktivt kunskapsutbyte från ett samnordiskt perspektiv. Att utveckla en modell för beräkning av de framtida kostnaderna i syfte att skapa tillförlitligare och robustare uppskattningar av kostnaderna i ett tidigt skede, i vissa fall innan avvecklings- och rivningsprocessen har inletts, är en angelägen uppgift.

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Resultat av studien

I denna rapport ges explorativa beskrivningar av vunna erfarenheter från tidigare nordiska projekt. Genom att beskriva hur dekontaminering och avveckling av äldre kärntekniska anläggningar tidigare har gjorts kan ett underlag skapas för fortsatt analys och diskussion kring hur kostnadsberäkningar på bästa sätt kan utvecklas..

Effekter av SKI finansierad forskningsverksamhet

Genom att utveckla metoder för att skapa en god praxis för kalkylering av kostnader i ett tidigt skede i planeringsprocessen för avveckling och rivning av kärntekniska anläggningar är det möjligt att tillse att nutida generationers användning av nukleärt alstrad elenergi verkligen bär sina kostnader. Detta leder i sin tur till att framtida generationer inte behöver ta något konsumtionsutrymme i anspråk för dessa frågor, utan kan istället ägna sig att lösa de specifika frågor som de framtida generationerna kommer att möta.

SKI kommer att använda resultatet från denna studie i den årliga granskning som göras av den kostnadsberäkning som AB SVAFO lämnar in i enlighet med ”Studsvikslagen”. Denna kostnadsberäkning ingår som en central del i det förslag till avgifter som SKI:s styrelse lämnar till regeringen. Denna forskningsrapport kommer att ingå i det granskningsmaterial som SKI analyserar i samband med framställningen av ett förslaget till avgifter för år 2008..

Behov av fortsatt forskning

De empiriska beskrivningarna som presenteras i rapporten kan ligga till grund för en konstruktion av en modell för beräkning av framtida kostnader i de nordiska länderna. Genom att sedan validera de beräkningsresultat som modellen genererat kan en utvärdering göras av modellens reliabilitet och validitet. En sådan jämförande analytisk utvärdering kan endast göras om flera länder deltar i forskningsprocessen. I ett andra steg bör en gemensam modell tas fram.

Projektinformation

På SKI har Staffan Lindskog varit ansvarig för att samordna projektet. Forskningsarbetet har koordinerats av Rolf Sjöblom på TEKEDO AB.

SKI referens: 2005/584/200509079

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Summary

Today, it is recommended that planning of decommission should form an integral part of the activities over the life cycle of a nuclear facility (planning, building and operation).

It was only in the nineteen seventies that the waste issue really surfaced, and together with it to some extent also decommissioning. Actually, the IAEA guidelines on decommissioning [3-7] have been issued as recently as over the last ten years, and international advice on finance of decommissioning is even younger [1,8]. No actual international guideline on cost calculations exists at present.

Intuitively, it might be tempting to regard costs for decommissioning of a nuclear facility as similar to those of any other plant. However, the presence of radionuclide contamination may imply that the cost is one or more orders of magnitude higher as compared to a corresponding inactive situation, the actual ratio being highly dependent on the level of contamination and later use of the facility in question.

This implies that cost calculations cannot be performed with any accuracy or credibility without a relatively detailed consideration of the radiological prerequisites. Consequently, any cost estimates based mainly on the particulars of the building structures and installations are likely to be gross underestimations.

The present study has come about on initiative by the Swedish Nuclear Power Inspectorate (SKI) and is based on a common need in Denmark, Finland, Norway and Sweden.

It was found in various studies carried out on commission by SKI (see e g [33-37] where [36] is included in the present report in the form of Appendix F) that the intended functioning of a system for finance requires a high precision even in the early stages of cost calculations, and that this can be achieved only if the planning for decommissioning is relatively ambitious. The following conclusions were made:

- IAEA and OECD/NEA documents provide invaluable advice for pertinent approaches.
- Adequate radiological surveying is needed before precise cost calculations can be made.
- The same can be said about technical planning including selection of techniques to be used.
- It is proposed that separate analyses be made regarding the probabilities for conceivable features and events which could lead to significantly higher costs than expected.
- It is expected that the need for precise cost estimates will dictate the pace of the radiological surveying and technical planning, at least in the early stages.

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- It is important that the validity structure for early cost estimates with regard to type of facility be fully appreciated. E g, the precision is usually less for research facilities.
- The summation method is treacherous and leads to systematical underestimations in early stages unless compensation is made for the fact that not all items are included.
- Comparison between different facilities can be made when there is access to information from plants at different stages of planning and when accommodation can be made with regard to differences in features.
- A simple approach is presented for “calibration” of a cost estimate against one or more completed projects.
- Information exchange and co-operations between different plant owners is highly desirable.

The present report represents a realisation of the above thoughts in a Nordic context. It is an interim report covering the work for the year 2005. Consequently, the coverage for the countries is yet incomplete and also not fully organised. Furthermore, additional material will be compiled on cost estimation strategies and methodologies. There will also be a discussion and conclusion section based on a compilation of the various findings in the work.

At present, the content of the report may be briefly summarised as follows.

A relatively ambitious background is provided since it is essential that the design and operation prerequisites and particulars are reasonably well understood when – at a much later stage – decommissioning is to be carried out. The background also comprises an overview of the various nuclear research facilities in the four participating countries: Denmark, Finland, Norway and Sweden.

The purpose of the work has been to identify, compile and exchange information on facilities and on methodologies for cost calculation with the aim of achieving an 80 % level of confidence.

The scope has been as follows:

- to establish a Nordic network
- to compile dedicated guidance documents on radiological surveying, technical planning and financial risk identification and assessment
- to compile and describe techniques for precise cost calculations at early stages
- to compile plant and other relevant data

A separate section is devoted in the report to good practice for the specific purpose of early but precise cost calculations for research facilities.

A separate section is also devoted to techniques for assessment of cost. Further material on this is planned to evolve during the work for the years 2006 and 2007.

Examples are provided for each of the countries of relevant projects. So far, the decommissioning on the reactors DR1 in Denmark and R1 in Sweden has been described. During 2006, additions will be made regarding the reprocessing pilot plant in Norway and the TRIGA reactor in Finland.

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1 Background

1.1 Introduction

Today, it is recommended [1-7] that planning of decommission should form an integral part of the activities over the life cycle of a nuclear facility (planning, building and operation). It is further recommended that funding of decommission should be a part of the overall planning and funding of the facility.

This recommendation did not exist in the nineteen forties when man-made radionuclides were generated in significant quantities for the first time in conjunction with utilization of chain reactions and associated neutron activation in nuclear reactors and nuclear explosives. It was only in the nineteen seventies that the waste issue really surfaced, and together with it to some extent also decommissioning. Actually, the IAEA guidelines on decommissioning [3-7] have been issued as recently as over the last ten years, and international advice on finance of decommissioning is even younger [1,8]. No actual international guideline on cost calculations exists at present.

This situation contrasts to that of radiation protection, where the need for it was actually realized from the very beginning of nuclear technology.[9-11] The x-rays had been discovered half a century earlier and had become utilized on a grand scale virtually overnight. Application of x-rays in medicine improved diagnoses and thereby also treatment immensely, but lack of appropriate protection also led to many cases of health detriment. Consequently, a lot of experience and knowledge was available in the nineteen forties as well as methodology for radiation protection.[9-11]

Thus, focus was kept on radiation protection during operation of the facilities, and little or no precautionary measures were taken to facilitate the waste management and decommissioning. Eventually, and in the course of events, it was realized that the undertakings and costs for waste management and decommissioning would be substantial.

Intuitively, it might be tempting to regard costs for decommissioning of a nuclear facility as similar to those of any other plant. However, the presence of radionuclide contamination may imply that the cost is one or more orders of magnitude higher as compared to a corresponding inactive situation, the actual ratio being highly dependent on the level of contamination and later use of the facility in question.

This implies that cost calculations cannot be performed with any accuracy or credibility without a relatively detailed consideration of the radiological prerequisites. Consequently, any cost estimates based mainly on the particulars of the building structures and installations are likely to be gross underestimations.

There are a number of reasons why cost estimates for decommissioning are considerably more difficult to make for old nuclear research facilities as compared to modern nuclear power plants:

- Plans for decommissioning do not exist

- They were not designed with regard to decommissioning
- They are small (which means that investigations can become expensive in relation to the total cost)
- They are very different in character
- The types of contamination are different, e g with regard to radionuclides and activity levels (which relates to detectability / penetration of the radiation), spatial distribution, surface or bulk, wet/dry, soluble/non-soluble e t c
- Different methodologies for decontamination and dismantling are appropriate depending on the circumstances
- The buildings were constructed and operated at a time when the regulations were considerably less strict than today
- Incomplete documentation of the operation history, accidents and incidents causing contamination
- Institutional memory has been lost and people who know what took place may no longer be alive
- The efficient and economical application of methodologies developed for large scale applications at nuclear power plants

Accordingly, general figures on the international nuclear legacy are difficult to find and do not exist with any precision. It was presented recently[12] that the environmental management cleanup cost for Department of Energy in the US amounted to 6,2 G$ for the fiscal year 2004. It was said in the presentation that it might be expected that this effort will be continued for a few decades.

It seems plausible that the international nuclear legacy associated with nuclear research, development and defence may exceed 1 T$. This figure is comparable to that of the gross national product of the Nordic countries combined (0,91 T$ in the year 2003).

However, there exists valuable information from a large number of decommissioning projects that have been completed. Many of those have been successful in technical as well as financial terms. A general feature of those projects is that they have included appropriate planning and consideration of the specifics of the facility in question. This experience forms the basis for the present day recommendations mentioned above on planning for decommissioning throughout the various phases of the life cycle of a facility.

Several countries have requirements on collection of funds during the operation of a facility. In such cases the overall planning might be prompted and promoted by the financial requirements.

1.2 General international development

The early developments of nuclear technology in the Nordic countries were strongly influenced by the preceding international events.

Nuclear fission was discovered just before the start of the Second World War. It was soon realized the effect might be utilized for very powerful explosives. This led to the initiation of the Manhattan project in the United states and the subsequent bombing of Hiroshima (a bomb based on U-235) and Nagasaki (a bomb based on Pu-239).

The Manhattan project involved enormous resources and had a very tight time schedule. When the decision was taken on the project it was not known what, if any, route might lead to a functioning bomb. Therefore, alternative methods were being developed in parallel.

The abundance of U-235 in natural uranium is around 0,7 %. This would have to be increased to above around 80 % to be feasible in a bomb (actually much higher enrichment of uranium-235 was used).[1]

The plutonium-239 was obtained from reprocessing of natural uranium fuel used in a graphite moderated nuclear reactor. It is essential that the fuel has a low burn-up so that the transuranium isotopes formed consist almost entirely of plutonium-239.

The United States had no access to heavy water in the Manhattan Project, so only graphite was used as a moderator in the reactor.[2]

The nuclear technology underwent continued rapid growth during the post-war years. The cold war meant further development of nuclear weapons technology. The access to enriched uranium made way for the development of very compact light water reactors for use in submarines.

Various civilian uses were investigated, including ship vessel propulsion, but it was nuclear reactors for electricity generation that became the dominating application. Three

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[1] Two methods were applied for the enrichment: mass spectrometry and gas diffusion. In mass spectrometry ionic species of uranium are accelerated in vacuum and subjected to a strong magnetic field. The deviation of the trajectories in this field is slightly different for the two isotopes, and they can be collected at different target areas. The diffusion process is based on the fact that the diffusion is slightly different for gaseous species of uranium. (Uranium hexafluoride is used for this purpose, and fluorine has the advantage of having only one isotope).

[2] A moderator slows down the neutrons formed in the fission process. Low energy neutrons (thermal neutrons) are much more efficient for fission processes than fast neutrons and are essential for the neutron economy.

In a nuclear reactor, moderation competes with absorption. Carbon atoms have a mass that is considerably higher then that of a neutron and graphite is therefore a less efficient moderator than heavy water or light water. Light water is the most efficient moderator, but absorbs neutrons to some extent and can therefore only be used in conjunction with fuel that is somewhat enriched in uranium-235. Since large volumes of graphite are required in a graphite moderated reactor, it is essential that the graphite is very pure so that the absorption of neutrons is sufficiently small.

types of moderators are used in civilian reactors today: light water, heavy water and graphite. Most reactors use light water, but graphite moderated reactors were designed and used in the former USSR, and heavy water reactors are used in Canada. The high efficiency of the moderation of the light water enables the corresponding reactors to use a pressurized vessel for the entire reactor. For the other moderators, pipe designs are common. The pipes surround the fuel but not the main part of the moderators, and thus the fluid in the pipe can be pressurized and also take up the very most of the energy released.

The pressurized light water reactor used widely today for electricity generation has a design that is similar to that of the early submarines. Alternative reactor design principles were studied intensely internationally in the early days of nuclear technology, but have with few exceptions[3] received little attention during the last several decades. However, an number of studies have dealt with the thorium cycle[see e g 13] for several reasons including less long-lived transuranics and non-proliferation. Heavy water moderation constitutes a significant part in these studies.

There are a number of other reactor types that have been studied, e g Magnox and AGR reactors (gas cooled reactors) as well as breeder type of reactors. They are not dealt with here because they have not had any influence of any magnitude on the nuclear development in the Nordic countries.

Waste management (together with reactor safety) has been a dominating issue since the nineteen seventies. It was realized that attention had to be paid also to protection of the environment ant to the long-term safe disposal of nuclear waste.

Perhaps somewhat later came the full realization of the significance of the nuclear legacy in terms of decommissioning and dismantling.

1.3 Nuclear technology development in the Nordic countries

It was realized also in Germany during the war that it might be possible to utilize controlled nuclear chain reactions as well as nuclear explosives.

Essential in this regard is the availability of uranium and a moderator. It has already been said that heavy water is more efficient than graphite, and thus a more compact reactor might be designed if heavy water is available.

Through the occupation of Norway, Germany had access to the heavy water generated as a byproduct at the Norsk Hydro A/S water electrolysis plant at Rjukan.[4] The plant was, however sabotaged through a combined action of the Norwegian resistance movement and allied forces. Nonetheless, a shipment of 614 litres went underway to Germany, but was sabotaged and sunk deep in a the lake Tinnsjø. It has been

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[3] E g nuclear reactors for space ships.

[4] There is a strong isotope effect in electrolysis. Enrichment of heavy hydrogen can therefore be achieved in an electrolysis plant for water by applying appropriate “logistics” for the water used.

assessed[10] that this quantity might have been just what was needed in order for the Germany to succeed in her experiments on a nuclear reactor.

After the war it was realized that the heavy water could provide an important basis for a domestic Norwegian Nuclear programme[9-11,14]. The first Nordic research reactor was commissioned at Kjeller in Norway already in July 1951, preceded only by facilities in Canada and the four great powers United States, The Soviet Union, Great Britain and France.[14] It was clearly stated that "*the project should be open and without any secrecy arrangements*" and that the Institute for Atomic Energy, IFA, should aim at establishing co-operation with other countries having similar approaches, e g Sweden and France. (In 1980 the Institute for Atomic Energy, IFA, changed its name to Institute for Energy Technology, IFE.)

The five Nordic countries became active participants when new international organisations were planned in the nineteen fifties and it was in Norway that the first international nuclear conference was organised already in 1953.[15] This was two years before the conference on the Peaceful Uses of Atomic Energy (*The Geneva conferences*) held by the United Nations.

At the time of the commissioning of the JEEP 1 reactor (in Norway) in 1951, the great powers had control over most of the uranium available. Nonetheless, IFE managed to purchase uranium from the Netherlands. This contract also included co-operation, which continued in various forms for a long time. The moderator and medium for heat transfer used in the core of the JEEP 1 reactor was heavy water, which was obtained domestically. The core was surrounded by a reflector made of graphite that was obtained from France.

The first Swedish nuclear research reactor was located at the Royal Institute of Technology in Stockholm and was commissioned in 1954 (see Appendix E and Reference [16]). The moderator consisted of heavy water and the natural uranium for the fuel (three tonnes) was "borrowed" from France.[11,15] Sweden has huge natural resources of uranium. At the time, uranium-bearing shale was mined for oil production. An auxiliary mineral in this shale is "kolm" the ash of which contains percentage quantities of uranium. Such uranium was beneficiated from 1953 at a capacity of five tonnes per year.

Self-sufficiency was important and Denmark (Grönland), Norway (Einerkilen) and Sweden (Kvarntorp and Ranstad) had domestic programmes for uranium mining, beneficiation and processing. Iceland had natural resources in terms of hydropower which relates to beneficiation of heavy water.[15]

Denmark acquired two reactors from the United States in 1956, and a larger one from Great Britain in 1957.[15] They all used enriched uranium in the fuel. The small training reactor used uranium dissolved in a liquid homogeneous liquid reactor, and this concept was subsequently studied in Denmark for power generation purposes.

Finland started its nuclear technology in 1956 by a subcritical pile, which used natural uranium as fuel and light water as moderator. Next step was the purchase of a TRIGA reactor from USA and to balance the political situation small amount of enriched fuel for the subcritical pile was bought from the Soviet Union in order to increase the reactivity of the subcritical pile. In both purchases there was a third party, IAEA in the agreements. The TRIGA reactor went critical in 1962 and has been in operation since that time.

Initially, the purpose of the research and development work in the Nordic countries was very broad, and military applications were not excluded until around the late nineteen fifties. Civilian applications included ship vessel propulsion, although no specific reactors were tested for such purposes.

Important prerequisites for the work included independence with regard to the resources required, and to keep options open with regard to e g reprocessing, enrichment and moderator requirements (absorption to moderation ratio, and moderator efficiency).

In Sweden, “the Swedish strategy” (“den svenska linjen”) was established and applied. It consisted of use of heavy water (from Norway) as a moderator and natural uranium, mined and processed domestically. In addition, reprocessing was included, and comprehensive research and development work in this area was carried out at IFA in a Nordic collaboration. The pilot plant for reprocessing (“Uranrensanlegget”) at IFA was commissioned 1962 and decommissioned in 1968.

Further research and development facilities in the Nordic countries include the JEEP 2 (2 MW) and the Halden (25 MW) heavy water reactors in Norway. In Sweden, the R2 (50 MW) light water reactor was commissioned in 1961 and shut down in 2005.

The first reactor for energy generation in the Nordic countries was the Ågesta heavy water reactor (65 MW, 10 MW for electricity generation and 55 MW for district heating) in the southern part of Stockholm. It was commissioned in 1963 and shut down in 1973.

All in all there are a fair number of facilities that have been commissioned and operated at different stages in the overall progress and for various purposes. They are described briefly in Section 1.4.

The early work on nuclear technology development included a lot of co-operation between the various research establishments in the Nordic countries, and further information on this can be found in [15, see also 9-11,14,17]. This situation contrasts to that of power generation in the larger facilities commissioned from 1970 in Sweden and Finland, which mainly concerns these two countries.

Nordic co-operation in the fields of nuclear technology and safety have kept on in new areas of common interests, see [15].

1.4 Present status of major Nordic facilities for nuclear technology development

1.4.1 Denmark

Facilities of interest to consider for the proposed information exchange e t c, cf below, are as follows. (It is not expected that each participant will include all of its facilities listed in the project work).

Risö, Denmark

- DR 1. A 2 kW thermal homogeneous, solution type research reactor which uses 20 % enriched uranium as fuel and light water as moderator.
- DR 2. A tank type, light water moderated and cooled reactor with a power level of 5 MWth. It was finally closed down in 1975 and was later partially decommissioned.
- DR 3. A research reactor built to test materials and new components for power reactors. It uses ≈ 20 % enriched uranium and is moderated and cooled by using heavy water. The power output is 10 MWth.
- Fuel fabrication facility (for the DR 3 reactor)
- Isotope laboratory. Management of irradiated samples.
- Hot cell laboratories. Six concrete cells used for post irradiation investigations. The facility has been partially decommissioned.
- Waste management plant and storage facilities

The reseach reactor DR1 was decommissioned during 2005 and the reactor building and site area have been free released without restrictions by the Danish nuclear authorities. The research reactor DR2 is presently (May 2006) undergoing decommissioning and the site is planned to be free released without restrictions during the first quarter of 2009.

Further information on the Danish programme can be found in Appendices A and B.

1.4.2 Finland

Otaniemi, Espoo, Finland

- FiR 1. A 250 kW TRIGA research reactor, operated since 1962. A special U - ZrH_x - fuel, uranium enrichment 20 %. Light water moderated. The main purpose of the operation of the reactor is BNCT (Boron Neutron Capture Therapy) as well as isotope production.
- Radiochemical laboratory
- Hot cell laboratory with e g testing of irradiated steel samples from nuclear power plants, especially samples from pressure vessels

In particular, an environmental impact assessment work of the decommissioning of the reactor is planned to be carried out next year.

Further information on the TRIGA research reactor can be found in Appendix C.

1.4.3 Norway

The major nuclear facilities in Norway in operation or decommissioned are:

- JEEP I, a 450 kWth research reactor at IFE, Kjeller.
- The NORA zero-effect research reactor at IFE, Kjeller.
- The Uranium Reprocessing Pilot Plant at IFE, Kjeller
- The Halden Boiling Water Reactor (HBWR) a 25 MWth research reactor at IFE, Halden.
- JEEP II, a 2 MWth research reactor at IFE, Kjeller.
- The radioactive waste treatment plant and storage facilities.
- Metallurgical laboratory II for post irradiation investigations of test specimens of fuel and other materials.

Short descriptions of these nuclear facilities are given below. According to the licence for operation of existing facilities, the Norwegian Radiation Protection Authority (NRPA) has required preparation of decommissioning plans for each of these facilities. IFE has thus prepared decommissioning plans according to IAEAs recommendations for "ongoing plans" during the operation of the facilities and to "stage 1: Storage with surveillance" or "stage 2: Restricted site use" as long as this is not in conflict with storage of spent nuclear fuel and long lived intermediate level radioactive waste. Recently the NRPA has asked IFE to take another step forward and extend these decommissioning plans to "green field"

Decommissioned facilities

JEEP I

The Dutch-Norwegian co-operation in the field of atomic energy was established in April 1951. The aim of the co-operation was at the time to complete the heavy water uranium reactor constructed at IFA, Kjeller in Norway. It was decided that a Joint Commission, consisting of three Norwegian members and three Dutch members, should lead further work in atomic energy in the two countries. The establishment at IFA, Kjeller, was included a Dutch-Norwegian organisation called Joint Establishment for Nuclear Energy Research (JENER). [18]

Operation started:	June 1951
Operation terminated:	December 1966
Thermal power from 1951 to 1956:	100 kW
Thermal power from 1956 to 1966:	450 kW
Fuel:	Natural metallic uranium, 2448 kg
Moderator and cooling:	Heavy water
Moderator temperature:	Around 50 °C at 450 kW
Pressure:	Atmospheric pressure

In 1956 the heat exchanger was replaced with a larger one and the capacity of the cooling of the light water system was improved by installation of a cooling tower. The thermal power of the reactor could then be increased to 450 kW. [19]

In April 1960 a leakage in the heavy water circuit was detected, necessitating the replacement of the reactor vessel. The reactor was started up again in October 1960 with a new reactor vessel. [19]

Today the reactor has been emptied of fuel and heavy water. The spent fuel is stored at IFE, Kjeller. The reactor vessel including the biological shielding is still not dismantled. The building containing the reactor is now used for housing a ^{60}Co irradiation facility.

There were several purposes of the JEEP I reactor. Atomic energy was a new and promising energy source in the 1940s and 1950s and reactor operation and reactor physics were two major fields of study.

Before JEEP I was built Norway had to import radioisotopes for medical and industrial use. Long delivery time, high transportation costs and problems with short-lived nuclides made it desirable to start production of radioisotopes in Norway. Research on production of radioisotopes for medical use and reactivation of radioisotopes for industrial use started in 1951-1952. During the period of 1952-1962 the production of radioisotopes increased tenfold and more than 75 % of the production was for medical use. The other Nordic countries showed at an early stage great interest in the Norwegian isotope production and exports of these products increased steadily. In addition to export of radioisotopes to the Scandinavian countries IFA also exported some products to the Netherlands and to a lesser extent to other European countries. [19]

After the start in 1951 it was possible to take up studies of neutron physics first by measurements of reactor characteristics and neutron- and γ-spectrometry. After building neutron diffractometers, fundamental studies of solid-state physics could be conducted. [19]

The NORA reactor

Based on the experiences for operation of the JEEP I reactor it was soon realised that its possibilities for reactor physics studies were limited and that flexibility is of greatest importance in this field. A plan for a "zero-effect" reactor (only a few watts), the NORA reactor, was therefore worked out in the course of 1958.

In January 1960 an agreement was signed between IFA and the International Atomic Energy Agency (IAEA) to put the NORA reactor at IAEA's disposal for a common reactor physics program. The IAEA contribution was to provide a fuel charge for the common operation. NORA also made it possible to continue and extend the work carried out with the ZEBRA-assembly in Stockholm by a joint Swedish-Norwegian-Dutch team. [19]

Operation started:	1961
Operation terminated:	1966

Thermal power:	Zero-effect (50 W)
Fuel:	UO_2 enriched to 3,41 wt% in ^{235}U
Weight of fuel in fuel element:	1598 $\pm$ 15 g U_2O
Moderator and cooling:	H_2O/D_2O (sometimes mixed)
Moderator temperature	Room temperature
Pressure	Atmospheric pressure

Variable core configuration, number of reference core configurations: 4
Configuration 1: Number of fuel elements = 248,
Configuration 2: Number of fuel elements = 240
Configuration 3: Number of fuel elements = 348
Configuration 4: Number of fuel elements = 424

This reactor would serve as an instrument for the reactor physicists in their work on the determination of fundamental physics problems and physics parameters for planned core geometries and fuel elements for both light water and heavy water reactors.

The reactor was housed in the "NORA" building which now is connected to the JEEP II reactor-building complex. The reactor is now completely decommissioned.

The Uranium Reprocessing Pilot Plant at IFA, Kjeller

Operation started:	1961
Operation terminated:	1968

The emphasis of this Norwegian-Dutch reprocessing pilot plant was on experimental reprocessing of natural uranium fuel elements from the research reactor JEEP I, and testing of the "Purex" process equipment, instrumentation and various flow sheets, especially for Eurochemic in Mol, Belgium. Another objective was to obtain operation experience and know-how for the design of a full-scale plant. The Swedish "AB Atomenergi" completed an additional facility in 1964 with the intention to study a separation process using a silica gel column. The Norwegian –Dutch "Purex" part and the Swedish "Silex" part were connected in 1964 to increase the purification capacity.

In the operation period about 1200 kg of uranium was processed, and plutonium and fission products separated by means of liquid-liquid extraction. The plant comprised a tube system of more that 6000 meters and a total of 50 tanks, evaporators and extraction columns.

The plant was shut down and partly decontaminated in 1968. The dismantling was delayed due to economic constraints and re-started in 1982 for one-year period. The decommissioning was resumed in 1989 and continued during the period 1989-1993 [20]. The purpose of the decommissioning was to remove radioactive and contaminated materials so that the building could be used for radwaste work. This required decommissioning to "Stage 2: Restricted site use" and "Stage 3: Unrestricted site use" according to IAEA nomenclature.

Facilities in operation

The Halden Boiling Heavy Water Reactor (HBWR) at IFA, Halden

The Halden Boiling Water Reactor (HBWR) was built by the Norwegian Institute for Energy Technology during the years 1955-1958 (as Institute for Atomic Energy) after a resolution by the Norwegian parliament and government. A photograph from the reactor is shown in Figure 1-1. From 1958 the Halden Reactor Project was established as a joint undertaking of the OECD Nuclear Energy Agency. An agreement was drawn up between nuclear organizations of different OECD countries sponsoring an experimental research programme to study the HBWR concept. The Institute for Energy Technology is the owner and operator of the reactor installation. The reactor operation is thus solely governed by Norwegian laws and regulations.

The HBWR does not produce any electricity but delivers process steam to the nearby paper mill (Norske Skog Saugbrugsforeningen).

Today the Halden Research Project has 17 member countries with more than 100 participating organisations. The project is operated in three- year programme periods.

Operation started:	June 1959
Operation terminated:	Still in operation
Thermal power:	25 MW
Standard fuel:	UO_2 enriched to 6 wt% in ^{235}U
Moderator and cooling:	14 tons of heavy water
Operation temperature:	240 °C
Pressure.	33.6 bar

The Halden Boiling Water Reactor (HBWR) started up in June 1959 and is still in operation. The core consists of standard fuel assemblies and test assemblies. The total number is in the range 80 – 120, of which around 20-35 are test assemblies. The standard fuel assemblies consist of UO_2 fuel rods with 6 wt % ^{235}U enrichment. The total mass of fuel in the core depends of the test program and will be in the range 400 – 600 kg. The reactor is located in a mountain hall that also serves as containment for the reactor. [21]

The main purpose of the HBWR is to carry out experiments to gain knowledge of optimal and safe operation of reactors and power plants over extended periods of time. Instrumentation of the test fuel assemblies has made it possible to make advanced studies in fuel-, material- and corrosion technology. Since the Swedish R2 reactor at Studsvik has been closed down an agreement between IFE and Studsvik has been signed for using the HBWR for experiments.

This licence period for operation the HBWR will terminate 31. December 2008. IFE will apply for a 10 years licence period for operation of the HBWR from 2009.

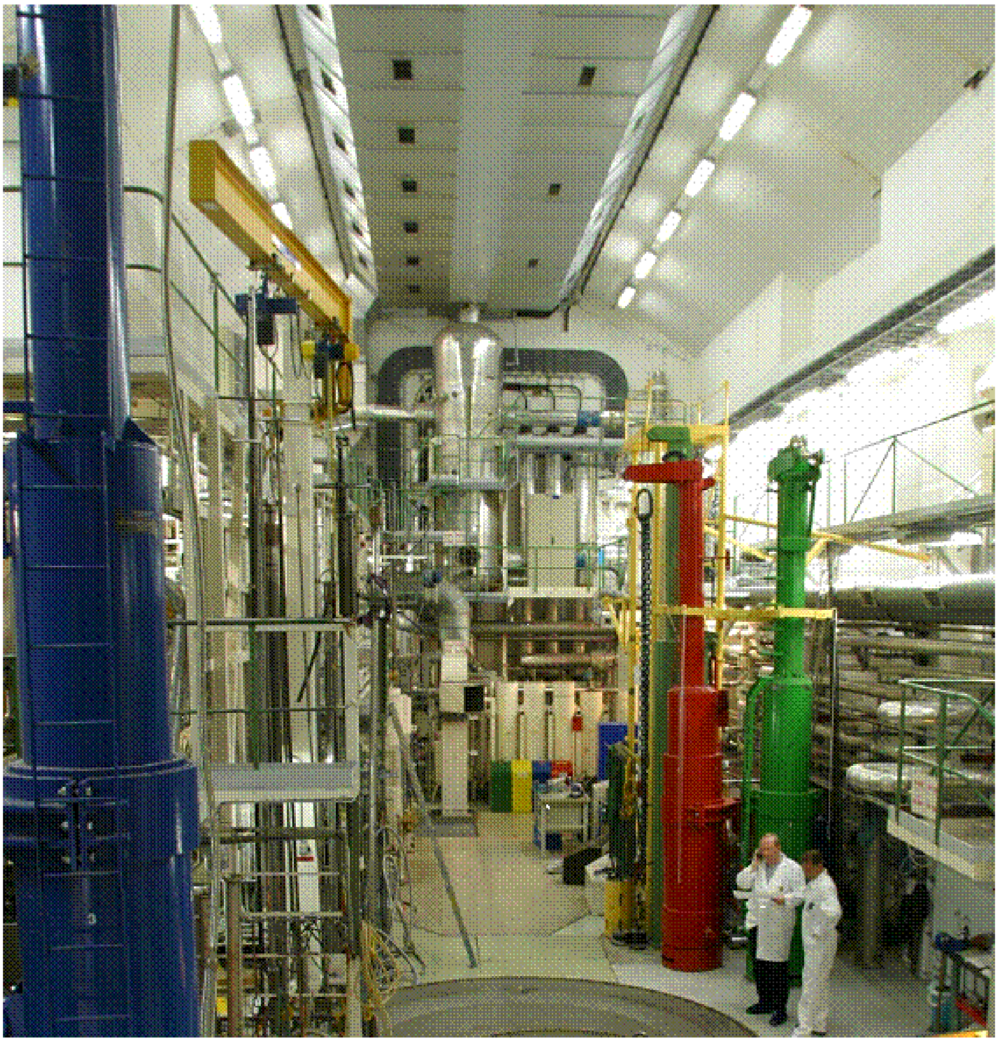

Figure 1-1. The Halden Boiling Heavy Water Reactor (HBWR) at IFA, Halden, Norway.

The JEEP II reactor at IFE, Kjeller

At the end of 1960 the JEEP I reactor had been in operation for about 10 years and a more modern research reactor with greater experimental possibilities was required. The dominant demand was for a higher neutron flux for the neutron physics work which was carried out at IFA, Kjeller, forming the main line of the academic research activity. This work was limited by the low neutron flux and the inadequate number of beam channels for physics experiments. The planning of the new research reactor, the JEEP II, was therefore started in 1959.

Operation started:	June 1967
Operation terminated:	Still in operation
Thermal power:	2 MW
Fuel:	UO_2 enriched to 3,5 wt% in ^{235}U, 250 kg
Number of fuel assemblies	19
Moderator and cooling:	5 tons of heavy water

Operation temperature:	55 °C
Pressure.	Atmospheric pressure

The reactor is housed in a steel containment and is operated approximately 10 months each year. This licence period for operation of JEEP II will terminate on 31st of December 2008. IFE will apply for a 10 years licence period for operation of JEEP II from 2009.

A photograph of the reactor is shown in Figure 1-2.

Figure 1-2. The JEEP I reactor at IFA, Kjeller, Norway.

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The core of the reactor has 51 vertical channels for fuel assemblies, control rods and for experiments, and 9 positions in the reflector for irradiation of silicon crystals and for isotope production. The reactor also has 10 horizontal beam channels where neutrons can be utilised for physics experiments outside the biological shield of the reactor.

The reactor is extensively used for doping of silicon crystals to produce semiconductors. Doping by use of neutrons gives a more homogenous doping throughout the crystals than other methods. Up to summer 2000 only silicon crystals having diameters of 3 " or less could be irradiated. In the autumn 2000 the reactor was stopped and a new top lid was built in order to enable irradiation of silicon crystals with diameters up to 5 ".

The reactor is also used for production of radioactive sources for industrial and scientific use. Radioactive isotopes can be used as tracers for studies of physical and chemical processes. Tracers are extensively used in detection of movements of fluids in oil reservoirs. Radioactive isotopes for use in nuclear medical diagnostic examinations are also produced in the reactor.   Another use of the reactor is neutron activation analysis. This is a much-used method in environmental technology and pollution studies.

One of the main uses of the JEEP II reactor is to supply neutrons for studies of static and dynamic structures in solid materials and liquids. The method used is neutron scattering and has many advantages in studies of materials as hydrogen and carbon, materials of high importance for storage of hydrogen and studies of nano-particles.

The Radioactive Waste Treatment Plant at IFE, Kjeller

The production of radioactive isotopes for medical use form 1951 resulted in radioactive waste products. The operation JEEP II also resulted in some radioactive waste. Up to 1954 this waste was collected and stored. In 1954 IFA was grated the permission from Statens Radilogisk-Fysiske laboratorium (now Norwegian Radiation Protection Authority) to discharge specified amounts of liquid radioactive waste to Nitelva river close to IFAs facilities at Kjeller in Norway. Unfortunately IFA had applied for permission to the wrong authority and this wrong authority had granted the permission. The discharge of liquid radioactive waste had therefore to be stopped in 1957 and the liquid waste must once again be collected and stored at IFA.

Planning of a radioactive waste treatment facility was started in 1957. The radioactive waste treatment facility was tested in 1961 and taken into ordinary use from 1962. The facility treated liquid radioactive waste to reduce radioactivity levels before discharges to Nitleva in accordance with discharge permissions given by the authorities. The facility also treated and stored solid radioactive waste. The present licence period for operation the HBWR will terminate 31. December 2009. IFE will apply for a 10 years licence period for operation of the HBWR from 2010.

Today the Radioactive Waste Treatment Plant receives waste from IFEs activities and from other users of radioactive materials and sources in Norway. It has been estimated that the volume of solid radioactive waste treated is 110 – 120 drum equivalents (equal 210 litre drums) per year. For IFEs own activity this comprises 80-90 drum equivalents and approximately 30 drum equivalents from other waste producing activities in Norway.

In 1970 the storage area for treated solid radioactive waste was filled to capacity. IFA was therefore granted the permission to establish a repository in clay at its premises at Kjeller in Norway. The repository contained 997 drums including 166 drums containing 35 grams of plutonium in a clay bed 2-3 meters below a lawn. Leakage from the repository was supervised by taking water and mud sampled from a drain sump at one end of the repository. Water from the repository running though the drainage sump was collected and treated in the Radioactive Waste Treatment Plant.

When the decision was made in the Norwegian Parliament to build a new storage and repository in Himdalen it was required that the old repository at IFE should be retrieved, the waste drums repacked into new drums and moved to the new repository in Himdalen. This operation was carried out in 2001. The free release limits for the clay bed were specified by the Norwegian Radiation protection Authority to 100 Bq/g dry weight for ^{137}Cs and 10 Bq/g dry weight for the sum of ^{239}Pu, ^{240}Pu and ^{241}Am. Testing of clay from the drums and in the clay bed showed levels of radioactivity below the free release limits. 200 m^3 of sediments from a clean up-operation at the end of an old discharge pipeline in Nitelva carried out in 2000 were filled into the empty clay bed. It had been proved that these sediments contained contamination levels below the free classification limits.

The Metallurgic Laboratory II

The Metallurgic Laboratory II (Met.Lab.II) at IFE, Kjeller, was built in the period 1961-1963 and has been in continuous operation since. A photograph from the laboratory is shown in Figure 1-3. The Nuclear Materials Technology department (NMAT) of the sector for nuclear safety and reliability at IFE operates the laboratory. The current licence period for operation the laboratory will terminate 31. December 2008. IFE will apply for a new10 years licence period for operation from 2009.

The main activities in the laboratory are:

- Production of UO_2-pellets and fuel rods for the two Norwegian test reactors JEEPII and HBWR.
- Production of instrumented, experimental test fuel rods for the HBWR by refabrication and instrumentation of irradiated fuel rods and by encapsulation of MOX-fuel (Mixed Oxide Fuel).
- Post-irradiation examination of irradiated experimental fuel assemblies and rods.
- Examination of irradiated construction material samples.
- Management and storage of spent fuel and high-level radioactive waste.

The main part of the work at the laboratory is Post Irradiation Examination (PIE) of fuel rods and irradiated structural components from the HBWR.

Figure 1-3. The Metallurgic Laboratory II at IFE, Kjeller, Norway.

The main installations in the Met.Lab.II are:

- A pilot production plant for experimental nuclear fuel rods with a complete line for fuel pellet production.
- A Hot Laboratory. The hot laboratory has several hot cells for the handling of high-level radioactive materials and sources. The hot laboratory has three concrete shielded cells with 1 m thick concrete walls and 4 windows with 1 m thick lead glass incorporated in the front wall of the caves. The cells are furnished with a periscope and movable equipment for non-destructive (NDT), destructive tests (DT), and benches for re-fabrication/instrumentation. Additionally there are separate lead shielded cells (4 + 1 + 1) with lead-glass windows furnished with various movable equipment for DT PIE, namely cutting devices, equipment for metallographic and chemical sample preparation, a macroscope, optical

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microscopes, etc. Work in the hot cells is done by using mechanical and electrical manipulators.

- Laboratories with glove boxes for work with non-irradiated fuel and MOX.
- Laboratories with fume hoods/boxes and partly shielded equipment for work with non-irradiated fuel and low radioactive materials.
- Auxilary installations such as an unloading bay for shipping flasks, storage pits, decontamination rooms, maintenance room for active components etc.
- A dry storage area for spent fuel from the JEEP II reactor, experimental fuel from the Halden reactor and high level radioactive waste. The storage consists of 84 vertical steel pipes in a concrete block blow the ground. The pipes are locked and shielded by lead plugs.

Nuclear materials stored at the laboratory are under continuous control and inspection by the International Atomic Energy Agency (IAEA) and by the Norwegian Radiation Protection Authority.

1.4.4 Sweden

The R2 Research reactor

The reactors R2-0 and R2 were commissioned in 1960 and were taken out of operation in 2005. They have been used mainly for materials and fuel testing purposes, isotop generation and silicon doping.

The reactor building comprises reactor hall for the reactors and a cellar for auxiliary equipment. There are three pools, one for each of the two reactors and one for interim fuel storage.

The R2 reactor was of a tank type and had light water as moderator. The neutron flux was high and so was the level of enrichment. The thermal power was 50 MW.

The R2-0 reactor was of pool-type. Maximum power was 1 MW and it was cooled by natural convection.

Decommissioning is planned to take place around 2027. The plans include the service operation and maintenance during the meantime.

The use of the R2 reactor has mainly been geared towards nuclear power generation issues and the incentive for Nordic co-operation has consequently been small.

Three alternatives are planned for the decommissioning. *Alternative 1* implies that the R2 building and auxiliary buildings, including the centre for isotope production are evacuated before the service operation for the decommissioning is incepted. *Alternative 2* includes emptying of the pool of the R2 reactor as well as the R2 building itself, but no further evacuation. *Alternative 3* implies continued operation of the systems for the R2 reactor including the maintenance of the integrity of the pool system for the purpose of radiation protection.

All three alternatives include the removal of the reactor fuel as well as active fuel specimens from the interim pool storage as a first step. Also a thorough cleaning and radiological surveying are included.

The special facility for spent fuel in pool storage need be prepared for receiving the fuel. Assessments need be made for fuel test pins as to whether they should be regarded as waste and managed for final direct disposal, or what should be stored for other dispositions, and where the appropriate storage is to take place.

References on the R2 reactor are [22] and [23].

The Hot Cell Laboratory

The Hot Cell Laboratory was commissioned in 1960 and is still in operation. The Laboratory is important for the continued operation of the Swedish Nuclear Power plants and there are no plans for discontinuing the operation.

The Laboratory is used for investigation of radioactive material such as fuel elements, fuel rods and core components. It is designed for work with specimens having a high level of gamma radiation.

In the plan for decommissioning and the associated cost calculations it is assumed that the decommissioning of the facility will start in the year 2031.

There has been a conference around Hot Cells in the Nordic countries, and nowadays there is a European co-operation on the topic.

Further information can be found in [24].

The storage for old intermediate level waste

The storage for old intermediate level waste (SOILW) was erected in 1960 and taken into operation in 1961. The plant is in operation but essentially all of its intermediate level waste has been treated and is presently being stored elsewhere. Nonetheless, it is planned that the decommissioning will take place during 2036 – 2039.

Presently SOILW is used mainly for reconditioning and storage of old waste. The main floor of the store is at ground level. The store includes pipe positions as well as concrete cells, all well shielded relative to the floor above. The atmosphere at the various positions is at a slight underpressure and the air is evacuated through a slit in the concrete construction underneath the storage positions.

There has been no Nordic co-operations related to this facility.

The continued operation of this facility is related to that of the R2 reactor, cf above. The facility will be needed when the R2 reactor is to be decommissioned.

Further information can be found in [25].

The interim store for spent nuclear fuel

The interim store for spent nuclear fuel (ISSNF) was taken into operation in 1965 and is still in use for interim storage of spent fuel from the R1 and other reactors.

The facility is hosed in a separate building together with an auxiliary building. It comprises water filled pools for storage of irradiated fuel.

There are no plans at present to discontinue the operation of the facility.

There has been no Nordic co-operation projects.

The license of operation extends to the year 2014. In the planning for decommissioning and the associated cost calculations it is assumed that the decommissioning takes place in the year 2034.

Further information can be found in [26].

The active Central Laboratory

The active Central Laboratory (ACL) was commissioned in 1964 and was taken out of operation in 1997.

The facility was a qualified general purpose active laboratory and the use included the following:

- analysis of cladding and other materials
- decontamination and repackaging of glove boxes
- pyrolysis of ion exchange resing
- manufacturing of Sr-90-radiation sources
- mechanical workshop for radioactive components
- experiments with “radiation knife” for treatment of cancer tumors
- experiments with eluation of radioactive elements from ion exchange and the subsequent absorption on inorganic ion exchange material (zeolites)
- compaction of waste drums
- leach tests of glass from reprocessing
- storage and handling of fissionable and other radioactive material
- storage of uranium hexafluoride
- manufacturing of equipment for concrete solidification
- filter tests
- testing of materials
- manufacturing of isotope batteries and overvoltage surge protection
- laboratory for reactor chemistry

- gammacell for irradiation
- experiments with iodine in fuel
- etc

The facility is decommissioned and declassified.

Various international co-operation has taken place including OECD/NEA and the Nordic countries.

Further information can be found in [27].

The scrap melting facility

The plant was commissioned in 1960 for reprocessing of heavy water. During the 1970'ies it was exhaust gas laboratory under the auspices of the Swedish Environmental Protection Agency. In 1985 the scrap melting facility was taken into operation. The facility was substantially extended in 2005.

There are no plans for discontinuing the operation of the facility.

The plant is being used for handling and melting of low active scrap metal from the nuclear industry with the purpose of free release, recycling and volume reduction (of material that is to be stored).

The plant has facilities for sorting, fractioning, mechanical decontamination and melting of scrap metal. The operation is batchwise.

There exists a decommissioning plan.

There has been no Nordic co-operation in connection with this facility.

Further information can be found in [28].

The R1 research reactor at the Royal Institute of Technology

The R1 research reactor at the Royal Institute of Technology is described in Appendix E, and the decommissioning work is described in Section 6.

1.5 Present systems in the Nordic countries for funding decommissioning of nuclear research facilities

1.5.1 Denmark

In Denmark the only existing nuclear facilities are the above mentioned research facilities at the Risø National Laboratory. The Risø National Laboratory is owned by the state, and therefore the decommissioning costs will be paid by the state. The following text is taken from Reference [29] which is included in full in Appendix A, see also Appendix B and Section 5.

As part of Risø's strategic planning in 2000 it was taken into account that the largest research reactor, DR 3, was approaching the end of its useful life, and that the decommissioning question was becoming relevant. Since most of the other nuclear activities at Risø depended on DR 3 being in operation, it was decided to decommission all nuclear facilities at Risø National Laboratory once the reactor had been closed. Therefore, a project was started with the aim to produce a survey of the technical and economical aspects of the decommissioning of the nuclear facilities.

The survey should cover the entire process from termination of operation to the establishment ofa "green field"1, giving an assessment of the manpower and economical resources necessary and an estimate of the amounts of radioactive waste that must be disposed of. The planning and cost assessment for a final repository for radioactive waste was not part of the project. Such a repository is considered a national question, because it will have to accommodate waste from other applications of radioactive isotopes, e.g. medical or industrial.

In September 2000 Risø's Board of governors decided that DR 3 should not be restarted after an extended outage. The outage was caused by the suspicion of a leak in the primary system of the reactor, and followed after the successful repair of a leak in a drainpipe earlier in the year. Extensive inspection of the reactor tank and primary system during the outage showed that there was not any leak, but at the same time some corrosion was revealed in the aluminium tank. According to the inspection consultant the corrosion called for a more frequent inspection of the tank. Therefore, the management judged that the costs of bringing the reactor back in operation and running it would outweigh the benefits from continued operation in the remaining few years of its expected lifetime.

The closure of DR 3, of course, accentuated the need for decommissioning planning and for the results of the above-mentioned project. By the end of February 2001 the project report [30] was published. The study was followed by other studies in order to prepare a proposal for legislative action by the parliament to provide funding for the decommissioning. Among other aspects, possible decommissioning strategies were evaluated. Two overall strategies were considered, (1) an irreversible entombment where the nuclear facility is covered by concrete and thereby transformed into a final repository for low- and medium level waste, and (2) decommissioning to ‘green field’ where all buildings, equipment and materials that cannot be decontaminated below established clearance levels are removed. The entombment option was rejected rather quickly as not being acceptable, among others for ethical reasons ("each generation should take care of its own waste"). Instead, three different decommissioning scenarios were considered with ‘green field’ as the end point, but with different durations, viz. 20, 35 and 50 years, respectively.

After thorough preparations, including an Environmental Impact Assessment, the Danish parliament in March 2003 gave its approval to funding the decommissioning of all nuclear facilities at Risø National Laboratory to "green field" within a period of time up to 20 years. The decommissioning is to be carried out by a new organisation, Danish Decommissioning (DD), which is independent of Risø National Laboratory, thus avoiding any competition for funding between the decommissioning and the continued research activities at Risø.

In the year 2000 the Minister of Research and Information Technology requested that a survey be conducted which comprises the entire process of decommissioning from termination of the operations to the establishment of “green field” conditions. As a result, a report was published in 2001 [30] with descriptions of the above mentioned facilities together with cost calculations. During the project it became evident, however, that for many of the decommissioning tasks the extent of the work and the costs can only be assessed with considerable uncertainty (± 30 %) at that stage. More detailed assessments of the decommissioning costs are to be conducted during the more detailed planning of the decommissioning projects for each facility.

1.5.2 Finland

The nuclear waste management plan is based on immediate dismantlement after the final shutdown of the reactor. Experienced personnel will be still available to conduct the decommissioning work. The decommissioning waste is supposed to be disposed of in the repository constructed in the bedrock of the Loviisa nuclear power plant site at the depth of 110 m. At the moment preparatory work has been done to clarify the possible problems of the decommissioning waste of the TRIGA research reactor (cf Section 1.4.2) in the surroundings of decommissioning waste of the nuclear power plant. The Finnish goal is to work out an agreement between VTT and the Loviisa NPP about the final disposal of our decommissioning waste in the said repository.

The decommissioning waste studies concentrate mainly on the long term safety of the decommissioning waste disposal. The main part of the active reactor components will be packed in concrete packages in the waste disposal facility, which means an additional barrier against the ground water flow. Among others the amount and behaviour of some long-lived radioactive isotopes like ^{14}C belong to these studies. TRIGA reactors have typically in plenty irradiated graphite consisting components.

In Finland the producer of nuclear waste is fully responsible for its nuclear waste management. The financial provisions for all nuclear waste management have been arranged through the State Nuclear Waste Management Fund. The cost estimate of the nuclear waste management will be sent annually to the authorities for approval. Based on the approved cost estimate the authorities are able to determine the assessed liability and the fees to be paid to the Fund [31]. The main objective of the system is that at any time there shall be sufficient funds available to take care of the nuclear waste management measures caused by the waste produced up to that time. The details can be found in the Finnish legislation [32]. The funding system is applied also to government institutions like FiR 1 research reactor operated by the VTT.

1.5.3 Norway

There exist no funding for decommissioning of Norwegian nuclear research facilities today. It is IFE:s opinion that this is a national responsibility in Norway. The question of funding of decommission of these facilities will be elucidated by the Norwegian Ministry of Trade and Industry.

1.5.4 Sweden

It has been described in Section 1.3 (see also Section 1.4) that substantial development work was carried out before and in conjunction with the introduction of nuclear power in Sweden, and much of it took place in the facilities at the Studsvik site. Consequently, it has been decided that that it is those who benefit from the electricity generated by the nuclear power plants who shall pay the costs for the decommissioning, decontamination, dismantling and waste management which is required when the old research facilities at are no longer needed.

Thus, the Law on financing of the management of certain radioactive waste e t c (SFS 1988:1597) states (§1) that "*fee shall be paid to the Government in accordance with this law as a cost contribution*" to amongst other things "*decontamination and decommissioning of*" a number of facilities listed in the law.

The Ordinance (SFS 1988:1598) on financing of the handling of certain radioactive waste e t c states (§4) that the funds collected should be paid to cover the costs incurred. It also states (§4) that "*payment will be carried out only for costs which are needed for*" the decontamination and commissioning "*and which have been included in the cost estimates*" required.

According to the Law on financing of the management of certain radioactive waste e t c (SFS 1988:1597, §5), cost calculations shall be submitted to the Swedish Nuclear Power Inspectorate (SKI) each year. They shall comprise estimates of the total costs as well as the costs expected to be incurred in the future with special emphasis on the subsequent three years.

The Swedish Nuclear Power Inspectorate (SKI) has the responsibility (SFS 1988:1598, §5) to review the cost estimates and to report to the Government if there is a need to change the level of the fee. The SKI also has the responsibility (SFS 1988:1598, §4) to decide on the payments to be made.

It might be added that according to its instruction (SFS 1988:523, §2) SKI also has the responsibility "*in particular … to take initiative to such … research which is needed in order for the Inspectorate to fulfil its obligations*". The participation in the present project is an example of such an undertaking by SKI.

The legislation referred to above can be downloaded from SKI's website (www.ski.se) or from Rixlex (www.riksdagen.se/debatt/).

1.6 Rationale for Nordic co-operation on decommissioning

The present study has come about on initiative by the Swedish Nuclear Power Inspectorate (SKI) and is based on a common need in Denmark, Finland, Norway and Sweden.

It was found in various studies carried out on commission by SKI (see e g [33-37] where [36] is included in the present report in the form of Appendix F) that the intended functioning of a system for finance requires a high precision even in the early stages of cost calculations, and that this can be achieved only if the planning for decommissioning is relatively ambitious. The following conclusions were made:

- IAEA and OECD/NEA documents provide invaluable advice for pertinent approaches.
- Adequate radiological surveying of a facility is needed before precise cost calculations can be made.
- The same can be said about technical planning including selection of techniques to be used.
- It is proposed that separate analyses be made regarding the probabilities for conceivable features and events which could lead to significantly higher costs than expected.[5]
- It is expected that the need for precise cost estimates will dictate the pace of the radiological surveying and technical planning, at least in the early stages.[6]
- It is important that the validity structure for early cost estimates with regard to type of facility be fully appreciated. E g, the precision is usually less for research facilities as compared to nuclear power plants.[7]
- The summation method is treacherous and leads to systematic underestimations in early stages unless compensation is made for the fact that not all items are included at early stages (since they cannot be identified then).
- Comparison between different facilities can be made when there is access to information from plants at different stages of planning and when accommodation can be made with regard to differences in features.
- A simple approach was presented [35-36] for "calibration" of a cost estimate against one or more completed projects.

[5] In practice, in most cases discovery of unexpected features leads to additional costs.
[6] This is clearly the case in countries where funds are collected far in advance of the decommissioning operations. Otherwise, pace may be dictated by the technical planning and the associated cost estimates.
[7] This has to do with the research facilities being more different in comparison with each other which makes it less efficient to apply previous experience. They are also smaller which makes it more difficult to rationalize the work.

- Information exchange and co-operations between different plant owners is highly desirable.

These conclusions are in concordance with and are supported by a very recent report by an expert group at the IAEA[1].

Denmark is presently moving ahead with the implementation of the decommissioning of its old research facilities and have already completed the work on their first reactor. A thorough planning – including cost calculations – was carried out before the practical work was started. The experience from this approach is very positive.

The pre-studies carried out in Finland and Norway, as well as the previously completed decommissioning of the Uranium Reprocessing Pilot Plant ("Uranrensanlegget") at Institutt for Energiteknikk (IFE), also clearly indicate the necessity of appropriate technical and financial planning. The work at the Norwegian pilot plant also showed the importance of associated development work.[14,38]

Information exchange and co-operation on decommissioning of old nuclear research facilities – among owners, contractors, and authorities – will improve the efficiency of the planning and implementation processes. For such systems for finance where funds are to be collected now and costs are to be incurred in some future, such interactions are even necessary prerequisites since experience and data on finished and on-going projects are needed for assessments regarding future ones. (This is explained further in Section 4.2.2.)

2 Purpose and scope

2.1 Purpose

The purpose of the present work is to identify what knowledge and methodology is required for sufficiently precise cost calculations for decommissioning of nuclear research facilities. The purpose is also to exchange and compile[8] such information, data and methodology so that they become available in a suitable format. Furthermore, the purpose is to establish a Nordic network for information exchange and co-operation.

The work is to be carried out during a period of three years, and the present report presents the findings from the first year.

The emphasis for the first year is on networking, collection and compilation of data and guidance documents, and to a lesser extent on schemes of calculation. There will be more focus on the latter during the second year. For the third year establishment of a searchable database is also anticipated.

It has been assessed [34-36] that a confidence level of 80 % might be attained even at a relatively early stage. It is highly important in this regard that differentiation is made with regard to stage of planning, cf [4,39].

2.2 Scope

The scope of the present work is as follows:

1. Establishment of a Nordic network in the field including an Internet based expert system
2. A guidance document for the prerequisites for precise cost calculations, including
    - radiological surveying
    - the technical planning
    - financial risk identification
3. Descriptions of techniques that may be applied at early stages of calculations and assessments of costs
4. Collection and compilation of data for plants, state of planning, organisations, e t c.

[8] I e make searchable and comparable.

3 Good practice

3.1 Strategy and planning

The overall purpose of decommissioning is actually the protection of man, the environment and natural resources. In the case of Sweden, the basis for this is defined in a law called "*The Environmental code*" (SFS 1998:808) . According to part one, chapter one, section one of this code, it "*shall be applied in such a way as to ensure that human health and environment are protected against damage and detriment, … biological diversity is preserved, … the use of land … is such as to secure a long term good management … and reuse and recycling … raw materials and energy is encouraged*". This is further specified in the Swedish radiation protection law SSI FS 1988:220 which has the following corresponding wording (1§): "*The purpose of this Act is to protect people, animals and the environment against the harmful effects of radiation*".

The strategy and legislation is similar in all of the Nordic countries.

Planning for the financing - including the establishment of reliable cost estimates – is a part of this strategy, c f section 1.5. Cost calculations can, however, not be performed as an isolated or incidental event. They must be part of an integrated strategy and planning involving all relevant aspects over the life cycle of a plant. Cost calculations are required in all the Nordic countries in all stages of planning, c f Section 1.5. Therefore, sufficient strategic decisions and technical planning must exist at all times.

For practical purposes this implies that the mainly technical staff that in practice performs the planning for decommissioning must set their objectives based on non-technical – economical - needs and criteria. It is essential in this regard that clear functional requirements are set as to the tolerable levels of uncertainties in the cost calculations and that their implications are fully communicated, realized and considered.

Ideally, decommissioning should start already at the design phase of a plant and be part of the overall long-term planning and management. By including decommissioning aspects from the beginning, the actual cleaning and dismantling operations can be carried out very efficiently and with insignificant impact on health, environment and natural resources.

Conversely, if no provisions and preparations for decommissioning were made in the design and construction phase of a facility, it is imperative that planning is being commenced "*as soon as possible*"[4], and that it also includes "*the costs of the decommissioning and the means of financing it*"[5]. In such a case, the extent of efforts required might be rather fortuitous, depending on e g what design features were actually chosen, and what foresight has been applied during the operation. This applies also to the possibility to assess the extent of efforts required.

Nonetheless, the increasing realisation of these prerequisites in the international nuclear communities has lead to the establishment of certain procedures and development of tools to manage the situation. In this regard, the IAEA has compiled the vast international experience into a number of Safety Guides [4-7] dealing primarily with management, safety and technical matters. National guidelines include [2, 40]. Strategy and costs are discussed in e g reports from IAEA[1] and OECD/NEA[8,41], but no international guideline on how to achieve requirements on cost calculations has been identified in the present work[9].

Sections 3.2 – 3.4 summarizes good practice needed as a basis for cost calculations. The sources for the account include the above references as well as experience from the organisations of the present authors. The proposed practice is based on a requirement on precision in the cost calculations of ± 20 %. The word "precision" has the meaning that there should be a 65 % probability that a cost estimate would fall within ± 20 % of the actual cost as incurred after the project has been completed. This figure was put forward in [34, see also 36] as being achievable for decommissioning of nuclear research facilities. This requirement is in reasonable concordance with the figure of ± 15 % mentioned in [41], the ± 20 for 60 % probability in [42] and the ± 20 % in [43] for nuclear power reactors.

It was mentioned in both of these cases[34,41] that such a level of precision can be achieved for a decommissioning project only if the approach is rather ambitious. This includes the actual calculations as well as the basis for them. Thus, following the international standards [4-7] e t c is highly recommended but will not be sufficient in general. The good practice described in the following is intended to fill in this gap, at least partially.

It should be pointed out that the precision of ± 20 % might not be attainable – or rather reasonable to aim at achieving – for some systems. However, the requirements of accuracy in the cost calculations in general still apply. Consequently, deviations should be accepted only when justified, when the reasons for them are properly accounted for, and when an estimate or at least a verbal description of the level and nature of the uncertainty is documented. Such information will constitute part of the basis for assessment of pertinent levels of fees as well as for transparency around the finance system.

A prerequisite for the high precision is that management and staffing is adequate, see e g [44]. It might be indicated, though, that proper management is imperative, and that staffing should preferably include people having experience in operation of the plant in question as well as in previous decommissioning projects. Since these experiences mainly rests with different individuals it is an important management task to promote the appropriate integration between the two.[44]

[9] Quote T. S. LaGuardia in [XC]: *"An international organization such as the International Atomic Energy Agency (IAEA) or OECD/NEA, or both need to re-establish a committee to promote the standardization of cost estimation guidelines and methodology. The committee should seek adoption of cost estimating guidelines and methodology, and provide training as required for implementation of its use. Similarly, the committee should be directed to continue to accumulate actual decommissioning costs and convert them into a form that does not compromise proprietary information. From this data base, consensus can be achieved."*

3.2 Methodology selection

It might be tempting to make the selection of technology straight from knowledge of the equipment and building construction in combination with experience from conventional cleaning and disassembly operations. In such a case, it will most likely be realized sooner or later in the project that other techniques will have to be or should have been applied due to the implications of the radiological contamination.

At first sight, the statement just made might appear as self-evident or even commonplace. However, it is frequently difficult even for experienced people and specialists in the area to fully apprehend its implications. For instance, a certain technique might appear appropriate, considering the amount of efforts estimated initially. However, it might become apparent through the course of the work that this estimate is in error, and thus another method would be preferable. In such a case, it may be imperative that an alternative and supplementary technology it available, at the time when it is needed, and that those responsible are prepared to reconsider their selection of technology on a continual basis.

Actually, no rational selection of technology for decommissioning of a nuclear facility can be made without a sufficiently comprehensive radiological survey (cf Section 3.3). Even when such a survey exists, it may not be sufficient for all of the needs. For instance, some of the activity may not be possible or feasible to measure before certain sources or bulky components and/or structures have been removed. Such cases call for contingencies in terms of alternative plans and methodologies.

Actually the graphite in the R1 reactor (cf Section 5.3.1) is an excellent example of this. The radiological survey preceding the decommissioning included sampling and measurement of the graphite neutron reflector around the core. However, it was not appropriate for radiological reasons to make the sampling and characterization comprehensive (and give rise to an increased dose to the staff), and thus some uncertainty remained. It turned out that the rest of the graphite was more radioactive than the sample taken, and consequently the work had do be carried out somewhat differently and therefore took some more time. (The over-all outcome was very good, however, see below).

It is sometimes thought that decommissioning of a nuclear facility requires the availability and use of novel techniques that have to be developed in conjunction with a project. Indeed, it is a good idea to carry out research and development work on decommissioning in order to come up with safer and more efficient methods and also to improve the planning and operation as well as the cost calculations. However, the general experience is that the technologies for decontamination, dismantling, demolition, size reduction and assaying and packaging need not be nearly as sophisticated as those used for the construction of the plant.[44] It is important to use proven technology which will provide for reliable planning and costing rather than theoretical approaches with advanced technology and potential – but not necessarily actual - cost reductions.

Further support for such an approach can be found in [45] where an evaluation is made of the availability of technologies and where it is concluded that most of the techniques required are widely available at present. Rather, it is the interfacing between techniques in combination with the radiological prerequisites that constitute the challenge.[45]

However, availability on the world market in general does not necessarily mean that a technology is readily available for use in decommissioning at a nuclear research facility. The deregulated markets enable companies to invest in development of techniques to be used in commercial decommissioning operations. This gives rise to a selection of vendors and techniques as well as competitive prices.

The other side of the coin is that each vendor will defend its information and only participate in projects on its own conditions. This may not be suitable for small projects with research facilities where it might not be feasible to call in staff of a supplier from another part of the world to undertake minor tasks. Conversely, methods which have been used successfully in the past and which are familiar to the existing staff might not be the best choice in a new situation.

Thus, many considerations apply when methodologies and their interfaces are to be selected, and the analysis of the best choices might be complex. In order for a selection of technology to be systematic, transparent, integrated, and defensible in retrospect e t c, it is a good idea to use some kind of systematic approach. There are a number of books available on the principles of decision making and References [46-47] represent the analytic hierarchy process methodology. Application of such a systematic approach means that the selection process can be described, and thus be communicated to interested parties and stake holders. It also substantially reduces the risk of bias including the risk of others suspecting that bias is involved.

Much of the material needed for such evaluation and comparison can be found in the literature. This includes the methods themselves and their specifics as well as various projects that have been carried out. It is of special value if it is possible to find a plant that is similar so that the experience is particularly relevant.

An example of this can be found in [34-35] on an intermediate level waste storage facility at Studsvik where a similar but largely completed project was found at the Argonne National Laboratory in Illinois, USA. The experience with the drilling rig included difficulties with drilling with sufficiently high precision as well as loss of drilling liquid and potential contamination of the drill fluid due to voids in the concrete.

No plan or selection should be made without extensive contacts with people at other similar facilities. Nothing can replace such input. There are many lessons learned and much is published in the literature, but the benefit will be much larger if such studies are combined with plant visits and meeting the staff. There is an overrepresentation of success stories, and they have a high value as good examples, but it is equally important to learn from mistakes or difficulties, and such aspects may be easier to communicate on an informal basis.

When the R1 reactor at the Royal Institute of Technology in Stockholm was to be decommissioned by Studsvik in the early 1980's, three persons went literally around the globe and visited a large number of facilities. This caused a few eyebrows to be raised among the colleagues, including those of one of the present authors, but it can safely be said in retrospect that this was completely warranted. It is also in concordance with advice generally given in the literature.

It is assessed as likely by the present authors that much of the success in the R1 project (c f section 5.3.1) is due to the careful planning and the ability to find and make use of experience from other facilities.

3.3 Radiological surveying

It has been said already that the cost for decommissioning of a nuclear research facility with typical levels of contamination may be two or more orders of magnitude higher than for a corresponding (hypothetical) non-radioactive plant.

The presence of radioactivity gives rise to increased cost in a number of ways:

- The practical work will have to be with the precautions necessary with regard to the radiological health hazard (remote handling, radiation monitoring, dust control, e t c)
- The sources containing most of the radioactivity will have to be removed and managed separately
- The general contamination will have to be reduced by decontamination
- The residual levels will have to be determined to be sufficiently low as to allow reasonable management of the waste

However, major radioactive sources might not be possible to remove until bulky components have been taken apart. In some cases novel and somewhat sophisticated techniques might be applied to at least allow the major sources to be characterized, e g to insert radiation probes into pipes.[45]

Radiological surveying for decommissioning work is very different from that of ordinary operation of a facility. The main reason for this is that the purpose is different. For the ordinary work, it is the general level of radiation together with the potential for contamination that constitutes the health hazard. For decommissioning, knowledge is needed also on concealed radionuclides that might not even show up on the readings of the instruments.

Examples of such concealed activity may be surface contamination that has become stabilized by means of paint. In such cases, smear tests will not unveil its presence. Other cases include deposits on the inner surfaces of pipes and other equipment, and deposits in fissures and fractures. A special case of concealed radiation sources is where components have become activated in their interior, which may be the case for items that have been exposed to radiation by neutrons.

The prospect of finding concealed activity is related to the ability of the radiation in question to penetrate. Here alpha and beta emitters have a short range, especially in condensed matter, and the penetration range of gamma rays is highly dependent on their energy (which is different for different radionuclides).

Also the potential health hazard varies highly between external exposure, respiratory intake and oral intake, which in turn are different for different radionuclides.

With time experience will develop as to what to look for, and efficient means of controlling the radiological hazard have been developed for facilities that are either large or many of a kind (or both). Thus, in light water reactors with little fuel damage[10], activation products from outside the fuel (but including the outer surfaces of the fuel pins) dominate the hazard, and among them cobalt-60. It has a half life of around five years which is sufficiently long for it not to decay in a short time, and yet sufficiently short in order for the unstable nuclei formed to transform to a stable state at a considerable rate. In addition, the energy of the gamma rays emitted is high, and so the radiation is quite penetrating.

Consequently, much of the time simple instruments measuring cobalt-60 can be used, and the hazard of other radionuclides can be evaluated by inference (e g transuranics).

For a nuclear research facility, such commonplace features might not necessarily apply. For instance, if alpha radiating specimens without accompanying gamma emitters have been handled, contamination might be very difficult to find since the alpha radiation is very easily shielded. Another example might be standard assumptions used in order to determine the amount of activity inside a pipe. If the calculation is based on cobalt-60 while the actual radiation is something else, then it is likely that the inventory is underestimated since the radiation from cobalt-60 is more penetrating than for most other sources.

Thus, a radiological survey of a nuclear research facility for the purpose of decommissioning should thus start with a recapitulation of what the facility was used for and an analysis of what might be expected in terms of radionuclides and contamination levels. The next step would be a general survey including hot spots, potential hidden activity and known sources.

The strategy, planning, methodology selection and uncertainty analyses are highly dependent on the results of the radiological survey. Most likely, such work based on a general survey will give rise to specific questions on the radiological situation. Thus an iterative approach should be applied and supplementary and specific surveys conducted.

Such iteration initiated work should include planning for the radiological follow-up of the decommissioning operation as well as the measurements intended for waste and for material to be released (unconditionally or otherwise).

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[10] In the case of fuel damage cesium-137 and strontium-90 will be of interest as well. Cesium-137 is also a gamma emitter albeit the energy is lower and the penetrability less than those of cobalt-60.

In some cases, it might be difficult to measure sufficiently well in order to achieve the requirement of ± 20 %. One reason might be if it is difficult to avoid dose to staff. Such cases should be documented and the associated uncertainty assessed. In this way, the total cost commitment may still be estimated and possible to find limits for. Hopefully, various uncertainties may even out and make the total uncertainty acceptable nonetheless.

In other cases, it might be warranted to carry out a limited amount of work prior to the actual decommissioning in order to be able to obtain good radiological data for the various other planning activities and for the cost calculations. Such work may include removal of sources and hot spots, emptying containers (e g with ion exchange resin) cleaning, e t c.

Sampling for the purpose of radiological characterization is a natural part of the radiological surveying and should be conducted to the extent needed and appropriate. Sampling may also include a certain but limited amount of decommissioning work, e g core drilling in concrete, or (perhaps temporary) removal of shielding or other entities in order to take samples.

Since the radiological work serves several purposes and concerns various groups of people and is carried out iteratively, it is important that there exists plans for this work and that they are properly updated. Similarly, it is important that the results are properly documented.

The basics of radiation and radiation protection are not explained in the above, and the reader is referred to the standard literature on the subject, see e g [48].

3.4 Uncertainty analysis

It has been pointed out in the previous sections (3.1-3.3) that the aim of ± 20 % in uncertainty might not be achieved for all systemss even if appropriate planning, methodology selection and radiological surveying is carried out. The knowledge needed for such a precision might not be reasonably achievable.

For such cases it is imperative that assessments are made regarding the possible size of the issue and the probability of various outcomes. As a minimum this should be carried out verbally with scenarios for various types of outcomes. It is also important that an upper bound of the magnitude of each case is stated.

Such uncertainty analyses can then be integrated in total assessments where the total uncertainty typically can be shown to be less than those of the constituents. Such conclusions can be made only if the various cases involved do not have common causes.

However, experience tells us that such analyses will only bring to attention part of the total uncertainties. If no further analyses are made it is likely that “surprises” will appear during the course of the work. Experience also tells us that such surprises are more likely than not to give rise to increases in cost.

Thus, some sort of extended uncertainty investigation and analysis need be made in which further features, processes and events which might cause increased cost can be identified.

Such risk identifications and assessments can be made using tools which are available from the area of technical risk analysis and which are described extensively in the literature, see e g [49-51]. Even when such an extended uncertainty analysis has been made, there may still be features which have not been identified and which constitute a residual risk. Such uncertainties can be managed by means including another factor for contingency.

An extended uncertainty analysis should start with a system description together with a definition of the boundaries for the analysis, which defines the border between internal and external features and events. If the parts of the work described in Sections 3.1-3.4 are well underway, much of what is needed has already been compiled. The two types of descriptions are not identical, however. For the extended uncertainty analysis it is beneficial to structure and analyse the systems in terms of the following[52-53]:

- the parts of the system in which or between which the different processes take place together with the relevant properties (*features*)
- initiating internal as well as external *events*
- the *processes* that occur during these events

After the system has been identified and described including its interdependencies, the next step should be to identify potential uncertainties, and especially all types of risks. Different sources should be consulted in order for the compilation to be as complete as possible. It is highly desirable that individuals with different kinds of competence and experience are involved in this work. A few examples of what might be attempted are given in the following:

- a systematic analyses of the various aspects of the facility
- brainstorming
- follow standard check lists
- review literature
- utilize feed-back from previous projects
- networking internationally

The assessment of the various types of uncertainties identified relates to the following questions:

- Where might there be deviations?
- How likely is it?
- What would be the consequences (including worst case)?

There are a number of methods available for risk / uncertainty analysis. They can be divided into inductive or deductive. For deductive methods assumptions are made on the final outcome and the task of the staff is to attempt do describe events that might lead to such a consequence. For inductive methods, some sort of error is assumed and the task is to foresee what consequences this might lead to. Methods that can be applied include the following[51]:

- Preliminary Hazard Analysis (PHA)
- What-if analysis
- Hazard operability analysis
- Failure modes and effects analysis
- Fault tree analysis
- Event tree analysis
- Cause-consequence analysis

It is important that the work is carried out in steps, and that checks are made from time to time to evaluate what level of effort is warranted. It is anticipated that for most purposes it will be sufficient with uncertainty identification together with expert judgement and assessment rather than a full analysis.

The result should be identifications of uncertainties together with assessments of their probabilities and consequences.

An example of an identification of a potential uncertainty was made in [35-36] where it was found that a pool for wet storage of spent fuel did not have the double containment that modern facilities do. Thus, conceivable leakage to the underlying rock and soil constitutes an uncertainty with regard to cost. The uncertainty was identified from systematic searches and studies in the literature of facilities. The probability and consequence were not evaluated, although it was assessed that the most probable case is an intact containment. In the case appearing in the literature, leakage had occurred and contamination had spread outside the facility, however.

It is important that the uncertainty analysis is properly documented. This will enable future analyses to start from where the previous ones ended. It will also make the process for financing transparent and thereby also credible to stake holders and interested parties outside the sphere of experts.

4 Techniques for assessment of cost

4.1 Cost structuring

Decommissioning is the final phase of the life cycle of a nuclear facility and is thus highly dependent on the design, operation, documentation and planning, etc. Nonetheless, it has been shown in a number of projects [54] on various types of facilities that technical methods and equipment are available today to dismantle safely nuclear facilities of whatever type and size.

Decommissioning projects for various types have also demonstrated that costs can be managed. However, comparisons of cost estimates for different individual facilities may show relatively large variations[54], even at late stages of planning, and both in relation to cost calculations for other facilities and to incurred costs.

In the past, cost estimates have been based on the world-wide experience from decommissioning projects as well as maintenance and repair work at facilities in operation. This experience has been compiled and utilized in the form of either costs for various tasks and / or unit costs for various basic decontamination and dismantling activities.[54]

A number of differences exist between the various facilities and projects constituting the original base for such per item data. Moreover, the prerequisites for extracting such per item data vary considerably since the method of calculation and the structuring of the cost items may also be very different.

Such errors may be strongly reduced if a common “standard” is applied on the structuring of the costs as well as on the schemes for calculation. This topic has been dealt with by OECD/NEA in collaboration with IAEA and EU and the resulting “*proposed standardised list of items for costing purposes in the decommissioning of nuclear installations*” has been documented in [54]

The group undertaking this work found that it is essential when cost figures from a project are to be used that the real content, i e what is actually behind the figures, be investigated analysed. Numbers taken at their numerical value, without regard to the specific context, can namely easily be misunderstood and misinterpreted.

Consequently, the group has also come up with a compilation of definitions of the technical cost groups, cost elements, and cost factors.

The document [54] consists mainly of listings of the various cost items. It is very detailed and extends over more than a hundred pages. Obviously, this structuring corresponds to the summation method

4.2 Cost estimation methodology

The OECD/NEA document [54] (cf section 4.1) does not say anything about how it should be applied with regard to the stage of planning. It is obvious from the document, however, that an underlying assumption is that estimates can be made on an item to item basis. This actually presupposes that a relatively detailed planning has been carried out (cf *appropriate planning* in Section 3.1) including methodology selection (cf Section 3.2), radiological surveying (cf Section 3.3) and uncertainty analysis (cf Section 3.4).

4.2.1 Cost calculations for new industrial plants in general

The topic of cost calculations in early versus late stages of planning has been dealt with in the literature on cost calculations for industrial plants in general [55]. Actually, early cost calculations may call for approaches that differ from those of late ones. State of the art in this area might be briefly summarized as follows.

As soon as the final process-design stage is completed, it becomes possible to make accurate cost estimations because detailed equipment specifications and definite information are available. However, no design project should proceed to the final stage before costs are considered. In fact, cost estimates should be made throughout the various stages of planning, development and design in spite of the fact that complete specifications are not available.

Thus, cost estimates can be made even at the earlier stages and are then referred to as predesign cost estimations. If the design engineer is well acquainted with the various estimation methods and their accuracy, it is possible to make remarkably close cost estimations even before any detailed specifications are given. Such cost estimates frequently form the basis for the management in their decision on investments.

Five categories of cost estimates have been identified to be applied to the successive stages in a large chemical plant project[55]. These are as follows:

1 Order of magnitude (ratio estimate) based on similar previous cost data; probable accuracy of estimate over +/- 30 percent.

2 Study estimate (factored estimate) based on knowledge of major items of equipment; probable accuracy of estimate up to +/- 30 percent.

3 Preliminary estimate (budget authorization estimate; scope estimate) based on sufficient data to permit the estimate to be budgeted; probable accuracy of estimate within +/- 20 percent.

4 Definitive estimate (project control estimate) based on almost complete data but before completion of drawings and specifications; probable accuracy of estimate within +/- 10 percent.

5 Detailed estimate (contractor’s estimate) based on complete engineering drawings, specifications, and site surveys; probable accuracy of estimates within +/- 5 percent.

Predesign estimates are based mostly on historical data from similar facilities together with utilisation of adjustment factors for cost increase with time, size of the facility and/or composition of the intended equipment. Late estimates are instead largely based on detailed specifications and summations of all the items which contribute to the total cost.

It is important to realise the uncertainties associated with the various stages and possibilities for estimation. Some of them are arbitrary in character as the ones given in the listing above. Others are systematic in character and thereby perhaps more treacherous.

Pitfalls in this context include the following:

- Conceptual error. Performing the "correct" calculation for the wrong process, or for an incomplete one.
- Methodological error. Applying the summation method at too early a stage when only a fraction of all items to be included can be identified.

In the vast majority of cases such systematic errors lead to underestimation of the actual cost.

4.2.2 Early stage cost calculations for decommissioning of nuclear research facilities

In practice, the summation method is frequently being applied at early stages in spite of its inherent tendency to give rise to underestimations of the costs. One important reason for this is that more suitable calculation techniques have not been developed or at least are not generally available.

It is therefore highly desirable to somehow "calibrate" results of early estimates against known costs of already completed projects of similar kind.

An example of such an approach is presented in [34-36], see also Appendix F, and the main features are as follows.

Let the cost for a plant be given by the equation:

$$K^c = \sum_i p_i \qquad (1)$$

Where
K^c = the total calculated cost
p = cost item, and
i = index for cost item

A fit to actual cost K^a for a completed project can be made using the weighing factors wi and a scaling factor s according to the following equation:

$$K^a - K^c = s \sum_i w_i p_i \qquad (2)$$

:

The weighing factors may be obtained by assessment of which items should have a small, intermediate, large or very large influence on the difference between calculated and actual values. For instance, a weighing factor can be given one of the values 1, 2, 4 or 8. The scaling factor can then be calculated using the equation:

$$s = (K^a - K^c) / \sum_i w_i p_i \qquad (3)$$

For a plant for which a refined cost calculation is to be made, the cost items can be calculated first, and then the total cost according to the equation (1) above.
After that, an adjusted calculated total cost can be calculated using the equation:

$$K^{adjusted} = \sum_i (1 + sw_i) p_i \qquad (4)$$

where s and wi have been derived from a similar reference plant and p_i for the plant for which a refined calculation is to be made.

The application of equation (4) implies an improvement compared to a simple over all scaling since differences in the assessed cost structure influences the result.

The example illustrates how some of the systematic errors might be avoided, or at least turned into errors that are random in character. For projects having a fair size random errors frequently even out. Systematic errors such, most of which give rise to underestimations, add up and give rise to a total error (figured as percentage) which is just as large as the small ones.

It should be noted that the above approach is just an example and that many schemes might be worked out to the same end. Ideas in this regard might be found e g in Reference [55].

5 Reactor DR1 at Risø National Laboratory in Denmark

5.1 General approach

5.1.1 Prerequisites and method used for cost assessment

The material below is mainly taken from [30] as well as a document with the title "*Decommissioning in Denmark*" (cf Appendix A, see also Appendix B [56]); it is also presently available at the website of Danish Decommissioning (http://www.ddcom.dk).

Risø National Laboratory (RNL) was established in the late 1950'es as a Danish research centre for preparing the introduction of nuclear energy in Denmark. Three research reactors and a number of supporting laboratories were built. However, Denmark has not yet built any nuclear power plants, and in 1985 the Danish Parliament decided that nuclear power should no longer be an option in the national energy planning. The facilities at RNL thus are the only nuclear facilities in Denmark. Subsequent to the Parliament's decision the research at RNL related to nuclear power was reduced and the utilisation of the facilities concentrated on other applications, such as basic materials research, isotope production and silicon transmutation doting. Already in 1975 one of the reactors had been taken out of service for economical reasons and the activities moved to the 10 MW materials test reactor, DR 3. Furthermore, in 1989 the hot cell facility was closed, and over the next four years it was partly decommissioned.

As part of Risø's strategic planning in 2000 it was taken into account that the largest research reactor, DR 3, was approaching the end of its useful life, and that the decommissioning question was becoming relevant. Since most of the other nuclear activities at Risø depended on DR 3 being in operation, it was decided to decommission all nuclear facilities at Risø National Laboratory once the reactor had been closed. Therefore, a project was started with the aim to produce a survey of the technical and economical aspects of the decommissioning of the nuclear facilities. The survey should cover the entire process from termination of operation to the establishment of a "green field"[11], giving an assessment of the manpower and economical resources necessary and an estimate of the amounts of radioactive waste that must be disposed of.

After thorough preparations, including an Environmental Impact Assessment, the Danish parliament in March 2003 gave its approval to funding the decommissioning of all nuclear facilities at Risø National Laboratory to "green field" within a period of time up to 20 years. The decommissioning is to be carried out by a new organisation, Danish Decommissioning (DD), which is independent of Risø National Laboratory, thus avoiding any competition for funding between the decommissioning and the continued research activities at Risø.

[11] In this context "green field" means a situation where facilities and areas are free released to other use without any radiological restrictions. Thus clean buildings and equipment may be re-used for other purposes than nuclear.

As the facilities are (and were) different with respect to complexity, the assessment of labour and cost of decommissioning has been approached differently. For some facilities, such as the Isotope Laboratory, the necessary work could easily be identified, whereas for others a systematic approach was necessary. In particular for DR 3 a standard list of costing items[54] (cf Section 4.2.1) was used as a template for specifying the costs of decommissioning operations. It is aimed at nuclear power plants, but most of the items listed are valid for a research reactor, as well. Also for other facilities than DR 3 the list has been used as a checklist.

For each of the items addressed the required labour effort was estimated - either by Risø staff, where it was felt that they had sufficient insight, or with the help of consultants or the PRICE programme, described below. A standard rate of 231 DKK/hour ([30] was published in the year 2001) was used to calculate the labour cost. This cost was obtained by calculating a suitable average of the costs of the staff categories foreseen for the decommissioning organisation. For DR 3 the costs were entered into an Excel sheet, based on the costing items in the above mentioned standard list. For DR 1, DR 2 and the Hot Cell facility decommissioning operations were identified by Risø staff and PRICE was used to calculate the cost. One point where we have deviated from the list is in the assessment of the health physics assistance needed. Here the list prescribes the specification of health physics effort for each task. However, it was found that the necessary health physics staff and the required equipment can be assessed on an overall basis, taking into consideration more broadly the tasks that are to be performed.

The approach taken by Danish Decommissioning is to find a sufficient knowledge base so that the summation method (cf Section 4.1) could be applied and justified. This was achieved through a combination of compilation of existing data together with supplementary investigations along the lines described in Section 3. The underlying descriptions together with the actual assessments are documented in [30].

5.1.2 The computations using the computer program PRICE

The PRICE programme has been developed by the UKAEA and is being used by a number of institutions in other countries, as well. During the project Risø was given the opportunity to have PRICE for evaluation and the programme was found very suitable for our purpose, so that Risø decided to buy the programme.

PRICE incorporates:

- a standard Work Breakdown Structure (WBS)
- a methodology for mensuration of component quantities
- a classification system which relates to the physical complexity of the task ("Complexity" classification)
- a classification system which relates to the radiological condition and the level of radiological protection required ("Task" classification)

In PRICE a facility is broken down into simple building blocks or "Components". For each component data is stored on the resources (man-hours) required to remove unit quantity of that component. This is termed the "Norm", which varies depending on the "Complexity" and "Task" classification attributed to the component. Components can have up to five "Complexity" classifications and three "Task" classifications and thus any one component can have up to 15 "Norm" values. Each of the standard components is sub-divided into a range of five complexity ratings ranging from "Complexity 1" for relatively simple to "Complexity 5" for the most complex. The Task classification provides a means of taking into account the degree of radiological protection required when dealing with the standard components. There are three available Task classifications as follows:

- Task R - "Remote" Defined as operations where operatives at the work face use manipulators, robotics, hot cells etc.
- Task C - "Complex protection" Defined as operations where operatives at the work face must wear pressurised suits.
- Task M - "Minimum protection" Defined as operations where the protection of operatives at the work face necessitates, at the most, the wearing of ori-nasal masks.

A single aggregated man-hour rate or "Unit Rate" for a typical mixed grade team, together with tools and plant, is applied to all components. The system does however allow the user to add a unique "user defined cost" to a task.

The overall cost estimate is produced by summating the individual component costs plus additional sums for items which cannot be treated in this way i.e. capital cost items such as RH equipment, change room facilities, waste packaging facilities etc.

PRICE offers a hierarchical approach that can be used to identify costs in key areas and also those associated with identified "stages" throughout a project lifetime. The hierarchical structure or Work Breakdown Structure used by PRICE is shown in Figure 5-1.

5.1.3 Limitations

It should be underlined that the study reported here is the first attempt to go into detail in the assessment of costs of the operations to be performed when decommissioning Risø's nuclear facilities. Therefore, there are many tasks for which no prior experience exists concerning the manpower needed. As far as possible, experience from other countries has been taken as a guideline; but it must be anticipated that the cost estimates given in [30] will change as experience grows and the study can go into more detail.

The study has focused on estimating the total labour effort to be put into performing the various tasks without going into detail concerning the size of the staff needed at a given time or during a given period to perform the work. This question, of course, will be an important part of the planning to be carried out by the decommissioning organisation.

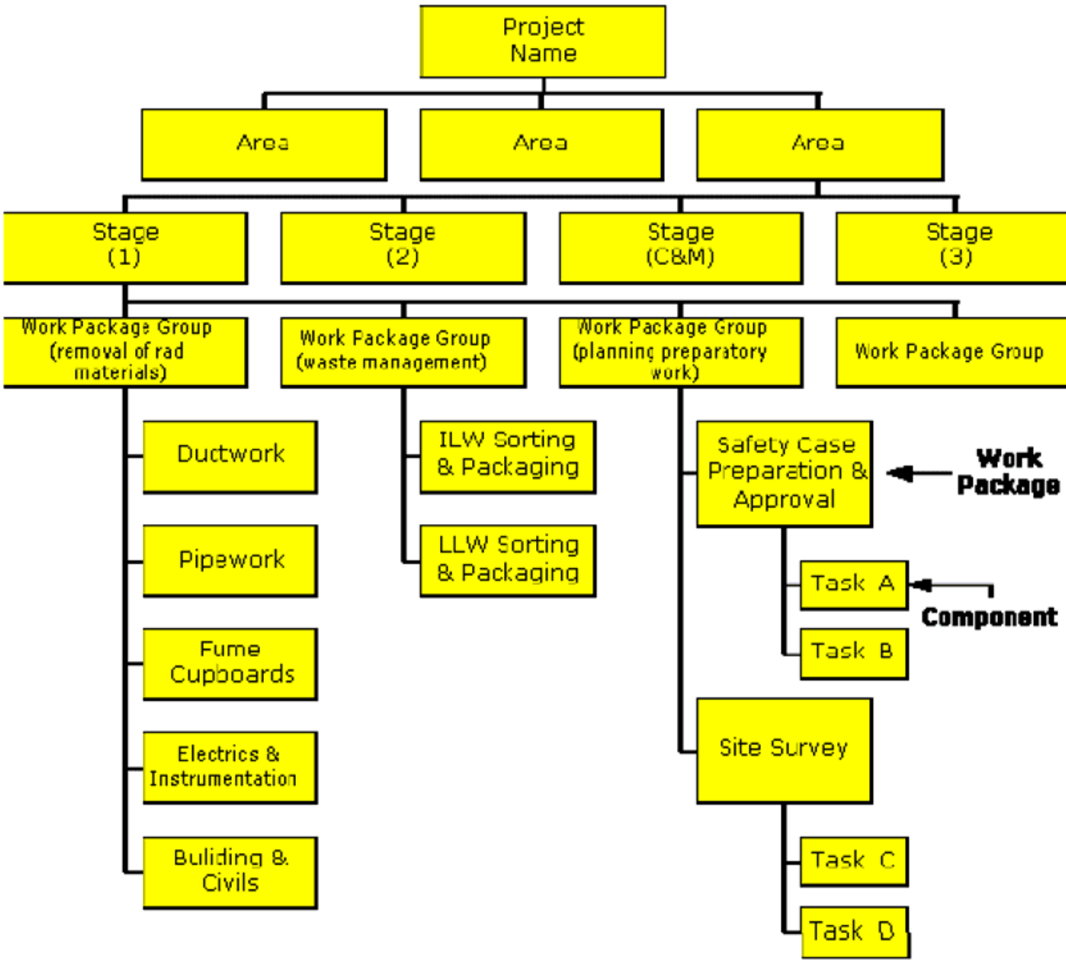

Figure 5-1. The hierarchical structure or Work Breakdown Structure used by the cost calculation programme PRICE.

In awareness of these limitations, Dansk Dekommissionering analyses and assesses the total decommissionning project of the nuclear facilities at the Risø National Laboratory on an iterative basis by means of the ”Successive approaching calculations –principle” supported by the Programme ”Futura Nova” and facilitated by Lichtenberg&Partners consultants. This principle gives a good possibility to identify and rank the decisive factors of uncertainty.

5.2 Estimated and actual costs for the decommissioning of Reactor DR1

The DR1 research reactor was stopped permanently in year 2001, and it was decided to start immediate planning of the decommissioning.

The reactor was a small “University reactor” with a thermal power of 2 kW, used mainly for basic reactor physics experiments and for educational purposes. It is briefly described in Sections 5.2.1 – 5.2.3.

As a part of the description of the project for the decommissioning of the research reactor DR1 an estimate of the total costs were carried through (cf Section 5.1 and [30]).

The total project was broken down in sub- projects, and the project group discussed the necessary man hours and expenditures related to the sub projects, based on the group members' experience from related work operations in the past. The hourly cost rate was calculated as a weighted rate, taking into account the composition of the necessary work force i.e. technician or engineer, and furthermore took into account an estimate of the distribution between external- and internal workforce hours, as described in the calculation scheme in Table 5-1.

At present (i e December 2005) the main part of the DR1 decommissioning project has been finished- the final radiation survey still remains. (A general description of this decommissioning project can be found in [57].)

Therefore a summing up of the actual costs has been performed as shown in Table 5-2.

Some of the tasks in the actual project were carried out in an order different to that shown in the original plan, and the activities were similarly accounted otherwise. This has been marked with notes a, b, c, etc. in Table 5-2.

Some estimated costs (plastic tent around the biological shield during demolition, demolition of the reactor building, several health physics radiation measuring equipment, waste registration system) have been omitted or accounted for outside the DR1 project and consequently have been removed from the original cost estimate as they were shown in Table 5-1.

It should be noted that as well the estimated costs, as the actual costs are without overhead.

If the external costs about 2.5 million Dkr are subtracted, the total costs of the project are about 2.9 million Dkr, which primarily are internal wages and costs for concrete containers.

If overhead of 112% is added to this amount we get internal costs of 6.1 million Dkr which added to the external costs of 2.5 million Dkr brings the total project costs to 8.6 million Dkr.
As can be seen, the total actual costs at present only sums up to about 5.4 million Dkr, compared to an estimated total cost of 7.3 million Dkr. For the still unfinished tasks the estimated costs have been used in the total summation.

The difference between estimated- and anticipated actual costs thus is about 1.9 million Dkr or 26% lower than the estimated total project costs. A deviation of 26% is within the usual interval of plus and minus 25%-30%, which normally is considered to be the uncertainty of an initial cost estimate of a decommissioning project.

Table 5-1. Costs for decommissioning of DR1 estimated before the start of the project.

1 working week = 5 working days	F1= DKK 247	Ext. Tecnician	F2= DKK 216	F= DKK 224	F = (1/4 F_1 + 3/4 F_2)
1 working day = 7,4 hours	E1= DKK 380	Ext. Engineer	E2= DKK 322	E= DKK 337	E = (1/4 E_1 + 3/4 E_2)

Activity	F/E	Number of persons	Working time in man-days	Hourly salary	Calendar time		Manpower expenses	Acquisitions + External assistance	Total cost	Accumulated cost	Remarks
			Days	DKK	Weeks	Days	DKK	DKK	DKK	DKK	
Flushing of fluid level meter (has been completed)	E	1	10	337	2	10	24 901		24 901	24 901	
Plan for removal of fuel solution in DR 1 (J.nr.: RD-2001-412-1-Dok. 3, Rev. C)											
Planning	F	1	70	224	12	60	115 903	120 000	609 418	634 319	4 Containers, 4 lead flasks and 4 carts
	E	1	150	337			373 515				
Removal of fuel solution (has been completed)	F	1	20	224	8	40	33 115		132 719	767 038	
	E	1	40	337			99 604				
Flushing of primary system (has been complete	F	1	20	224	8	40	33 115		82 917	849 955	
	E	1	20	337			49 802				
Determination of Sr-90 content in core solution								20 000	20 000	869 955	NUK
Clearing and removal of sources etc.	F		130	224	6	30	215 248		464 258	1 334 212	
	E		100	337			249 010				
Removal of recombiner	F	3	30	224	3	15	49 673	10 000	139 376	1 473 588	NUK incl. Nonbøl (10000) +
	E	3	30	337			74 703	5 000			Misc. Accessories (5000)
Removal of control- and safety rods	F	3	30	224	3	15	49 673	50 000	149 475	1 623 062	NUK incl. Nonbøl (20000) +
	E	3	20	337			49 802				Flask (30000)
Removal of reflector and core	F	4	160	224	8	40	264 920	45 000	524 128	2 147 190	Graphite analysis by NUK
	E	3	80	337			199 208	15 000			Special tools
Removal of remaining parts of the primary system	F	3	60	224	4	20	99 345		174 048	2 321 238	
	E	2	30	337			74 703				
Removal of cooling system	F	3	30	224	2	10	49 673		99 475	2 420 713	
	E	2	20	337			49 802				
Cleaning of the reactor- and recombiner caves	F	4	80	224	3	15	132 460	20 000	177 361	2 598 074	Cleaning agents + vacuum cleaner (20000)
	E	2	10	337			24 901				
Detailed characterisation of activity in shielding and reflector tank	F	2	50	224	12	60	82 788	20 000	292 194	2 890 267	Bore samples
	E	2	60	337			149 406	40 000			NUK
Detailed planning of demolition of shielding	F	1	15	224	6	30	24 836		99 539	2 969 806	
	E	1	30	337			74 703				

Table 5-1. Costs for decommissioning of DR1 estimated before the start of the project, continued.

Spot tests in reactor building	F	2	60	224	12	60	99 345		161 598	3 131 404	
	E	1	25	337	5	25	62 253				
Concrete containers, 3 pcs								120 000	120 000	3 251 404	
Demolition of shielding	F	3	120	224	8	40	198 690	500 000	998 294	4 249 698	Plastic tent (500000)
	E	1	40	337			99 604	200 000			Demolition and removal of reactor block
Cleaning and control measurements prior to breaking up the floor	F	3	60	224	3	15	99 345	250 000	399 147	4 648 845	Radiation monitor (mobile for floor) (25000
	E	1	20	337	2	10	49 802				
Disconnection of supplies	F	3	30	224	2	10	49 673	50 000	124 574	4 773 418	Transformer, electricity, water, sewer (5000
	E	1	10	337			24 901				
Release measurements of buildings	F	2	30	224	12	60	49 673		111 925	4 885 343	
	E	1	25	337			62 253				
Release measurements of reactor block	F	2	20	224	2	10	33 115		58 016	4 943 359	
	E	1	10	337	2	10	24 901				
Demolition of buildings	F	1	5	224	1	5	8 279	500 000	508 279	5 451 638	Contractor
Survey of areas	F	2	60	224	8	40	99 345	100 000	249 147	5 700 785	Bore samples
	E	1	20	337			49 802				Analysis
Measurement equipment for AHF (Applied Health Physics)								260 000	260 000	5 960 785	2 contamination detectors (100000), hand- and clothes monitor (1600000)
AHF education (for release measurements, 3 weeks)	F	11	88	224	3	15	145 706		220 409	6 181 194	AHF internally
	E	4	30	337			74 703				
Bathing- and changing facilities								300 000	300 000	6 481 194	Container with shower- and changing facilit
Tagging and registration of materials	F	1	100	224	20	100	165 575	300 000	963 595	7 444 789	Registration system (300000)
	E	1	200	337	40	200	498 020				
Transportation	F	1	100	224	45	225	165 575		165 575	7 610 364	Internal transportation
Planning	F	3	175	224	45	225	289 756		1 597 059	9 207 423	
	E	9	525	337	45	225	1 307 303				

Table 5-2. Costs for decommissioning of DR1 summarised after the completion of the project.

The first column shows the corrected estimated costs for the actual sub tasks in the project (Cost est.). The second column shows the accumulated estimated costs (Sum est.). The third column shows the actual costs (Cost act.), and the fourth column shows the accumulated actual costs (Sum act.).

Decommissionning of Reactor DR1 **07.11.05 KI**

Activity	**Cost est.**	**Sum est.**		**Cost act.**	**Sum act.**
Planning and preparing	1597059			1537591	1537591
Flushing of fluid level meter	24901	1621960	a		
Core sol. Flasks and planning	609418	2231378	a		
Remov. of core solution	132719	2364097	a		
Detremination of Sr-90 in core	20000	2384097	a		
Clearing and removal of sources	464258	2848355	a		1537591
Removal of recombiner	139376			100913	1638504
Removal of control and saf. Rods	149475		c		
Removal of reflector and core	524128			321617	1960121
Removal of remaining prim.syst.	174048		d		
Removal of cooling syst.	99475		d		
Cleaning of reator- and recomb. Caves	177361			59257	2019378
Detailed caracterization of react. block	292194			0	2019378
Planning of demolition of shield	99539		e		
Contamination spot meassurements	161598		e		
Demolition of shield	998294			2025379	4044757
Cleaning and contam. survey of floor	399147		b		
Disconnection of supplies	124574		d		
Clearance meassurements of buil ilding ongo	111925			111925	4156682
Clearance meassurements of shield	58016		b		
Clearance of site ongoing	249147			249147	4405829
Health phys. Educ. Fo clearance meassm.	220409			489356	4895185
Active bath and change facilities	300000			38685	4933870
Concrete containers 3 pcs. ongoing	120000			450000	5383870
Transport of materials	165575		e		
TOTAL		**7292636**			**5383870**

Notes:
a: Actual costs included in "Planning and preparing".
b: Included in Health phys.Educ. Fclearance meass
c: Included in "Removal of reflector and core
d: Included in "Reactor- and recomb. Caves"
e: Included in "Demolition of shield"
ongoing: means the activity is not yet finished, the estimated cost has been used as the actual cost, cost, although the concrete containers has been raised in price due to preliminary bids

5.2.1 Description of the facility and surroundings

DR 1 (Danish Reactor No. 1) was a thermal homogeneous research reactor with an output of 2000 watts. The reactor was supplied by Atomics International in the USA and was commissioned in August 1957. The design of buildings and installations and the set-up of the facility were by Danish companies under the guidance of technicians from Atomics International. The location of DR 1 on the Risø site can be seen from Figure 5-2.

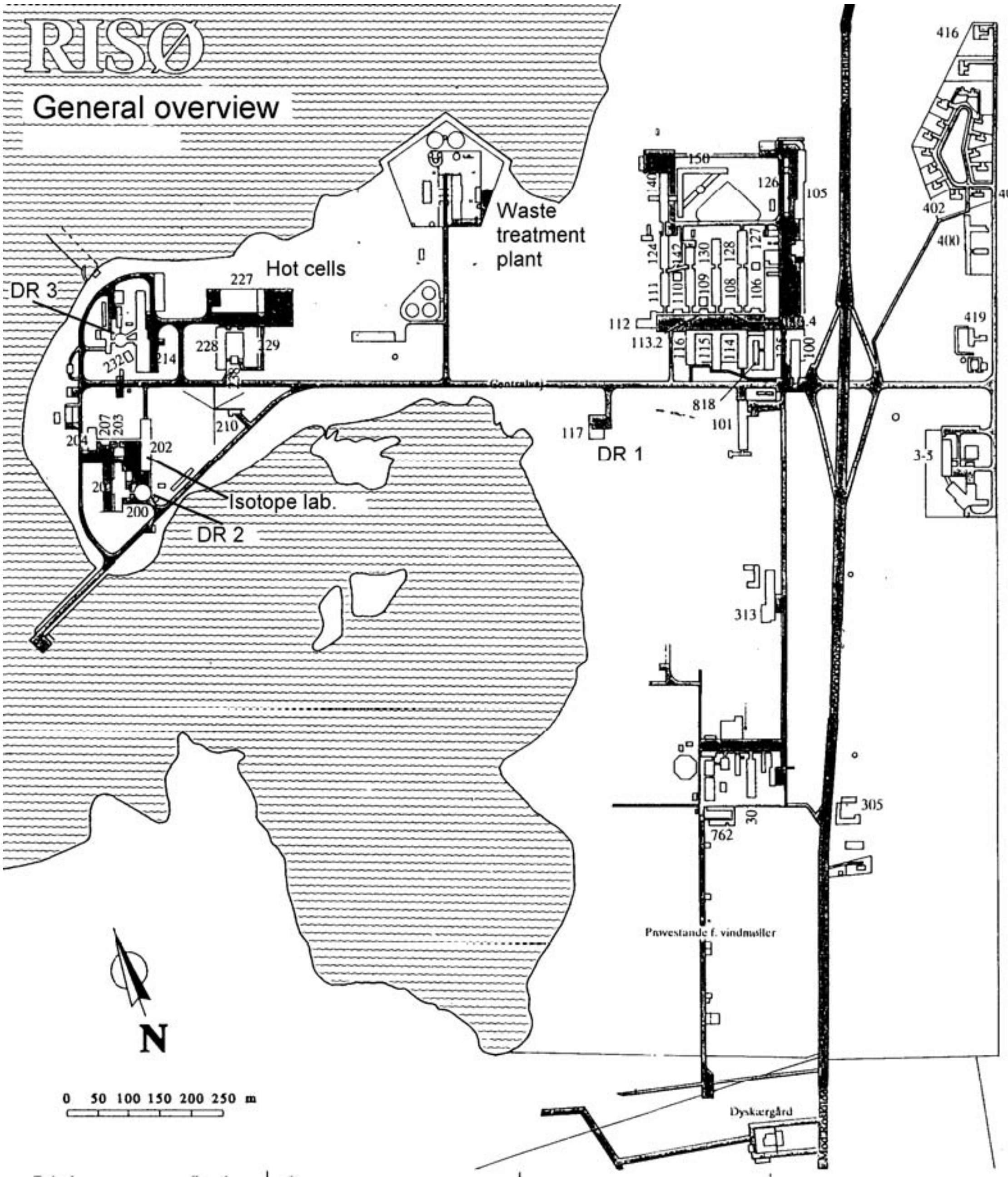

Figure 5-2 Map of Risø.

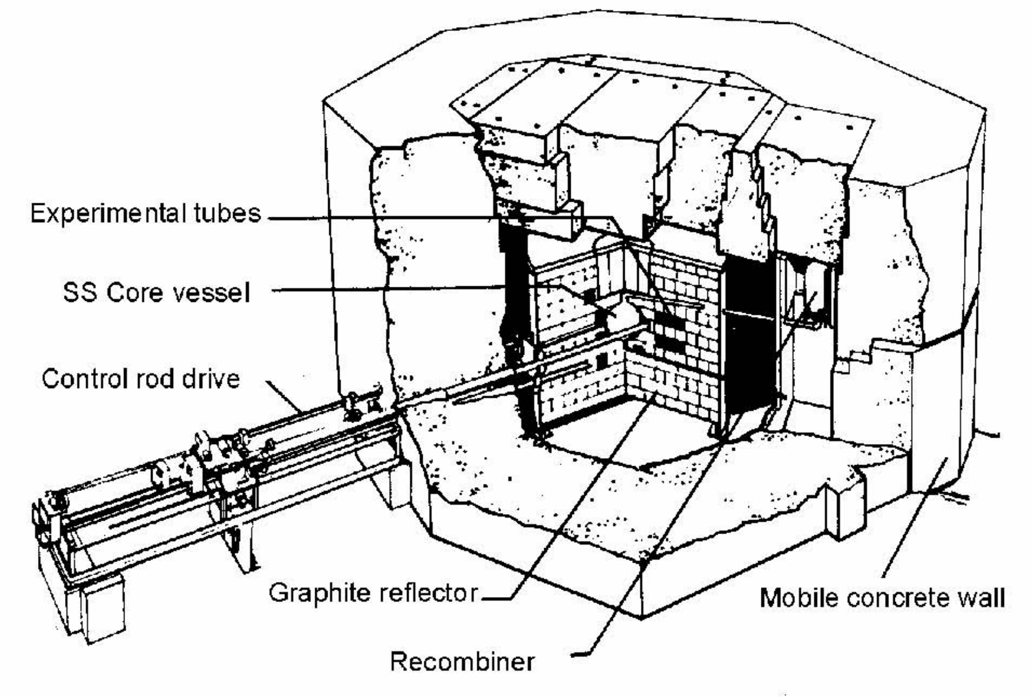

Figure 5-3. Sketch o/the structure o/DR 1.

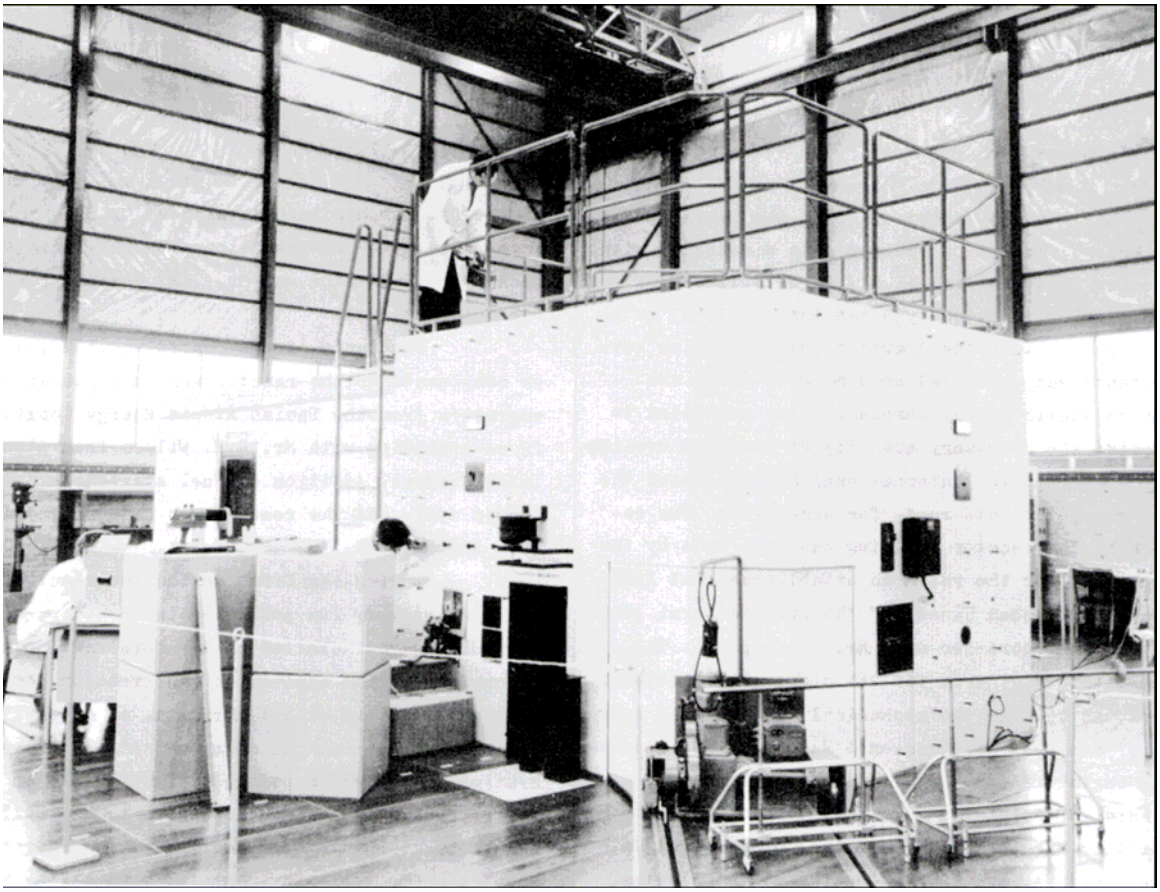

Figure 5-4. Reactor DR 1.

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Originally, the reactor was built to generate an output of 5 watts. In the spring of 1959, the output was increased to 2000 watts following the installation of cooling systems and improvement of the shielding and the reactor has been subjected to a test run at 2.3 kW. At an output of 2 kW, the maximum thermal flux in the reactor is approximately 6×10^{10} n/(cm2 · sec). The reactor used 19.9 % enriched uranium as a fuel in the form of uranyl sulphate dissolved in light water.

5.2.2 Reactor build-up

The reactor consists of a ball-shaped stainless steel vessel (the core container) with a diameter of 32 cm (See Figure 5-3.). When the reactor was started, 984 grams of U-235 was added; the solution volume was 15.5 litres. The surplus reactivity of the reactor was less than 1.5 %.

Around the core container is a graphite reactor in a cylindrical steel tank with a diameter of 1.5 m and a height of 1.3 m.

On its sides, the reactor is shielded by a 1.2 m thick heavy concrete wall, while on top the shield consists of 85 cm thick concrete blocks (See Figure 5-3. and Figure 5-4.).

During operation, water from the core solution decomposes into oxygen and hydrogen. A pipe connects the core vessel to a recombiner outside the reflector tank, in which the oxygen and the hydrogen are recombined into water that runs back to the core container. Recombination is effected by means of a platinum catalyst heated to 70-100 ºC. Together, the core container, recombiner and connecting pipe form a closed system kept at a negative pressure (See Figure 5-5.).

In 1959, the reactor was equipped with two independent cooling systems, cooling the core and the recombiner, respectively. Each of the systems consists of a primary system and a secondary system. The primary system contains demineralised water. The secondary systems are connected to the domestic water system. A thermal sensor in the core cooling system governs the water flow in the secondary system by means of a valve, thereby ensuring that the temperature remains at the desired value of between 20°C and 40°C.

The recombiner cooling system removes the heat generated in the recombiner during recombination. The water flow in the secondary system is controlled manually.

The output of the reactor is governed by two control rods and two safety rods, moved horizontally in the reflector tank just outside the core vessel. The rods consist of a stainless steel jacket containing boron carbide. Each rod governs approx.1.5 % reactivity.

The essential reactor instruments are located in the control room. The most important instruments are the four independent neutron flux channels including a period meter, as well as instruments for recording the temperature of the core vessel and the catalyst in the recombiner, as well as the pressure in the care vessel/recombiner. Furthermore, values are given for the radiation level in the ventilation pipe from the reactor block and in the reactor hall, as well as the temperature of the cooling circuits, etc.

A pipe with a 2.54 cm diameter goes horizontally through the centre of the care vessel. With the reactor running at 2 kW, the max. thermal flux in the pipe is approximately 6×10^{10} n/(cm2 · sec).

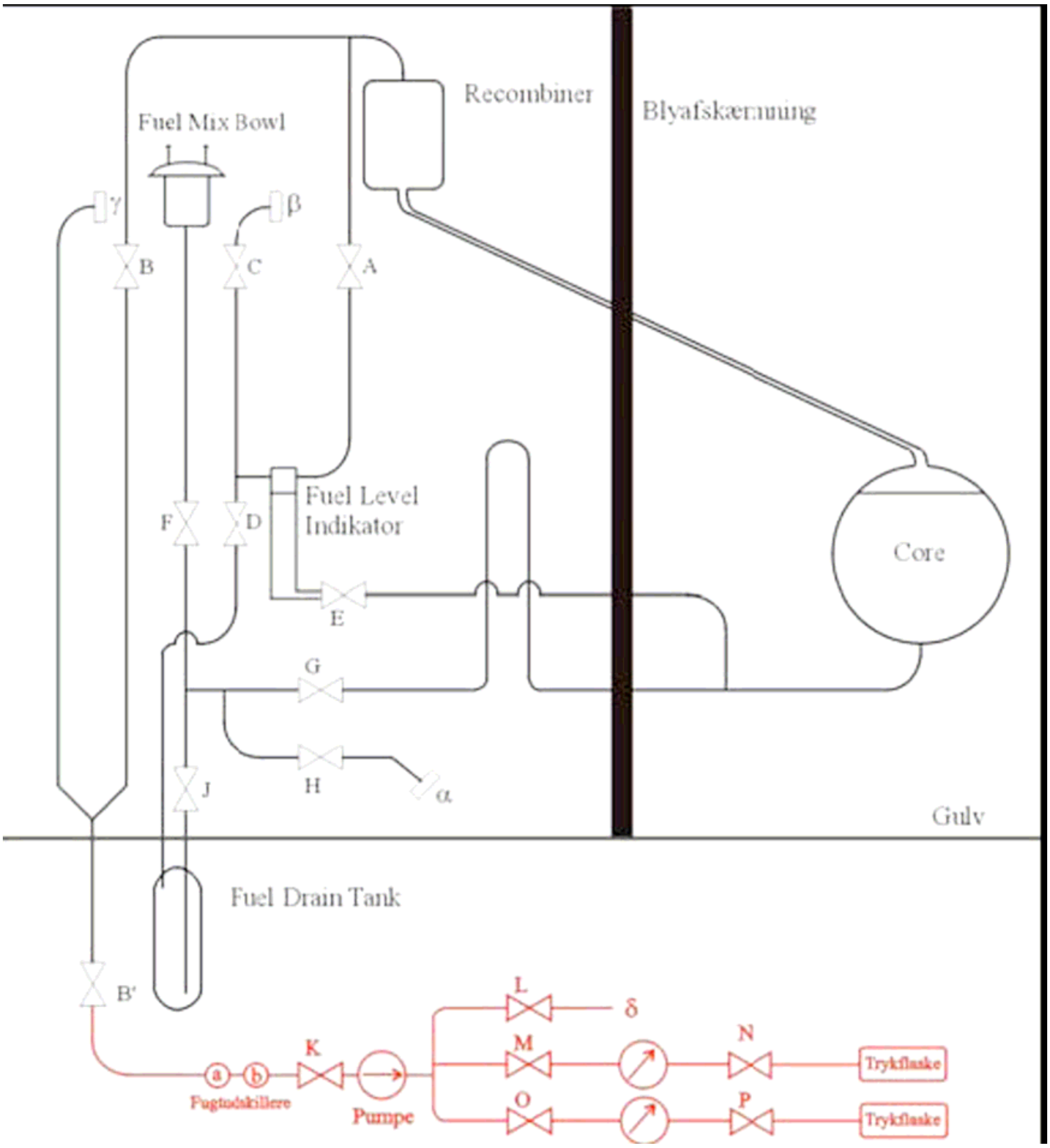

Figure 5-5. Block diagram of the primary core system.

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5.2.3 Reactor hall

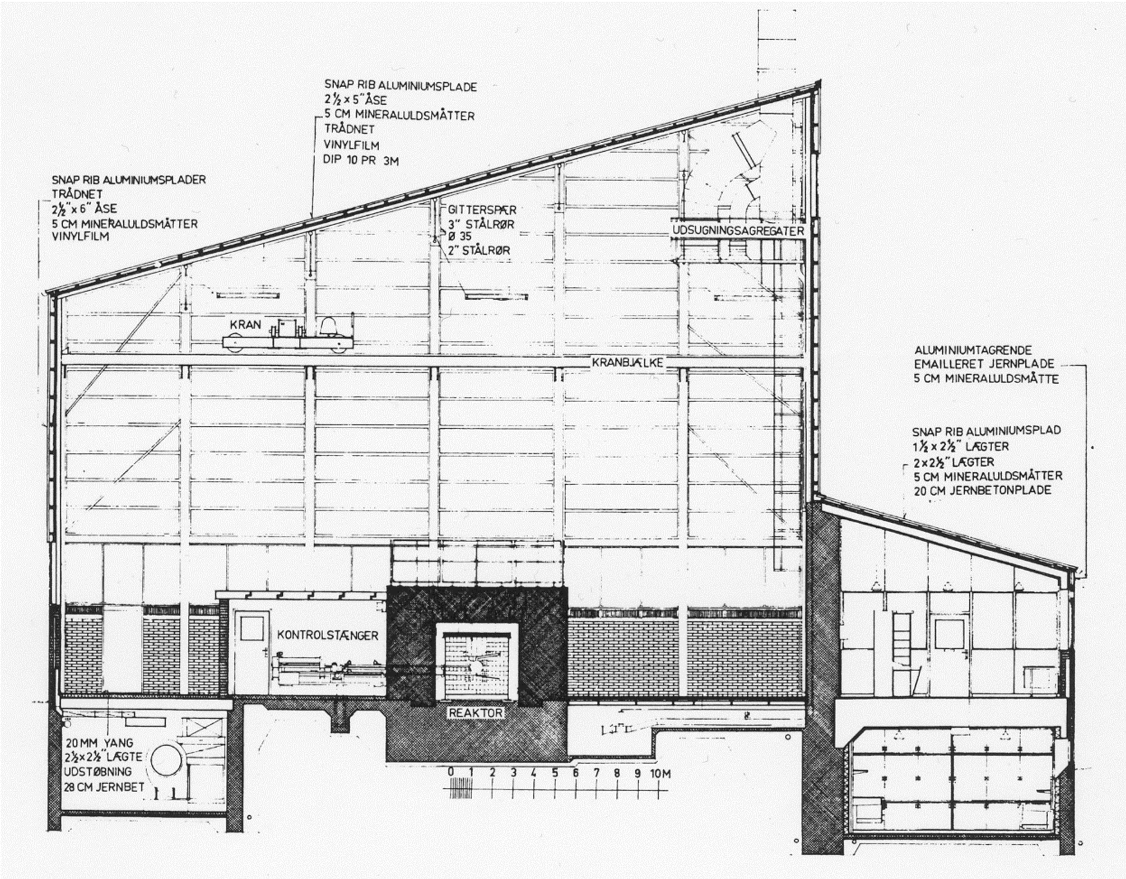

Figure 5-6 Vertical section of building 117.

The reactor building at DR 1 (see Figure 5-6.) consists of a reactor hall, a control room with an office and an entrance section, a counter room in the basement under the control room and an aggregate room for the air-conditioning system under the system end of the reactor hall (See Figure 5-7.).

The air-conditioning system blows warm air through the floor ducts along the facades and from here through ducts in the hollow parapets to injection grates underneath the windows. Under normal conditions, the ventilation was 9000 m^3/h, of which 6000 m^3/h was recirculated, which meant that fresh air intake corresponded to one exchange of air per hour (See Figure 5-6. and Figure 5-8.).

In 1960, the professional engineering journal "Ingenieren" published an interesting article about reactor DR 1 (and the two other reactors) which formed part of the background material for the planning of the decommissioning.

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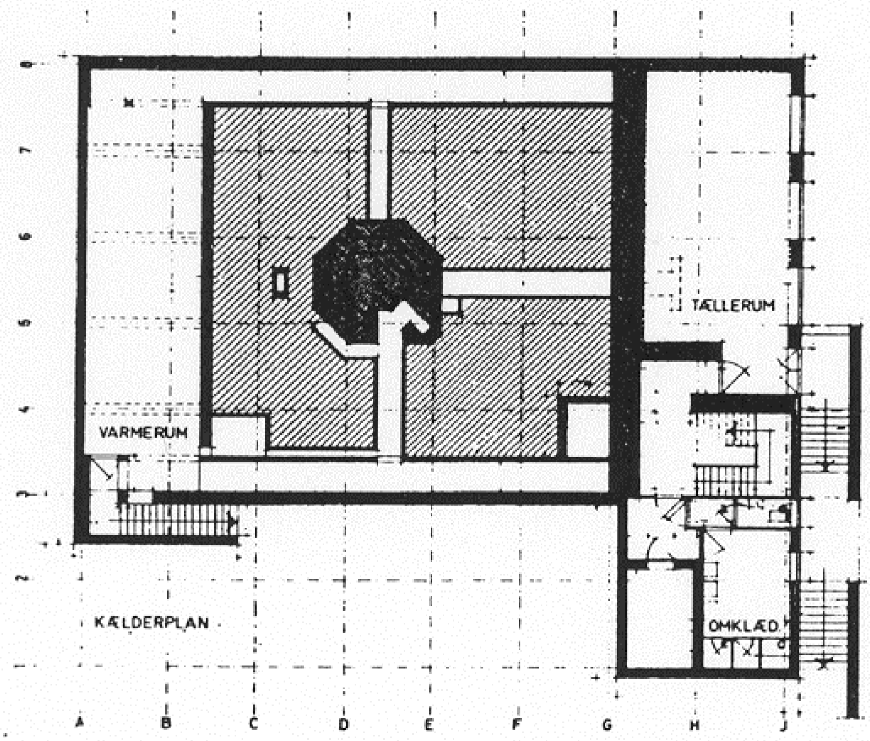

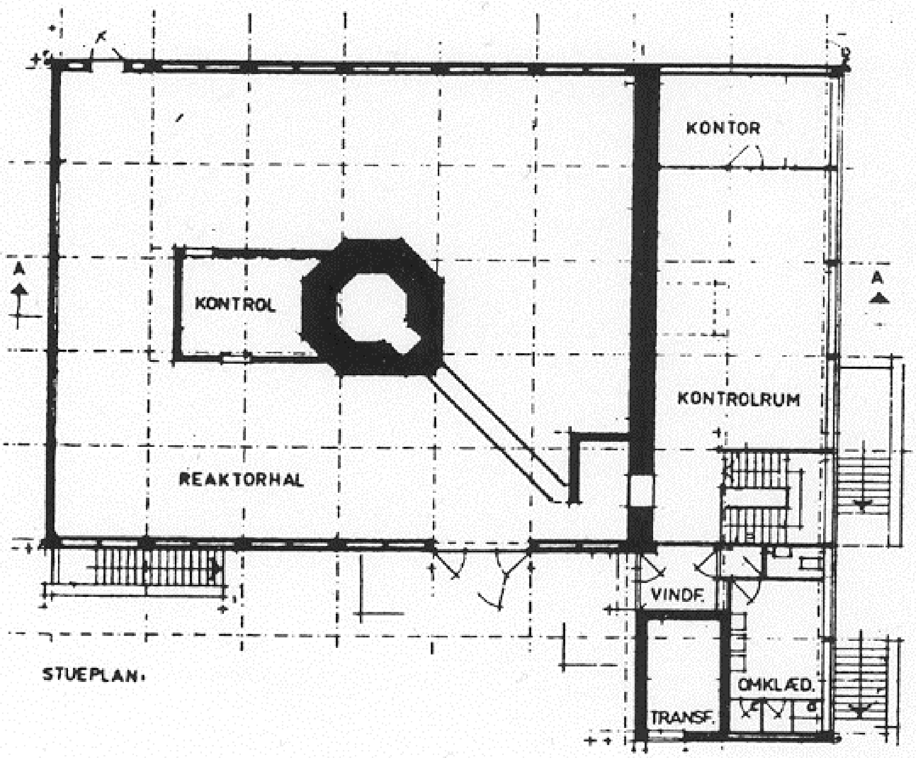

Figure 5-7. Horizontal section of the underground floor (far above drawing) and ground floor (just above drawing) of building 117.

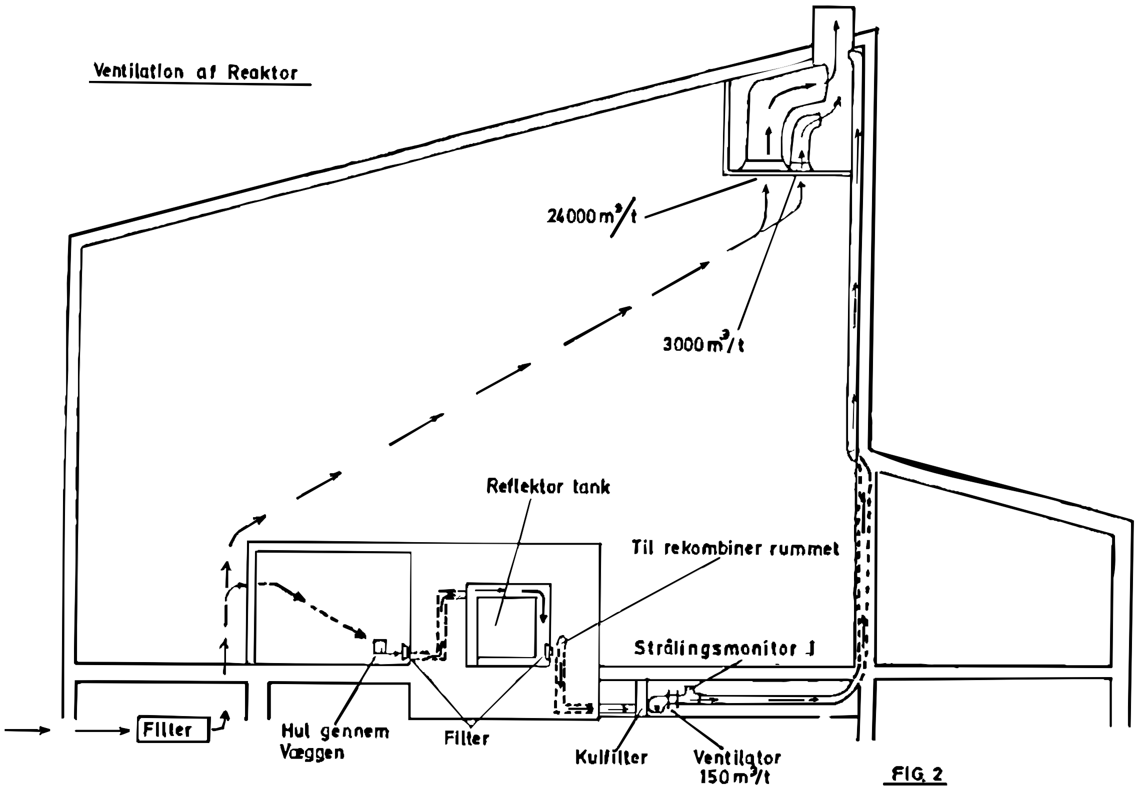

FIG. 2

Figure 5-8. Block diagram of the ventilation system.

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6 The decommissioning of Sweden's nuclear research reactor R1

6.1 Conclusion

Sweden's first nuclear research plant, R1, was located near the Royal Institute of Technology in Stockholm in an underground closed chamber. Further informationon the reactor and its operation can be found in [16], see also Appendix E. The research plant started operations in July 1954. After being used for research purposes and isotope production for 16 years and an operating time of 65000 hours, the reactor was finally closed down in June 1970.

In 1979, Studsvik suggested complete decommissioning of R1 and radiological decontamination. A radiological survey was started in May 1979, after which Studsvik made a detailed investigation for the demolition of the reactor. The preparation work began on site in April 1981 with an overview and continued until the end of October 1981.

During the planning of the decommissioning project the requirements of SSI (the Swedish Radiation Protection Authority) were the line of aim. Those requirements were meant for complete decommissioning of the plant and a "greenfield" level for the rock chamber. As a first step in the decommissioning project all the equipment in the plant hall and the areas nearby were surveyed before being handled as exempted material. As the project went on, bit by bit of the exempted material was screened and measured and then placed in Berglöv boxes, a special kind of box constructed for the purpose of transporting active waste, or placed inside the plant to be handled later on. In preparation for the exemption project the localities were divided into classified areas and non-classified areas. Thus all parts of the facility were searched and screened. Different methods were used to control the individual doses to which the staff was exposed.

A reactor plant has very little conventional equipment and structures and so the work had to be planned using special arrangements, specially constructed equipment and machines as well as different kinds of protective shields. The project experienced both drawbacks and progress. Some of the surprises that caused some problems were:

- The water pipes and lamps were in poor condition due to corrosion and the electrical equipment had to be replaced.
- When SSI changed the limits for decontaminated goods, the new limit was considerably lower than proposed from the project team so the amount of material classified as active waste increased a lot.
- Misjudgements were made about the activity in the graphite from the thermal column.
- There were problems in obtaining spare parts for the old equipment. Luckily some old spare parts had been left at the R1.

- There were problems in dealing with the decommissioning of equipment from areas that had not been classified before, which caused a lot of delay since discussions on this problem had to take place with the authorities at the end of the project.

There were also some circumstances and inventions that were important for the project and its progress:

- Much of the human capital was still accessible, from the time when the plant was in operation, and their knowledge was very valuable to the project.
- One of the advantages of the decommissioning project was that there had been no serious incidents in the course of the plant's sixteen years of operation.
- A lot of preparation work had been done when the plant was closed down.
- Transportation using the Berglöv boxes went almost twice as fast as expected.
- There were no accidents during the whole project due to the discipline among the whole staff.
- The special smear test equipment, Berthold LB2711 was a valuable help in measuring all the smear tests in the clearance project.
- The major success in this project was a newly invented machine called "MiniMax PH 250". This machine could handle the special kind of concrete in the biological shield.

The time schedule was followed and the radiological doses to the staff were under control and kept low. Studsvik was granted a total of MSEK 25 for the demolition of R1, starting in the second quarter of 1981, the demolition work lasting until May 1983. The expenses were underestimated and the budget was MSEK 21.7 instead of MSEK 25. The decommissioning project for Sweden's first nuclear research plant R1 proved to be a success financially and technically, and even the time schedule was followed almost as planned.

6.2 Introduction

It has proved to be very important to gather significant experience from different types of nuclear decommissioning projects in order to simplify the cost calculation for this kind of project. The most difficult part of these projects is estimating the cost, which is closely associated with the radiological and technical issues. Thus it is most valuable to gather experience and data from other projects on radiological, technical and financial aspects. It is most important for future decommissioning projects to have access to these different kinds of experience. Only a few nuclear facilities have been decommissioned completely. The decommissioning project for Sweden's first nuclear research plant R1 proved to be a success financially and technically and even the time schedule was followed almost as planned. The experience from this project may be very valuable for other projects in the future even if the conditions vary from one facility to another.

6.2.1 Background

Sweden's first nuclear research plant, R1, was located near the Royal Institute of Technology in Stockholm in an underground closed chamber. The research plant came into operation in July 1954. It had a rated effect of 1 MW. After being used for research purposes and isotope production for 16 years and an operating time of 65000 hours the reactor was finally closed down in June 1970. The reactor was cooled and moderated by heavy water. Metallic, natural uranium was used as fuel. After closedown, the fuel, heavy water and ion exchange system were transported to Studsvik. In the second half of 1970 work started on sealing the plant. A final radiological scan had been made before the plant was closed in 1971. The plant was sealed for eleven years before the R1 decommissioning project started in May 1979.

In 1979, Studsvik suggested complete decommissioning of R1 and radiological decontamination. A radiological survey was started in May 1979 and after this Studsvik started a detailed investigation for the demolition of the reactor. The preparation work began on site in April 1981 with an overview of the electrical installations and continued to the end of October 1981.

Studsvik was granted a total of MSEK 25 for the R1 decommissioning project. The project started in the second quarter of 1981 and the demolition work lasted until May 1983. The expense was underestimated and the budget was SEK 21.7 instead of MSEK 25 . The time schedule was followed and the radiological doses to the staff were under control and kept low. This report deals with the decommissioning of Sweden's first nuclear research plant R1 from three different points of view: radiological survey, technical planning and cost calculation.

6.2.2 Purpose

This report is for the purpose of analysing three main issues associated with the R1 decommissioning project. The three issues are: radiological survey, technical planning and cost calculation. There are some questions concerning these issues: What were the experiences during the project as regards those three main issues? Were there any positive surprises and/or negative surprises? What were the main criteria for this project to become a success?

6.2.3 Critical treatment of sources

During the major R1 decommissioning project at least 30 different kinds of reports were written. In this report mainly one of them is used as a reference, the Studsvik Report : *Rivning av forskningsreaktorn RI Stockholm* [58]. The report is actually a summary of the whole R1 decommissioning project .

This report is intended as an outline and the material and facts are gathered from the report mentioned above unless another source is referred to.

To provide the reader with the right background a conclusion in English of the Studvik Report Studsvik/NW-84/627:*Rivning av forskningsreaktorn RI Stockholm* [58] is attached to this report as a supplement.(Supplement 1).

6.3 Radiological survey

Initially a radiological survey was carried out of the whole site in 1979. (Supplement 2).
The whole project was planned in three different phases:

- Radiological survey of the whole facility.
- Planning for the segmentation of components and estimate of the individual doses.
- Planning how to handle the waste [59].

Later on a thorough schedule was made for the decommissioning work. This was done by Studsvik to obtain an estimation of the decommissioning project.
The preparatory work started off in April 1981. A special heavy-duty filter had to be installed for the air conditioning. Monitoring equipment to control the personal doses had to be built and protective equipment for the staff had to be arranged.

The individual doses were expected to be as low as 4 manrem because the activity in general in the facility was estimated as being low [60].

A lot of equipment to measure the activity on the localities and in material had also to be set up. All areas including the reactor plant had to be sorted into classified and non-classified areas. Special packaging for all the active waste and transportation of this material to Studsvik had to be prepared.

6.3.1 Preparation

Before the decommissioning work started all the localities were classified areas. Arrangements for stepover limits, dressing rooms, monitors for individual surveys and showers were made.

A study was made of how to measure the activity inside the Berglöv boxes. A Berglöv box was a special package for radiological waste.

Some concrete was extracted from the biological shield by drilling and tests showed that there was contamination only 25-30 cm from the inner part of the biological shield, as well as in some of the canals inside the shield. (Supplement 3).

Mapping

The preparatory project survey included the following:

- The rate of activity was measured on the spot by dosimeter etc.
- Measuring of the activity inside the graphite, the graphite that had been taken from the plant’s thermal column.

- Measuring of the boron guts taken from the plant's thermal column.
- An estimate was also made for the active/contaminated waste as follows [59]:

Carbon steel/ aluminium / lead	c. 110 tonnes
Cadmium sheet	c. 5 "
Graphite	c. 68 "
Concrete	c. 75 m^3

The activity in the construction was roughly estimated to:

- 1TBq CO-60
- 0,2 GBq Cs-B4
- 25GBq Eu-152
- 5GBq Eu-154

There was no evaluation of the amount of C-14 inside the plant at the first examination. The so called "Wigner-effect" was studied but there was no risk of spontaneous generation from that special phenomenon.

Method

During the planning of the decommissioning SSI's (Swedish Radiation Protection Authority) requirements were the line of aim. Those requirements were intended for complete decommissioning of the plant and a "greenfield" level for the rock chamber. Clearance levels were also proposed for the material and fromthis an estimate could be made of the amount of material needed to be stored in Studsvik and how much could be placed on a dumpsite.

The clearance levels fixed by the SSI were:
- < 5 kBq/kg material
- < 1 MBq/m^3 liquid

The levels fixed by the SSI were lower than expected and therefore the amount of active material to deal with was more than first estimated by Studsvik.

6.3.2 Radiological ongoing work

When all the localities including the reactor plant were divided into classified and non-classified areas the decommissioning project could be started.

Radiological survey during decommissioning

As a first step in the decommissioning project all the equipment in the plant hall and the areas nearby was surveyed before it was handled as exempted material. As the project went on bit by bit material from the plant was screened and measured before it was placed in Berglöv boxes or placed inside the plant to be handled later on.

The work on cutting up the reactor vessel was done down in the uranium container, where the reactor vessel was placed. (Supplement 4).

After demolishing the top of the plant the surface of the inside of the reactor vessel was screened.

After the whole decommissioning work on the reactor vessel a radiological survey was made inside the graphite reflector. The same procedure was followed with the thermal column although the lead door had first been replaced. The dose rate was found to be considerably higher than expected and therefore the procedure for handling the graphite material had to be reorganized. This was all due to the fact that the test material taken from the graphite column did not represent the total activity properties.

The whole work of decommissioning the graphite reflector gave a collective dose of 49 millimanSv divided between 8 persons. (Supplement 5).

After dismantling the graphite reflector another radiological survey was made inside the biological shield. The maximum dose-rate was 15 mSv/h of the surface. Thereafter the cadmium sheet metal was decommissioned and together with the mechanical components in the biological shield, this element of the project caused the greatest collective dose, a total of 56 millimanSv divided among 10 persons.

The concrete from the biological shield was tested during the preparation work, which made it easier because now the clean concrete could be torn down to prevent cross contamination.

The demolishing of the biological shield caused a collective dose of 16 millimanSv divided among 15 persons.

Demolition of the engine room equipment and cooling tower and the equipment of the laboratory areas went on without any negative surprises. All material and areas were thoroughly screened for contamination. In particular the cavity bellow the biological shield was measured and it was found that even more concrete had to be removed to get rid of all the activity.

Cleaning of the facility for clearance

SSI (Swedish Radiation Protection Authority) had fixed a limit for clearance of 8kBq/m^2. At this point no more cleaning was necessary.

Before the clearance project for the localities, all of them were divided into classified areas and non-classified areas. Thus all localities in the facility were searched and screened.

A vacuum cleaner was used in the reactor hall and nearby localities, and the surfaces were wiped. Radiological screening was again carried out first roughly and then more thoroughly, following a special schedule.

All surfaces in classified localities were checked into squares measuring one m² each. All the squares were numbered and smear tests were taken from all of them. They were evaluated for general beta as well as for tritium. There were also screenings of the surfaces from a portable instrument.

The non-classified localities were screened with a portable instrument and two smear tests had been taken from each.

All results had been recorded, archived and stored at Studsvik. The SSI has been given copies of all these records.

A lot of concrete was found to be still contaminated and had to be taken away. After another round of cleaning all surfaces they were washed with cleaning agent. The work went on like this in the whole facility and on the 10th June 1983 the classification into activity zones was no longer necessary.

An estimation of the activity still present was made from the smear tests taken from all the localities. Those turned out to be very low.

Those tests were batched and classified by gamma spectrometric instrument. All localities were controlled by smear tests and by measuring total beta. Some of these tests were batched and examined for type of nuclide and activity with regard to gamma nuclides. The batch tests showed very low values and thus that surface contamination was very low.

Because of the decommissioning of R1, SSI had required samples and analyses of the soil from the surrounding area. Samples were taken 50-1000 metres from R1. No high levels of activity were found.

Equipment and methods for individual dose control

Different methods were used for the control of the individual doses to the staff.

Individual- dosimeters, TDL (Thermoluminescence), were used for the staff at R1. The dosimeters were read once a month. For special tasks working-dosimeters were used to survey these special operations. This was requested by SSI. The background radiation could be separated using special dosimeters.

Whole-body radioactive contamination monitor: A monitor called Herfurth type 1361EC.

Whole-body counter: At Studsvik with the special whole-body counter called HUGO. This was done when the staff were occupied with critical tasks. After some critical tasks an internal *contamination count* was made on the staff. A total of 66 whole-body readings were made at Studsvik in the HUGO.

Blood tests were performed on the staff before and after the decommissioning of the Cd-walls in the biological shield.

The total dose to the staff participating in the decommissioning of R1 was 142 millimanSv, divided among 25 persons as follows:

1 person	28 mSv
6 persons	10-20 mSv
8 "	1-10 mSv
10 "	0.1-1 mSv

In the course of some parts of the project the staff used dosimeters to obtain information about the dose on that particular occasion, and the results are shown in Table 6.1.

Tabel 6-1. Compilation of the data from the dosimeters on the project staff.

Elements of work	**Collective dose (mmanSv)**	**Persons**
Lifting the tank and cutting the flange	4.4	7
Cutting apart the tank	6.4	5
Demolishing the graphite reflector	49	8
Demolishing mechanical equipment inside the biological shield	56	10
Demolishing the biological shield	16	15
Radiological survey	4.4	4
Transport	3.5	16
Lifting the tank and cutting the flange	4.4	7
Sum	**140**	

Radiological classification

Air

During the whole demolition project a HEPA-filter was installed in the air channel. This channel was connected with the chimney. The filter was changed every week and the dose rate of the surface of the HEPA-filter (special kind of fresh air filter) was controlled and analysed in a gamma spectrometer frequently. The total outflow of activity was 0.4 kBq/day during the 40 week period. Other arrangements made to prevent activity into the air were:

- Special equipment (Counting Ratemeter, RM-51M) was placed to control the air in the room next to the hall where the plant was situated.
- Breathing mask filters were controlled.
- Special kinds of portable equipment monitored the air.

During critical phases special tents made of plastic material were put together and used as protection from any spread of activity. There were special arrangements with extra filters and special arrangement that took care of air in special spots plus special filters.

Water

The water from the classified areas was separated from the water from showers and lavatory-basins. Thanks to this method the last mentioned category of water never exceeded an activity level of >50 kBq/m^3, 20 points below allowed limits. The total discharge of this kind of water was approx. 150 m^3. There was no discharge of water with an activity level of >50kBq/m^3. The upper limit allowed was <1Mbq/m^3 if the water was to be channelled to the wastewater vent. Water with >1MBq/m^3 was transported to Studsvik.

Waste control

All sorts of waste and recycling material produced from R1 were measured and registered.

A special kind of steel boxes, called Berglöv boxes, 600 litres; were used for storing the waste. Each box was registered, numbered and the activity and nuclides were measured. The equipment used for this purpose was a gamma spectrometer, Canberra S-85 and as detector GeMac-detektor (GeMac=Germanium Multi Attitude Cryostat). The calculations of the activity were made by a HP-97 calculator. The Berglöv boxes were measured from two different directions, thus making it possible to make a calculation of the gamma radiation in the material.

All the packages were controlled by smear tests and screening instruments before they were taken from the site. The smear tests were measured in equipment with beta detector. The detection limit was 2kBq/m^2. If the surface contamination exceeded 8 kBq/m^2 after it had been wiped off, the packages were sent to Studsvik.

Recycling material was carefully screened and no material was cleared if the detection limit 2 kBq/m^2 had been exceeded.

The measurable limit was fixed to 5kBq/kg, the same limit fixed for low active concrete at Studsvik's dumpsite. First there were a lot of problems due to the high sensitivity of the radiation detector and its equipment to vibrations and noise. The equipment was replaced and it was all sorted out. The equipment was also protected from the background radiation by 5 cm lead.

In order to gauge the average activity inside the concrete a small piece was taken for control.

All waste with an average of < 5kBq/kg was placed at the dumpsite at Studsvik and covered by at least 1 meter of earth.

Waste with an average of >5kBq/kg was placed at a separate location at Studsvik.
All the documentation dealing with waste management was stored and the waste placed in Studvik has been registered in special files.

Studsvik got permission from the Swedish Nuclear Power Inspectorate, SKI, to transport the material from the demolition of R1 to Studsvik. Active waste transports followed the European Agreement on the International Carriage of Dangerous Goods by Road (ADR). When the limits of the ADR were exceeded special permission for transportation from R1 had to be granted by SSI.

A form for external radiological transport had to be issued for all transportation.

Screening equipment

A Nuclear Enterprise PCM5 with double scintillation detector for both alfa and beta was used for local controls of contamination. The sensitivity was 4 kBq/m².

A radiation monitor specially designed for floors was used for large floor areas, FH 545. Sensitivity 30 cpm kBq/m². A PCM5 was used for small areas. Sensitivity 0.67 cps kBq/m².

Smear tests were also used as a complement at the clearing and the Berthol LB 2711 was most successful. Its sensitivity was 2 kBq/m². The GM-detector was also used for the smear tests. This equipment had a sensitivity of 10/100 seconds at each kBq/m²(Eu-152).

A gamma spectrometer, including 17% HPGE detector and 4000 channel Canberra 85 analysis equipment were used for screening surfaces.

The activity and nuclides were measured for each Berglöv box. The equipment used for this purpose was a gamma spectrometer, Canberra S-85 and as detector GeMac-detektor (GeMac=Germanium Multi Attitude Cryostat). The calculations of the activity were made by a HP-97 calculator.

Tritium- and gamma spectrometric classifications were made at the laboratory at Studsvik.

6.4 Technical Planning

A reactor plant has very little conventional equipment and structures. The biological shield inside R1 was made out of a special kind of concrete. The work had to be planned with special arrangements and protective shields. There also had to be plans for working at a distance, due to the radioactivity. Therefore a lot of special machines and arrangements had to be made. Some of the dismantled parts and equipment from the plant were extremely heavy and required special transportation.

6.4.1 Planning

Some technical preparations were made when the vessel was closed down. The vessel was drained of heavy water, which was transported to Studsvik. The heavy rods were placed in the uranium well for cooling. The plant was lined to prevent activity from leaking out. There was also a flood alarm system installed.

Before the practical decommissioning work started all those involved worked thoroughly on a project plan. This plan was carefully worked out and turned out to be very helpful throughout the project. It was a comprehensive plan dealing with the radiological work as well as the demolition work, transportation, organisation, time schedule, costs and environmental security.

6.4.2 Preparation

To prepare for the heavy transports the floor had to be reinforced in some places and a special wagon had to be constructed for the heavy components.

A special saw that could be manoeuvred remotely was constructed for cutting apart hot radiological components.

Equipment that could handle graphite blocks remotely, as well as equipment that could remotely demolish parts of the flanges was constructed.

There were a lot of tools designed solely for some special elements of the project. After a thorough examination of the electricity system it was found that several parts had to be replaced as well as some associated electrical equipment.

6.4.3 Technique for the demolition part of the project

All loose equipment was screened and transported out of the reactor hall and localities nearby. Engines and gears from the reactor construction were dismantled. The reactor hall was emptied. The uranium well was opened and its heavy lid was placed in a corner of the reactor hall. The uranium well was then filled and prepared for the reactor tank later on. This part of the project ended in cleaning and painting of the floor of the reactor hall. This was to prevent decontamination later on.

Work on the reactor tank

A major part of the work was how to deal with the reactor tank. The two big lead doors from the thermal column were taken away and using a specially constructed wagon, four blocks of 1 cm thick concrete, the previous radiation shield inside the thermal column, could be taken out. Using the same wagon a thick graphite pin inside the graphite column could also be taken away. All of the six lids were placed behind a wall of concrete blocks in a corner of the reactor hall and the first and most contaminated lid was placed underneath and covered by the others.

Working from a distance with a special saw the seven hot flanges could be cut loose from the reactor tank. The remote saw was placed behind a lead shield on the specially constructed wagon mentioned before. After cutting loose the hot flanges it was possible to lift the reactor tank out of the biological shield by means of an overhead crane. There had to be four more types of technical action before the reactor tank at last was placed inside the uranium well. In this position a lid from the biological shield covered the tank and this lid could also act as a platform during the work on dismantling the tank.

Some air conditioning arrangements had to be made before the major work of cutting apart the reactor tank could start. The reactor lid and five stainless flanges were dismantled and the lid could be taken up to the hall and placed on the wagon for transportation of heavy goods. From there it was cut apart by the remote saw, which was placed behind a radiation shield, and placed in Berglöv boxes for further transport. The flanges from the tank could be handled in the same way when they had been cut from the tank by a plasma cutting tool. (Supplement 4).

The plasma cutting tool was also used to cut apart the upper part of the tank. The lower part of the tank had to be cut with a saw.

Dismantling equipment inside the biological shield

The work on dismantling equipment from the biological shield went on well apart from a minor piece of equipment being corroded fast. In order to be more effective and reduce handling time a conveyer belt and some more equipment were obtained. By the thermal column the graphite reflector was dismantled and the conveyer belt could be placed in the centre of the biological shield. The graphite block could be placed in Berglöv boxes directly. For a short time one person had to loosen the blocks by hand.

The cadmium-and aluminium plate was dismantled by hand. They were folded together with the cadmium plate, covered by the aluminium plate and thereafter placed in Berglöv boxes. Other mechanical components inside the biological shield, such as the inner lead door, were cut and/or hatched down. Flanges were left behind for the moment but covered with lead blocks and lead carpets.

Dismantling of the biological shield

A newly invented machine called “MiniMax PH 250” was used to demolish the biological shield (Supplement 6). This was good both as regards radiological matter and the economical aspect. This machine could handle the special kind of iron ore concrete from the biological shield that was both soft and leathery. The MiniMax was driven by electricity and manoeuvred remotely by just one person. It hatched down the concrete with a hydraulic hatch hammer and the concrete fell right down into a Berglöv box. The hydraulic hatch hammer was also equipped with a jet and could spray water mist over the concrete dust and fix it on the spot. The reinforcing iron and beams, however, were cut off by fusing burner. The machine was so small that it could fit into the elevator. The technique of minimising contaminated concrete was to take away the clean concrete first so as to start from the outside to prevent cross contamination.

At special critical phases of the job with the biological shield it was necessary to build up a tent to protect against dust from concrete with high contamination. Some parts of the biological shield had surface dose rates as high as 20 mSv/ so had to be cut by a fusing burner working at a distance. Special air conditioning and extra evacuation inside a tent were arranged here.

Dismantling of equipment inside the engine house, cooling tower, laboratory areas etc

Special air conditioning and extra evacuation were set up when working in the laboratory areas. The MiniMax machine was also useful in all parts of the construction where walls and other parts were made out of general concrete and cast iron. They were pulled down and by the MiniMax and the parts were directly placed into Berglöv boxes and after measuring the activity they could be transported to Studsvik.

The big stainless waste reservoirs from the laboratory areas were closed and sent to Studsvik intact. In other areas the equipment was dismantled without any further problems.

The sewers in the facility were dismantled. Just one sink was left behind to take care of washing water. The waste water reservoir for showers and washing was also left.

6.5 Financial risk identification

The initial examination was comprehensive and dealt with estimates for the radiological work, transportation, organisation, time schedule, costs, collective doses and environmental safety. This examination was thorough and there was also a thorough lay-out dealing with the dismantling work that meant a lot to the progress of the decommissioning project and prevented drawbacks.

6.5.1 Progress

Since only eleven years passed from when the reactor was finally closed down in June 1970 until the start of the decommissioning project in May 1981 much of the human capital was still accessible, from the time when the plant was in operation, and their knowledge was very valuable to the project.

One of the advantages for the decommissioning project was that there had not been any serious incidents during the sixteen years the plant had been in operation.

A lot of work had been done when the plant was closed down, which was an advantage for the decommissioning project. For example the budget for the decommissioning project did not have to deal with the costs for drainage foil of the heavy water since this had already been transported to Studsvik. The fuel rods had been placed in the uranium well for cooling and thereafter they had been transported to Studsvik. The biological shield had been sealed in order to prevent any radiation leakage. In 1971 a radiological survey was made of all the localities.

During the whole project everything was noted in a journal which has been of great use. A reference group with members from the authorities and power industry was involved in order to exchange experience.

Transportation using the Berglöv boxes went almost twice as fast as expected. With a special kind of lifting equipment five lorries could be loaded instead of two or three. For that reason the demolition could go on with just half the number of stops expected. Thus there was less need for the hired crane lorry and the lifting truck.

There were no accidents during the whole project due to the discipline among the whole staff. Nobody accepted carelessness about protective equipment or protective measurement. The staff had good knowledge about the instructions concerning transportation and handling of heavy goods. They had also experience of radiological work or other difficult environmental work.

It was very helpful for the management of the project that the managers had been involved in the planning of the project and the radiological survey. Their sound knowledge of the facility and the condition of the plant meant that there were no discussions as to how and when different parts of the project were to be carried out.

6.5.2 Drawbacks

In the course of deliberations with the authorities, SSI (Swedish Radiation Protection Authority) and SKI (Swedish Nuclear Power Inspectorate) the limits for decontaminated goods were fixed to the level of <5 kBq/kg for the concrete waste for it to be allowed to be placed at Studsvik's dumpsite. The limit for discharging liquid waste to the municipal outflow was < 1 MBq/m^3. This was considerably lower than proposed by the project team. Thus the amount of material classified as active waste increased a lot.

Some misjudgements were made about the activity in the graphite from the thermal column. It was first thought that these tests could be representative for all activity in the inventory but it was discovered, when radiological screening was carried out inside the graphic reflector and the thermal column, that the activity was higher than expected. Then new tests were taken from the graphite from the reflector and these tests showed a level of activity 60 points higher than assumed. This caused a delay of four weeks.

The plant had been sealed for 11 years and during this time the temperature had been 10 degrees Celsius in a very damp environment. For this reason some of the equipment was corroded fast and caused some problems and delays. The water pipes, lamps were in bad condition and the electrical equipment had to be replaced, for example.

There were problems in obtaining spare parts for the old equipment. Luckily there were some old spare parts left at R1.

During the initial examination part of the project the project team had not discussed with SSI the problems of equipment from areas not classified before. This caused a whole lot of delay because the discussions had to take place at the end of the project. There were also some delays in dealing with the evaluation of some of the measurements.

6.5.3 Technical equipment successful for the project

The special smear test equipment, Berthold LB2711, together with scaffolding equipment LB1026 and a printer used in the second half of the project, helped in measuring all the smear tests in the clearance project.

The major success in this project was a newly invented machine called “MiniMax PH 250”. As mentioned before this machine could handle the special kind of concrete that the biological shield was made of. The MiniMax machine was also useful in all parts of the construction made of concrete. MiniMax saved more than MSEK 1.5 as less staff had to be involved than a conventional dismantling would have required. Although the start of the dismantling of the biological shield was delayed by four weeks because of the high radioactivity and 5 m^3 more concrete had to be dismantled, the time schedule could be followed thanks to the MiniMax.

6.5.4 Cost calculation

How to deal with the problems of depositing radioactive matter in the ground had never before been addressed by the authorities in Sweden. For that reason there were no routines for the actions of the authorities. In December 1982 some guidelines were given and in July 1983 decisions were made concerning permission under the special nuclear law. Therefore, the cost of the practical part of handling the low activity waste was planned in another project. This was because there was not enough time for the authorities to process the permits during the R1 decommissioning project.

Low and medium level waste was stored at Studsvik. This was an interim arrangement while the facilities for storing this kind of waste were under construction. This is obviously not included in the budget.

The documentation process was not as complicated as nowadays. For example there was no law about environmental impact assessment, security accounts and proposed decommissioning plans. There was no need for the budget to include these kinds of documents

Budget

The total cost for the decommissioning of the R1-plant was MSEK 21. 7 (with a granted budget MSEK 25). The overall allocation of the budgeted costs are shown in Table 6-2, and a more detailed itemisation is shown in Table 6-3.

Table 6-2. The allocation of the budgeted costs for the decommissioning of the R1 reactor.

Cost item	**Cost MSEK**
Preparatory study, radiological mapping, preparation work on site	2.9
Project management, staff management, communication with the authorities, reports etc.	4.5
Service and costs for running the facilities during the demolition period	0.7
Mechanical demolition, including taxes	9.5
Transportation, packing, garbage treatment	2.1
Radiation protection and decontamination	2.0
Total	**21.7**

Table 6-3. The allocation of the incurred costs for the decommissioning of the R1 reactor.

Cost item	**Cost MSEK**
Radiological survey and pre examination 1979-1980	1.2
Preparation on site until 1981, special equipment developed, initial experimental tests and measurement.	1.7
Communication with authorities, project management, management, reports and visits	4.5
Service and management at R1 1981-1984	0.7
Dismantling of the parts of the reactor and equipment inside the reactor hall apart from the concrete	1.7
Mechanical dismantling in engine room, laboratory etc.	4.0
Dismantling of the biological shield and the concrete in laboratory locations	3.1
Radiation protection including radiological measurements	1.3
Transportation including costs for packing (Berglöv boxes)	1.1
Waste disposal at Studsvik AB	1.0
Measurement for decommissioning, cleaning etc.	0.7
Tax	0.7
Total	**21.7**

6.6 Supplements

6.6.1 Supplement 1. Conclusions from the Studsvik summary report on decommissioning of the R1 reactor

This supplement is a translation from Swedish to English of the conclusions of the Studsvik summary report [58] on the decommissioning of the R1 research reactor.

The reactor was located near the Royal Institute of Technology in Stockholm in an underground closed chamber. The research plant started operations in July 1954. After being used for research purposes and isotope production for 16 years and an operating time of 65 000 hours the reactor was finally closed down in June 1970. The reactor was cooled and moderated by heavy water. Metallic, natural uranium was used as fuel. After closing, the fuel, heavy water and the ion exchange system were transported to Studsvik. The rest of the plant was sealed.

In 1979, Studsvik suggested complete decommissioning of R1 and radiological decontamination. A radiological survey was accordingly started in May 1979. Based on this, Studsvik started a detailed investigation for the demolition of the reactor.

Studsvik was granted a total of MSEK 25 for closing down R1, starting in the second quarter of 1981, and the demolition work lasted until May 1983.

The preparation work began on site in April 1981 with an overview of the electrical installations and continued until the end of October 1981. The R1 plant was then divided in different zones from a radiological and ventilation point of view. New in- and out ventilation filters were installed, lifting- and transportation routes were examined, sanitation equipment was completed, monitoring equipment for staff, waste, ventilation were installed and tested.

The actual demolition work started at the end of October with the scanning and removal of all movable equipment in the main hall and adjoining sectors. The so-called uranium container underneath the reactor floor was opened and prepared to be able to contain the reactor tank for its dismantling.

After the opening of the biological shield and the removal of the seven radiological flanges, the tank was lifted and put in the uranium container where it was cut up and prepared for the journey to Studsvik. The work was done with both plasma cutting as well as with more traditional mechanical cutting.

The graphite reflector, consisting of chunks of graphite weighing up to 60 kg, was removed from the biological shield via the thermal column with the help of a conveyor belt. The graphite was then packaged in steel crates and shipped to Studsvik. After the removal of the graphite from the biological shield, the mechanical components were removed.

We had now reached the stage where the disassembly of the exceptionally reenforced biological shield could begin. For the execution of this task we chose a company that had developed a special machine “MiniMax PH 250”. The machine is electro-hydraulic, can be manaeuvered from a distance and demands little manpower. Its jack-hammer was provided with four jets that sprayed water mist over the site in order to reduce the concrete dust. It did not take more water than was absorbed by the concrete waste. The demolition went according to plan. We first tore down the outer (approximately 1.5 m) concrete layer of the biological shield which according to earlier radiological mapping consisted of pure concrete. This material with an activity content of 5 kBq/kg could be deposited for disposal at Studsvik according to a decision by SSI (The Swedish Radiation Protection Authority). The remaining concrete with a higher activity content was treated like the rest of the radiological waste from R1.

Together with the demolition of the biological shield, dismantling of equipment in engine rooms, cooling towers and in laboratories was carried out. MiniMax was also used to demolish concrete containers and radiation shields in these areas.

All the waste and recyclables produced in R1 were documented and nuclide-specific measurements were made with a gamma spectrometer. Almost all the waste was transported to Studsvik. The exception was electrical engines, ladders, stairs and such items from non radiological spaces that after scanning and control by SSI were shipped off as junk. Solid waste, except for big lead doors and steel lids from the biological shield, was segmented and packaged in 600 litre steel crates for transportation. This also included concrete to the garbage dump in Studsvik. For transportation of the radiological hot stainless flanges a special lead shielded bottle was used.

The total amount of waste transported from R1: 750 tonnes of concrete to a regular landfill, 340 tonnes of concrete to a special radiological waste dump, 116 tonnes of metallic waste etc, 6 tonnes of liquid waste and 52 tonnes of graphite. The total activity content was approximately 800 GBq.

All the work in controlled areas was done with the staff dressed in special clothes. Protective measures for the staff were safety helmets, breathing mask, hearing protectors, special protection overalls covering the whole body with an air supply etcetera in accordance with normal workplace regulations and radiological considerations

The total collective dose to the staff participating in the project was 142 milliman Sv divided between 25 men. The dominating dose was from the demolition of the graphite reflector that gave 49 milliman Sv divided between 8 persons. Demolition of the mechanical equipment in the biological shield gave 56 milliman Sv divided between 10 persons. The staff was also controlled by whole body count in the HUGO-facility at Studsvik. No internal contamination was found.

On no occasion was measurable activity released to the environment during the demolition.

The technical demolition was finished in May 1983, about a month later than planned. At this point the radiological measurement for the clearance of the R1 localities started. All the surfaces in the rooms and spaces that had earlier been classified as radiological were now divided into 1 m^2 squares and were scanned with properly portable scanning equipment and were smear tested.

The surfaces in the non classified localities were scanned with the scanning equipment in the same way as the classified ones, but smear test were used to a smaller extent.

The limit for taking further decontamination was fixed at 8kBq/m^2 by SSI. None of the test results exceeded this limit and were in fact normally considerably lower. Collection of samples (batch measurement with the smear test) from the classified localities showed surface contamination on an average of 80Bq/m^2 and for unclassified localities 20Bq/m^2.

The measurements for clearance were terminated in October 1983. Application to SSI for clearance was made in February 1984. Thereafter SSI performed control measurements and in the beginning of February 1985 SSI concluded that no more restrictions from a radiological point of view were needed for the further use of the localities.

The total cost for the decommissioning of the R1-plant was MSEK 21.7 (with a granted budget of MSEK 25) and was allocated as follows:

Cost item	**Cost MSEK**
Preparatory study, radiological mapping, preparation work on site	2.9
Project management, staff management, communication with the authorities, reports etc.	4.5
Service and costs for running the facilities during the demolition period	0.7
Mechanical demolition, including taxes	9.5
Transportation, packing, garbage treatment	2.1
Radiation protection and decontamination	2.0
Total	**21.7**

6.6.2 Supplement 2. Survey over the reactor construction

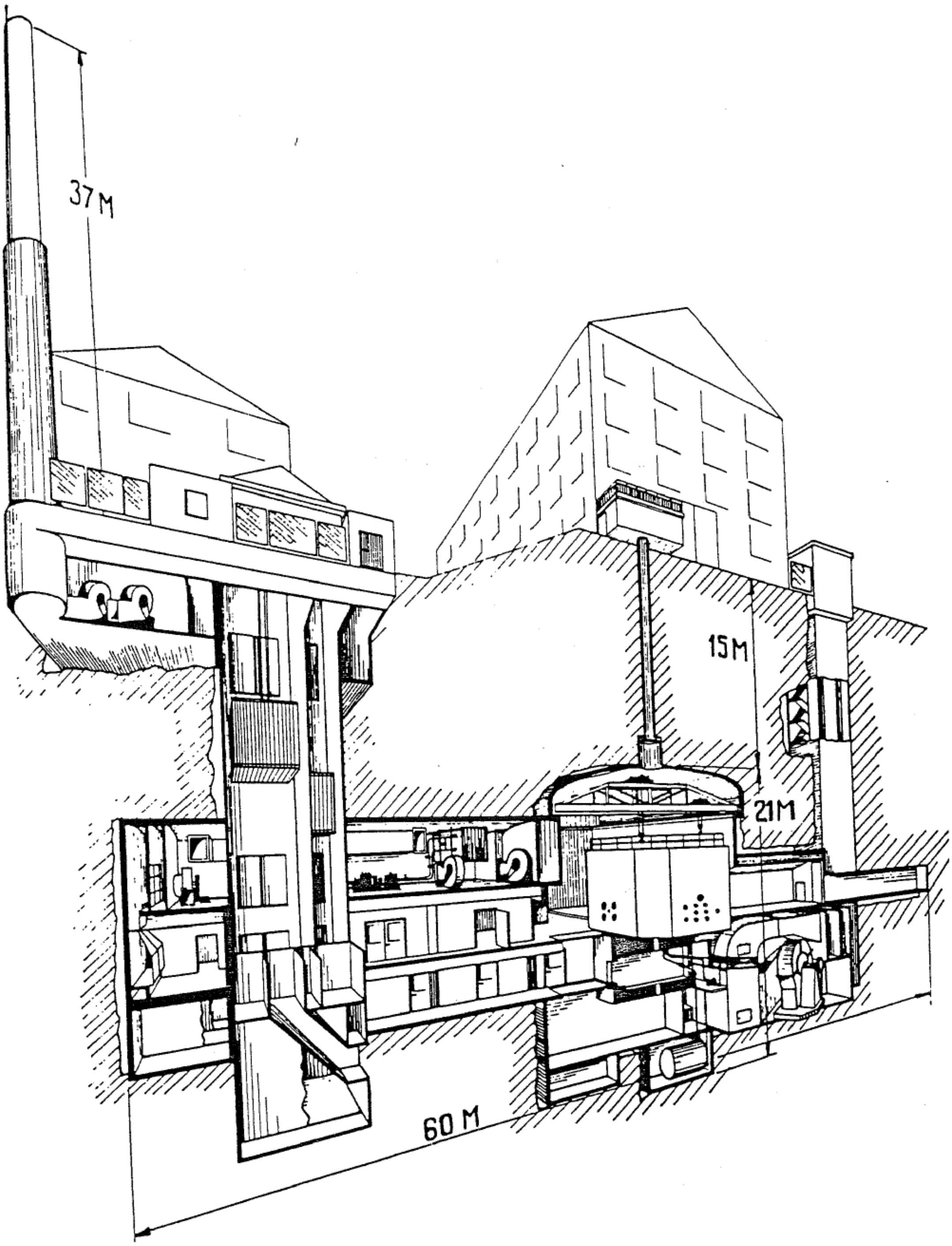

Fig 3-1 Reaktoranläggningen

6.6.3 Supplement 3. Inside the biological shield, the reactor vessel and the graphite reflector.

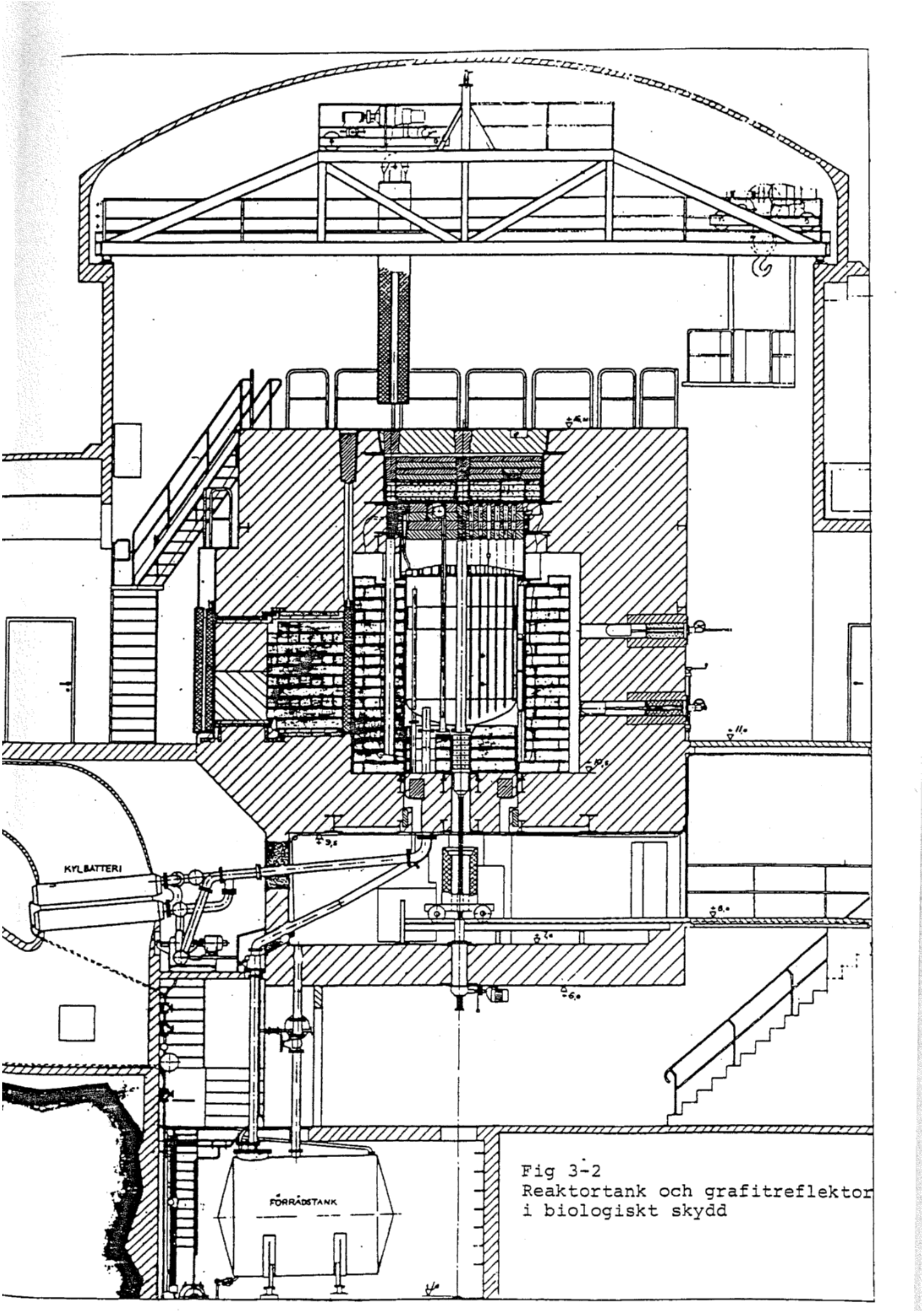

Fig 3-2
Reaktortank och grafitreflektor
i biologiskt skydd

6.6.4 Supplement 4. 8-1. The distance working saw. 8-2. The reaktor vessel placed in the uranium well. 8-3. The inside the graphite reflector .

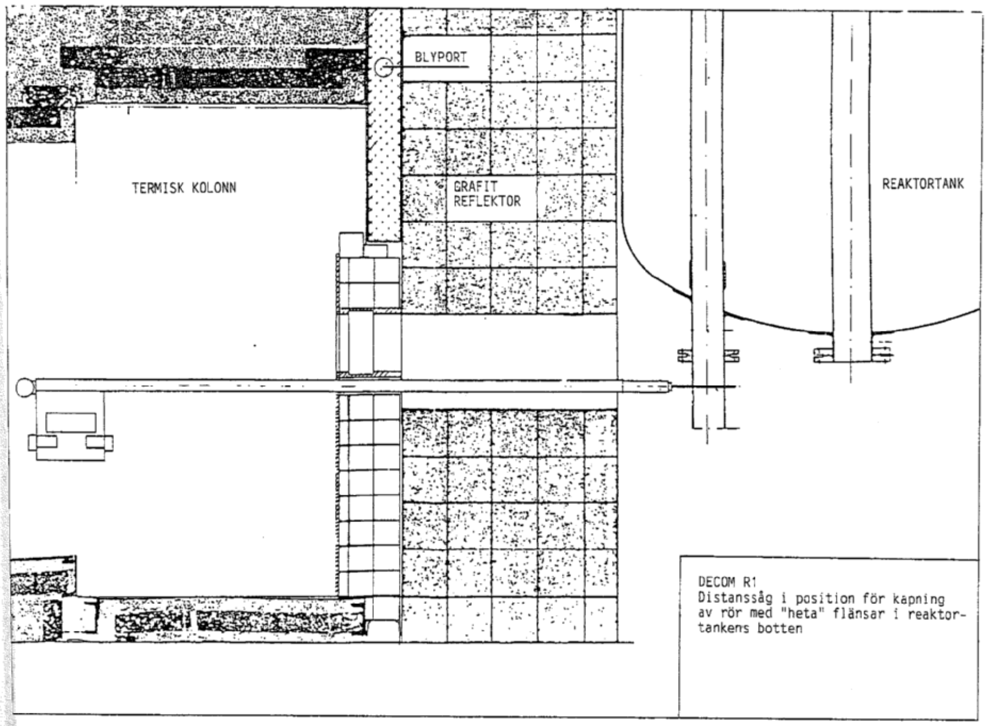

Fig 8-1 Distanssåg.

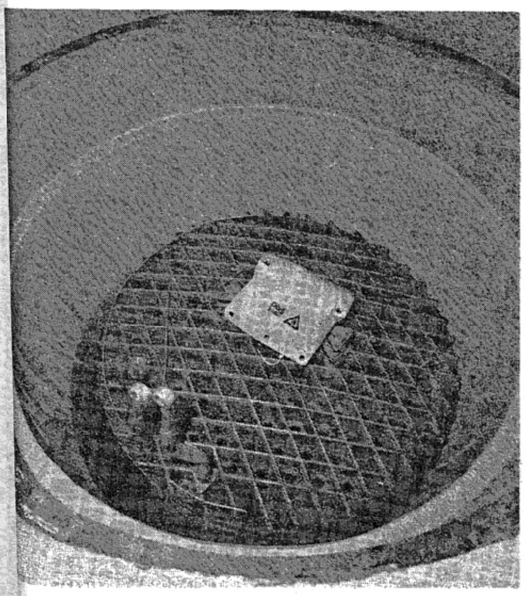

Fig 8-2 Reaktortanken nerställd i uranbrunnen.

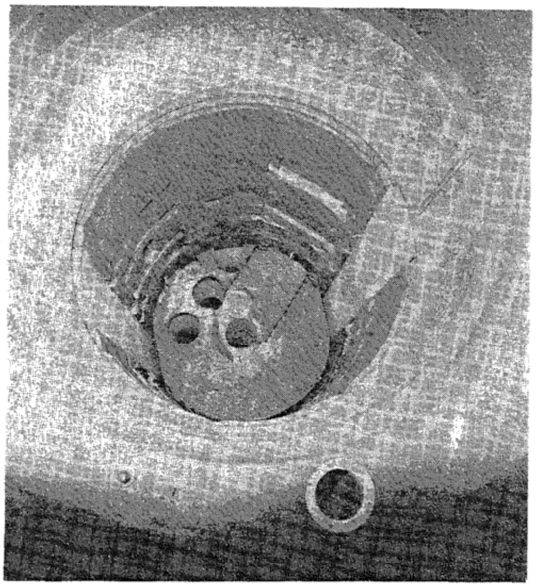

Fig 8-3 Grafitreflektorns inneryta efter lyft av reaktortank.

6.6.5 Supplement 5. 8-4. Dose rate inside the biological shield without the reactor vessel.

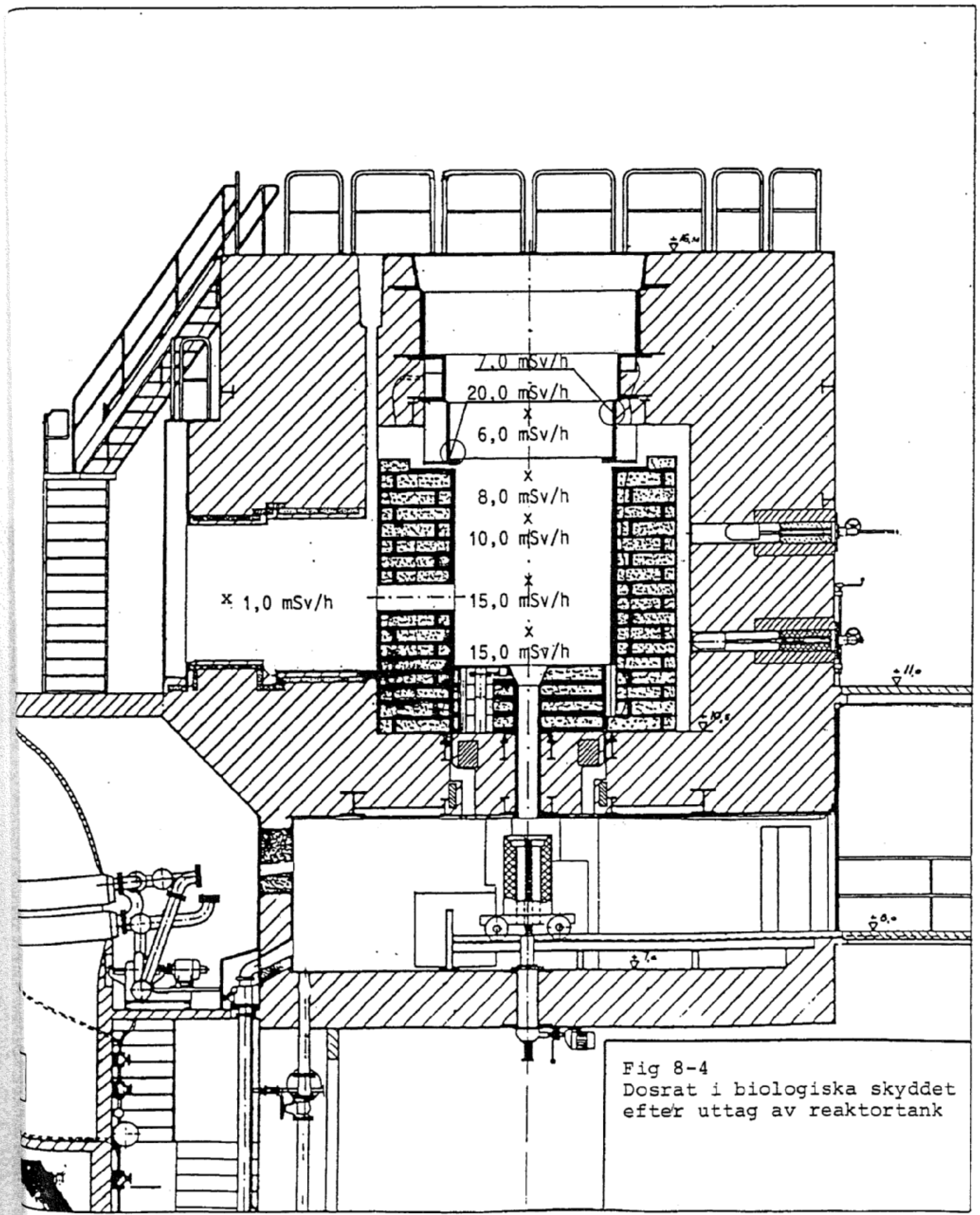

Fig 8-4
Dosrat i biologiska skyddet
efter uttag av reaktortank

6.6.6 Supplement. 8-8. MiniMax tear down the biological shield. 8-9.MiniMax tear down the concrete into a Berglöv box.

STUDSVIK ENFRGITEKNIK AB STUDSVIK/NW-84/627 53
1985-05-28

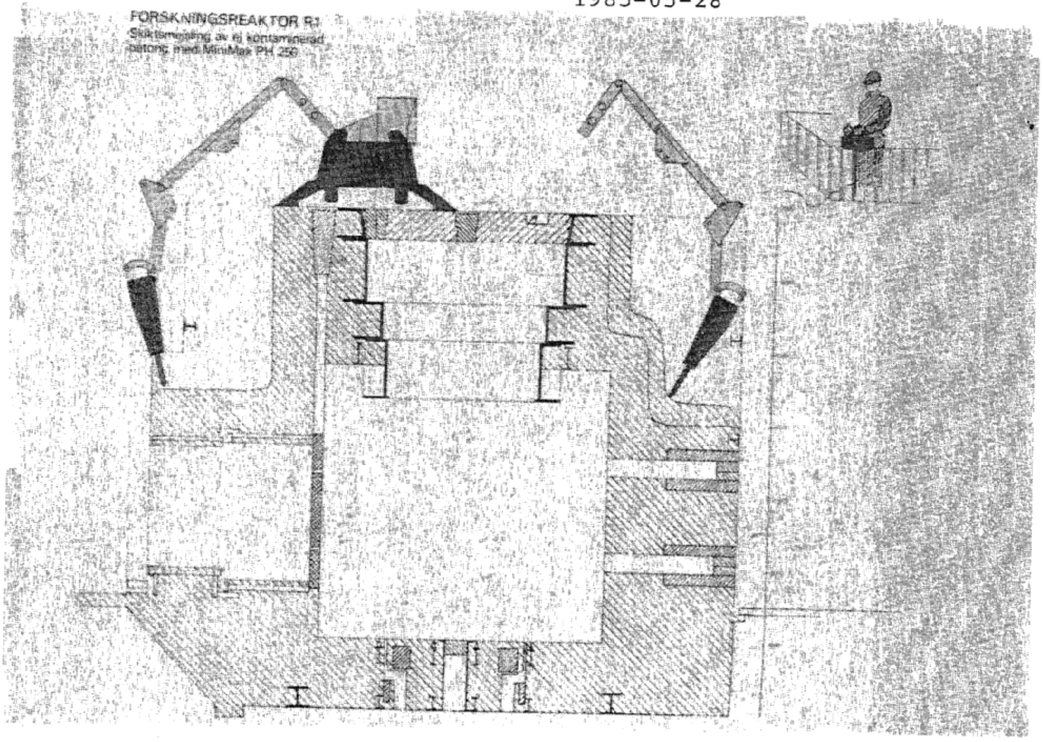

Fig 8-8 Princip för rivning av biologiska skyddet med MiniMax.

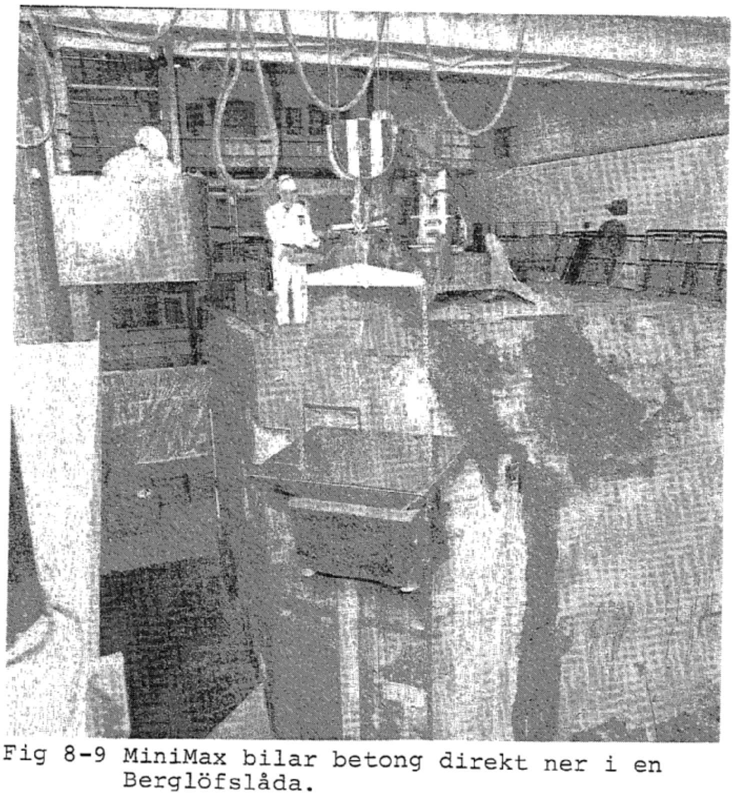

Fig 8-9 MiniMax bilar betong direkt ner i en Berglöfslåda.

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Abstract

Today, it is recommended that planning of decommission should form an integral part of the activities over the life cycle of a nuclear facility. However, no actual international guideline on cost calculations exists at present.

Intuitively, it might be tempting to regard costs for decommissioning of a nuclear facility as similar to those of any other plant. However, the presence of radionuclide contamination may imply that the cost is one or more orders of magnitude higher as compared to a corresponding inactive situation, the actual ratio being highly dependent on the level of contamination as well as design features and use of the facility in question. Moreover, the variations in such prerequisites are much larger than for nuclear power plants.

This implies that cost calculations cannot be performed with any accuracy or credibility without a relatively detailed consideration of the radiological and other prerequisites.

Application of inadequate methodologies – especially at early stages – has often lead to large underestimations.

The goals of the project and the achievements described in the report are as follows:

1	Advice on good practice with regard to
1a	Strategy and planning
1b	Methodology selection
1c	Radiological surveying
1d	Uncertainty analysis
2	Techniques for assessment of costs
2a	Cost structuring
2b	Cost estimation methodologies
3	Compilation of data for plants, state of planning, organisations, e t c.
3a	General descriptions of relevant features of the nuclear research facilities
3b	General plant specific data
3c	Example of the decommissioning of the R1 research reactor in Sweden
3d	Example of the decommissioning of the DR1 research reactor in Denmark

In addition, but not described in the present report, is the establishment of a Nordic network in the area including an internet based expert system.

It should be noted that the project is planned to exist for at least three years and that the present report is an interim one covering the work for approximately the first 16 months.

Key words: decommissioning, radiological survey, technical planning, methodology selection, nuclear research facility, cost calculation, early stage, cost estimation, Nordic, dismantling