The DR-2 project

Ølgaard, Povl Lebeck

Publication date:
2003

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Ølgaard, P. L. (2003). The DR-2 project. (Denmark. Forskningscenter Risoe. Risoe-R; No. 1427(EN)).

Risø-R-1427(EN)

The DR-2 Project

Povl L. Ølgaard

Risø National Laboratory, Roskilde, Denmark
June 2003

Abstract

DR-2 was a 5 MW tank type, water moderated and cooled research reactor, which was operated at the Risø National Laboratory from 1959 to 1975. After the close-down in1975 the DR-2 has been kept in safe enclosure until now. The aim of the DR-2 project reported here was to characterize the present state of the reactor and to determine, which radionuclides remain where in the reactor in what amounts.

The first part of the reactor to be investigated was the reactor tank. The lids at the reactor top were removed, air samples taken and smear test made in the tank. Then the control rods, the magnet rods and other active components were removed from the tank, measured, cut up, and disposed of in waste drums. The beryllium reflector elements were stored in specially prepared containers. When all movable parts had been taken out, the remaining radiation field was measured by use of thermo-luminescence dosimeters.

Next the hold-up tank room and the concrete cave (the igloo) in front of the thermal column were opened. They had been used as storage rooms for various components and all movable components were removed, measured and, if active, cut into waste drums. Only large and active objects remain stored in the igloo and in the hold-up tank room.

A number of graphite stringers were taken out of the thermal column and their activity measured. It was a surprise to find, that the stringers contained significant ^{152}Eu and ^{154}Eu activity.

Some of the beam plugs and irradiation tubes were extracted and reinserted after their activity had been measured.

The activity of the radiation shield of the reactor was measured in three different ways: By drilling two cored holes through the shield, by thermo-luminescence dosimeter measurements in vertical tubes in the concrete shield and by measurements through an open beam hole.

At the start of the project the activity in DR-2 was about 45-50 GBq. Now it is about 5-10 GBq.

Based on the results of the DR-2 project it is believed that the reactor can readily be dismantled.

ISBN 87-550-3255-9
ISBN 87-550-3256-7 (Internet)
ISSN 0106-2840

Print: Pitney Bowes Management Services Denmark A/S, 2003

Contents

Preface

The DR-2 Project was a typical teamwork, involving many persons from various departments of the Risø National Laboratory, whose contributions to the project were essential. Even running the risk of forgetting somebody, it seems proper to attempt to list all those who participated in the work in alphabetic order:

Axel Andersen, Inge Blyitgen, Helle Borch, Palle Bøgelund, Knud Brodersen, Steen Carugati, Jørgen Christensen, Knud Christiansen (Supervisor of the DR-2), Preben Ellebæk (former Daily Manager of the DR-2), René Eriksen, Joel Ethelfeld (responsible for the renovation of the reactor hall), Kari Fernstrøm, John Gade, Finn Grandal, Mogens Bagger Hansen, Klaus Iversen (Daily Manager of the DR-2), Nina Jensen, J. Sune Jensen, Per Hedemann Jensen, Henning Jørgensen, Rita Kragh, Morten Lillevang, Svend Lyster, Lars Mikkelsen, Freddy Mortensen, Anders Møller, Kirsten Nielsen (former Daily Manager of the DR-2), Morten Nielsen, Ove Nielsen, Peter Nielsen, Søren Nielsen, Erik Nonbøl, Preben Petersen, Thomas Petersen, Jens Rasmussen, Søren Roed, Brian Rømer, Joao Silva (made most of the radiation measurements), Allan Schösler, Knud Sejr, Preben Skanborg (former Head of the DR-2) and Arne Würtz.

Without the friendly and effective co-operation of all these people it would not have been possible to carry through the project.

Povl Ølgaard
Project leader

1 Introduction

The DR-2 research reactor was a 5 MW_t light water moderated and cooled tank type reactor. It started operation at full power on August 26, 1959, and it was finally shut down on October 31, 1975. The reason for the shutdown was that the DR-3 research reactor at Risø, a 10 MW_t heavy water moderated and cooled reactor with highly enriched uranium fuel, seemed to be able to cover all Danish needs for neutron beam experiments, reactor irradiations and radioisotope production. There was, however, some doubt as to whether this was correct, and for this reason it was decided that the DR-2 should be closed down in such a way that it could easily be restarted. The fuel was removed, the circuits drained and a lead shielding layer placed on the top of the reactor.

After a few years it was decided that there would be no future use for the DR-2 and that the reactor hall was to be used for chemical engineering experiments. Some parts of the reactor system were dismantled and the reactor was provided with additional shielding and sealed, i.e. kept in safe enclosure or IAEA stage 2 decommissioning. It was also decided that the dismantling of the DR-2 should be postponed until the dismantling of the other nuclear facilities of Risø, in particular the DR-3.

The chemical engineering experiments in the DR-2 hall were terminated in 1995/96 and in 1997 the DR-2 project was initiated. The purpose of this project was to

- investigate the state of the reactor
- determine where which radionuclides remained in what amounts
- plan the final dismantling of the DR-2
- use the experience gained to assist similar projects elsewhere

Starting the project in 1997 had the advantage that some of the people who had worked with and had knowledge of the DR-2 were still at Risø, although close to retirement. The project work was concentrated on investigations to characterize the state of the DR-2 and to determine where which amounts of radionuclides remain in the reactor. Further, co-operation on decommissioning of research reactors was initiated with the Salaspils reactor in Latvia. The planning of the dismantling of the DR-2 was to be taken up at the end of the project.

In September 2000 the Risø management decided to close down all nuclear facilities at Risø after doubts had been raised about the long-term integrity of the DR-3 reactor tank. This decision meant that it would be more logic to carry out the planning of the final dismantling of the DR-2 together with the planning of the decommissioning of all the nuclear facilities of the Risø National Laboratory. Nevertheless some considerations on the dismantling of the DR-2, based on the experience gained during the project, are given in section 14.

2 Description of the DR-2

DR 2 was a tank-type, light-water moderated and cooled research reactor, supplied by the Foster Wheeler Corporation, New York. It went critical on December 19th, 1958 and was finally closed down at the end of October 1975.

2.1 The Reactor Core

DR 2 was fuelled with MTR-type fuel elements. The standard fuel elements were approximately 8.0 cm by 7.6 cm in cross section and 87 cm long. Each standard element contained 18 curved fuel plates, 7.6 cm wide, 62.5 cm long and 0.25 cm thick. The fuel bearing length of the plates, i.e. the core height, was 60 cm. The plates were assembled by use of side plate and end boxes to form the complete fuel element. The fuel containing part of the fuel plates consisted of an alloy of 90% enriched uranium and aluminium with a thickness of 1.5 mm. This part was on both sides provided with a cladding layer of aluminium with a thickness of 0.5 mm. A standard element contained 186 g ^{235}U.

The special fuel elements were designed to allow the insertion of the control rods into these elements, i.e. into the core. Their design was similar to that of the standard fuel elements, but they lacked the central nine fuel plates. These were replaced by two aluminium plates with a 29 mm water gab between the plates. The control rods moved in this gab. The special elements contained only 93 g ^{235}U.

All fuel elements were positioned in holes in a 13 cm thick grid plate of aluminium. The cross section of the grid plate is 83 cm by 46 cm. The grid plate was provided with 48 element positions in a 6 by 8 arrangement. The central 36 positions were occupied by fuel elements, six of which were special fuel elements. One or more of the standard fuel elements could be replaced by irradiation facilities. The 6 positions in both ends of the grid plate were used for reflector elements, which had the same outer dimensions as the fuel elements. Initially aluminium clad graphite reflector elements were used, but they had a tendency to leak. They were therefore replaced by beryllium reflector elements. Four of these reflector elements were provided with a 2” central channel, which again contained a removable beryllium rod. Four were provided with a 3/4” central channel filled with water and four were solid beryllium blocks. The channels of the reflector elements were used for neutron irradiation.

Each element position in the grid plate is provided with a 6 mm diameter and 25.4 mm long stainless steel pin to ensure correct alignment of the individual elements. The grid plate, the top of which was placed 100 cm above the bottom of the reactor tank, is fixed to the square coolant channel below the plate by use of stainless steel bolts.

The reactor was controlled by use of one stainless steel regulating rod and five B_4C shim-safety rods. The control rods were 5.8 cm wide and 2.2 cm thick. The absorber length of the shim-safety rods was 67 cm. The absorber length of the regulating rod was 73 cm.

The shim-safety rods were held by electromagnets, which moved in stainless steel guide tubes. The guide tube were situated on top of the special fuel elements and mounted to them by four stainless steel bolts. When the reactor was scrammed, the magnets released the shim-safety rods, which then fell down into the special fuel elements by gravity. The fall of the rods was cushioned by shock absorbers attached to the top of the shim-safety rods. The magnet armature of the rods was placed on top of the shock absorber. The electromagnets of the shim-safety rods and the regulating rod were by use of long extension rods connected to the control rod drive actuators, which were situated in a steel box above the top of the reactor tank. The actuators were of the rack and pinion type and could be placed above any of the 24 central fuel element positions.

2.2 The Reactor Tank

The reactor tank is made of aluminium. It has a wall thickness of 9.5 mm, a diameter of 201 cm and a height of 808 cm.

The tank is provided with a spent fuel element storage rack, situated 91 cm above the top of the core. In this rack spent fuel elements could be stored to allow reduction of the decay heat and the γ-radiation before they were removed from the tank. The rack was also used for storage of the guide tubes and the shim-safety rods during refueling of the special fuel elements

The reactor was provided with beam tubes, irradiation tubes, a thermal column and a through-tube, penetrating into the thermal column. These facilities will be discussed under section 2.3 Experimental Facilities.

Below the core the reactor tank was provided with six thimbles, which from two directions runs from the reactor surface and almost to the center of the coolant channel below the core. These thimbles were used for the nuclear control instruments (neutron monitors).

Most of the top of the reactor was covered by 6.4 mm thick steel plates, which could be removed during refuelling, inspection and maintenance.

In Figures 2.1 and 2.2 vertical and horizontal cross sections of DR 2 are given. Figure 2.3 gives a cut-away drawing of the DR-2.

2.3 Experimental Facilities

The experimental facilities of the DR-2 consisted of beam tubes, a thermal column, a through tube, irradiation tubes and pneumatic tubes. The arrangement of these facilities are shown in Figures 2.1 and 2.2.

The reactor has eight beam tubes. Five of these, B-1, B-2, B-3, B-4 and B-5, are nominal 6” aluminium tubes with a usable inside diameter of 14.6 cm. B-6 and B-7 are nominal 4” aluminium tubes with a usable diameter of 11.9 cm. The last beam tube, B-8, was nominally a 13” tube with a usable inside diameter of 32 cm.

The outer aluminium sleeve of the beam tubes starts at the inner surface of the vestibule boxes at the surface of the reactor block, and it extends a short distance beyond the wall of the reactor tank. It is in contact with the concrete shield on the outside. Inside the outer sleeve is the removable inner aluminium liner, which is bolted to the inner surface of the vestibule box, and which extends all the way to the fuel elements of the core or to the reflector elements. Inside the inner liner is the removable shielding plug with a steel surface. The shielding material of the plugs may e.g. be heavy concrete or a mixture of resin and steel shot. The diameters of the sleeves, the liners and the shielding plugs are not constant, but are reduced by a step in the components to reduce neutron streaming (see Figure 2.4).

The initial shielding plugs supplied by Foster Wheeler consisted of two parts, a removable aluminium nosepiece (water filled during operation) and a barytes concrete cylinder, which at the end closest to the core was provided with a neutron-absorbing boral layer. The concrete cylinder was encased in a chromium-plated carbon steel tube. This plug was machined so accurately that the tolerance between the steel tube and the aluminium liner was 0.5 to 1.3 mm. Each plug was provided with three spiral stainless steel conduits, which ended in threaded holes at the nose piece, two for water and one for experimental use (See Figure 2.4).

All original beam plugs except that of the 13” beam tube were later on replaced by new ones, designed to suit the actual experiments at the beam tube, e.g. to permit a neutron beam to penetrate from the core to the experimental set-up at the outside end of the beam tube.

The thermal column is situated at the east face of the core. At the core end it is 64 cm wide and 97 cm high. Along its 163 cm length its cross section increases so that it is 132 cm wide and 157 cm high at the outer end. The graphite of the thermal column is placed in an aluminium casing, which at the inner end is provided with a 15 cm thick lead layer. The lead layer is bonded to the inside of the nose plate of the casing. The casing is inserted into a rectangular channel, which protrudes from the tank to the outer end of the column, and which is anchored in the concrete shield. At the outer end the casing is welded to the channel wall. Spacers between the channel and the casing permit circulation of tank water between the casing and the channel. The part of the casing, which is situated inside the concrete is on the inner sides lined by a 6.4 mm thick boral plate to reduce the activation of the concrete.

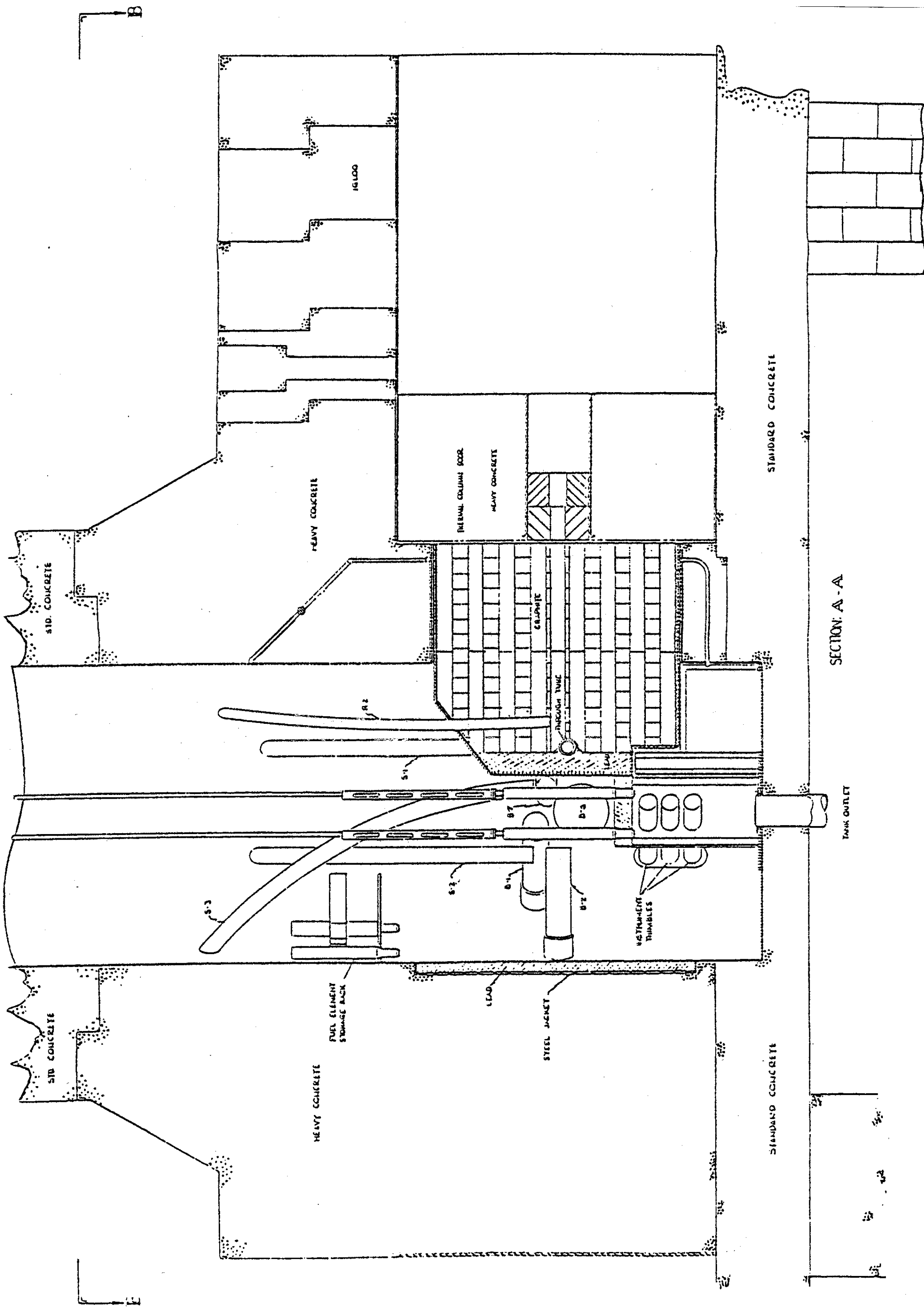

Figure 2.1. Vertical cross section of the DR-2. Diameter of reactor tank 2.0 m

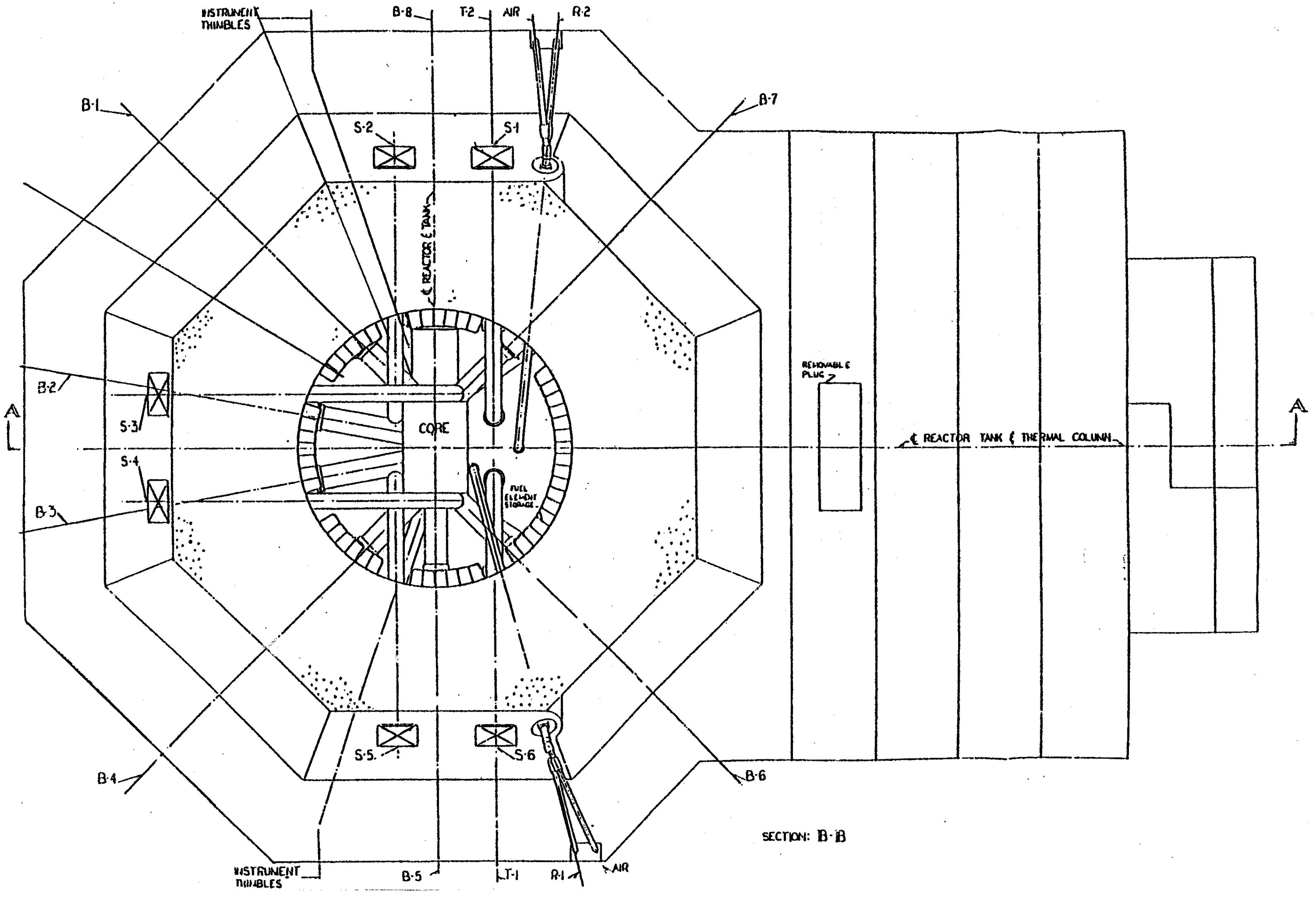

Figure 2.2. Horizontal cross section of the DR-2. Diameter of reactor tank 2.0 m

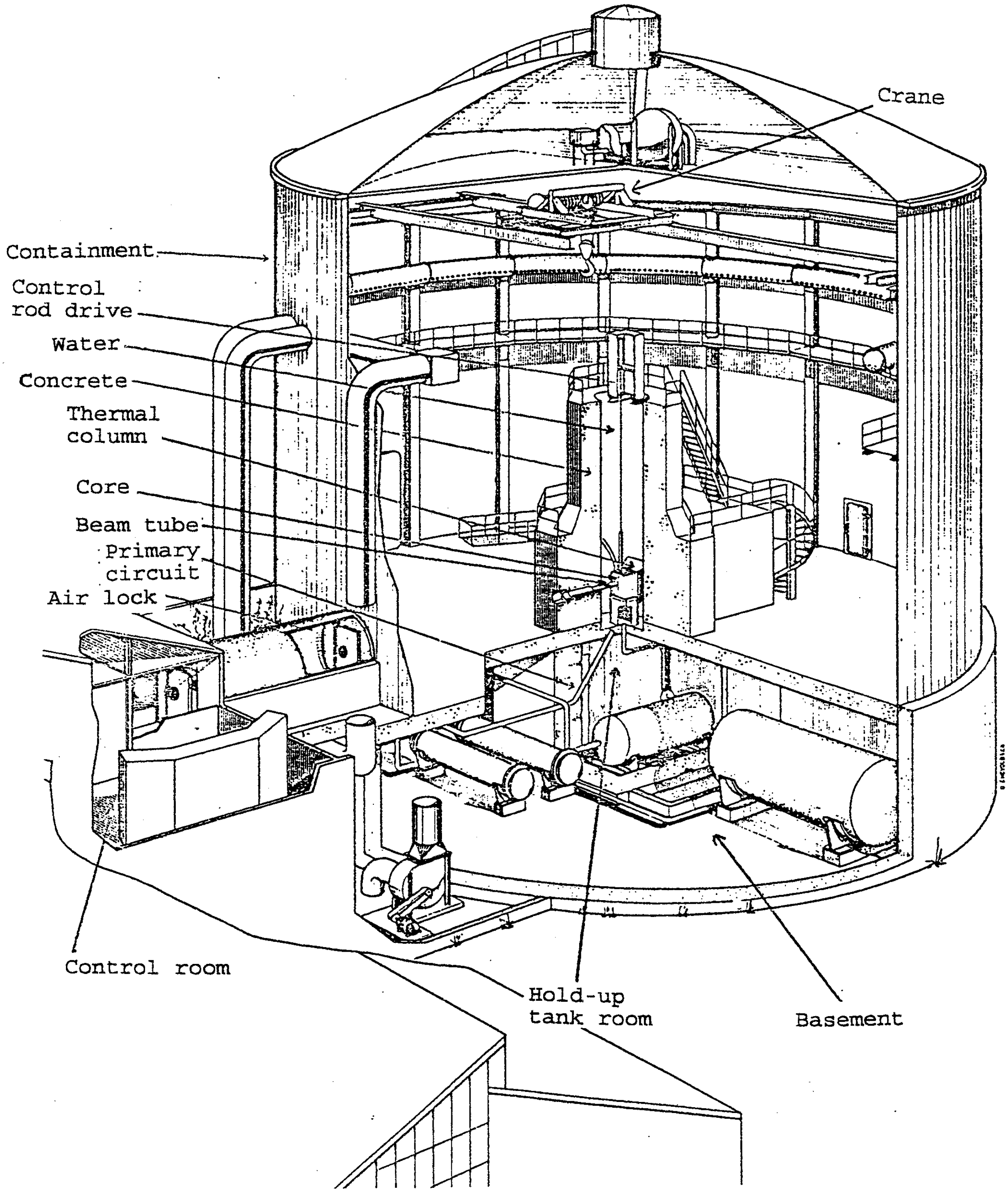

Figure 2.3. Cut-away drawing of the DR-2

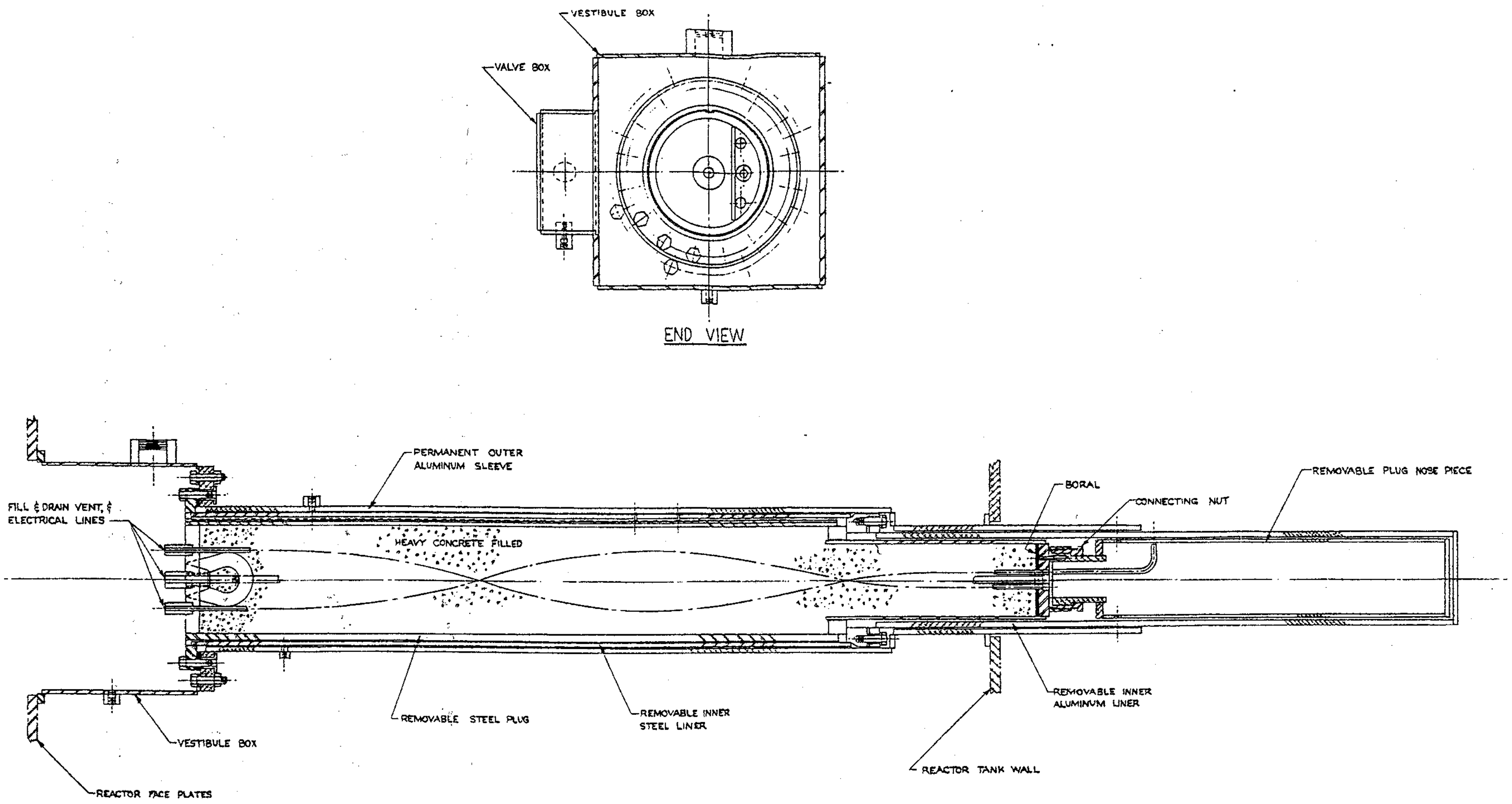

Figure 2.4. Vertical cross section of a beam tube and plug

The thermal column consists mostly of 10.2 by 10.2 cm graphite stringers. They are between 40 and 75 cm long and are stacked horizontally, alternatively across and along the axis of the column. The arrangement permits the removal of a central 36 by 36 cm section of stringers. Five of these stringers, consisting of an inner and outer stringer, may be removed independently through holes in the movable concrete door at the end of the column. These holes are provided with steel plugs. The thermal column was designed for a centerline thermal neutron flux of 5 10^9 n/(cm^2s) at a distance of 30 cm from the outer end of the column. The cadmium ratio at that point was designed to be above 1000. Irradiations in the thermal column were primarily performed in the inner stringer with the outer stringer withdrawn.

The igloo, built of heavy concrete blocks, is situated outside the thermal column (cf. Figure 2.1 and 2.2). The inner surface of the igloo is lined with boral plates to reduce activation of the concrete. The inner igloo door is usually situated at the outer end of the column. It is a concrete door, mounted on rollers and moving on rails by use of an electric motor on the door. The inner door has a thickness of 112 cm and is encased in a 1.9 cm thick steel plate. Its inner surface is lined with a boral plate and a wooden plate. When the wooden plate gets in contact with the thermal column, it activates an electric switch, which stops the door motor. The outer end of the igloo is closed by two 61 cm thick concrete blocks to provide additional shielding. This outer ”door” can only be ”opened” and ”closed” by use of the crane of the reactor hall.

DR 2 was provided with a through-tube (T1-T2), which runs through the thermal column behind the lead nose, but close to the core (cf. Figure 2.1 and 2.2). The through-tube is surrounded by aluminium sleeves in the concrete shield and in the thermal column to allow removal of the tube. The aluminium sleeves are flanged to the carbon steel vestibule by use of rubber gaskets to allow thermal expansion and prevent leakage of tank water.

From the balcony of the reactor block six irradiation tubes, S-1, S-2, S-3, S-4, S-5, and S-6, curve down to the reactor core through the concrete shield and the tank water (cf. Figure 2.1 and 2.2). The S-tubes have an outer diameter of about 11 cm and a wall thickness of 6 mm. Two of these tubes terminate in the thermal column (S-1 and S-6), two along the west side of the core (S-2 and S-5), and one along the north (S-3) and the south (S-5) side. All S-tubes are of aluminium. They were filled with water to provide the necessary shielding. The S-tube penetrations through the concrete shield are also provided with sleeves to allow the removal of the tubes.

DR 2 was provided with two pneumatic tube facilities, R-1 and R-2 (cf. Figure 2.1 and 2.2), which both had an outer diameter of 5.7 cm. R-2 extended from the send-receive station on the northern shield surface and down into the graphite of the thermal column. R-1 extended from its station on the southern shield surface into the lead layer of the thermal column. The R-tubes are in the concrete surrounded by aluminium sleeves, so that they can readily be removed. R-2 could be extended to an adjoining laboratory building. Shortly after the start of the DR-2 the R-1 was taken out of operation because the temperature was too high, and the facility was removed. Its aluminium sleeve was used for insertion of a tank water level meter. Instead the through tube was provided with a fast, pneumatic tube facility.

2.4 The Reactor Shield

The radial radiation shield of DR 2 consists from the core and outwards of three shielding layers. The first is 68 to 77 cm of tank water (neglecting the reflector elements). The second is a 6.4 cm thick and 183 cm high lead layer in an aluminium jacket surrounding most of the reactor tank at the level of the core and above and below it. The third layer is about 2 m of barytes concrete with a density of 3.4 g/cm^3. The barytes concrete reaches from the hall floor and 4.1 m upwards to the reactor block balcony. The remaining 3.6 m of the reactor block is made of ordinary concrete. The lower part of the outer surface of the shield is lined by 19 mm steel plates. The radial shield is of course perturbed by the experimental facilities such as beam tubes, S-tubes and the thermal column. In addition the concrete shields is penetrated by air and water tubing as well as reinforcing steel rods at its inner and outer parts.

Above the core the shielding consisted essentially of 6 m of water. The shielding below the core consisted of the 13 cm thick grid plate, 85 cm of water and the floor of the reactor hall, which below the reactor tank is about 25 cm thick. This floor is at the same time the roof of the hold-up tank room. The floor is penetrated by one outlet tube and four inlet tubes of the primary circuit.

2.5 The Primary Circuit

During reactor operation the cooling water flowed down through the fuel elements to the hold-up tank in the hold-up tank room in the basement directly below the reactor. In the hold-up tank the ^{16}N activity, produced by fast neutron capture in the oxygen of the coolant during passage of the core, were allowed to decay. From here the coolant continued through two parallel circulation pumps and two parallel tube-and-shell heat exchangers after which it returned to the bottom of the reactor tank (see Figure 2.5).

There were three circulation pumps, but only two were working at a time while the third was kept in reserve. All components of the primary circuit are made of aluminium except for the circulation pumps and the valves, which are made of steel. Isolation sections are inserted at appropriate points in the circuit to prevent galvanic corrosion between the iron and the aluminium.

To keep the demineralized water of the primary circuit clean, a by-pass stream was continuously withdrawn from the primary circuit and sent through an ion exchange demineralizer and filter unit (see Figure 2.5). The unit contained a separate cation exchanger and a mixed-bed demineralizer.

The bottom of the reactor tank was connected to a 38 m^3 dump tank in the basement. The drainage was done by gravity. The primary circuit was also coupled to two 5.5 m^3 liquid waste tanks. The pumps, heat exchangers, demineralizers and the tanks were all placed in the operational basement area. The remaining part of the basement was the experimental area, used in connection with reactor experiments.

2.6 Operational History

As mentioned above the DR 2 started to operate on full power, 5 MW$_t$, on August 26th, 1959. It operated with three shifts per day, five days per week until the end of October 1963, i.e. for about 1525 days. During this period the integrated power was 2450 MW$_t$d. From November 1st, 1963 and until the final closedown at the end of October 1975 the operation was reduced to one shift per day, five days per week. During this period of about 4380 days the integrated power was 3038 MW$_t$d. Thus the total integrated power of the DR-2 during its operation was 5488 MW$_t$d.

The core loading consisted usually of 28 to 29 standard fuel elements, six special fuel elements one or two experimental facilities (always the V-tube facility, often an irradiation rig) and 12 beryllium reflector elements. The core contained up to 6 kg 90% enriched uranium, which was supplied from the US and returned to the US in the form of spent fuel.

The average thermal neutron flux in the beryllium elements has been estimated to be 3.9 10^{13} n/(cm^{2}s) and the epithermal flux to be 1.75 10^{12} n/(cm^{2}s) at full reactor power.

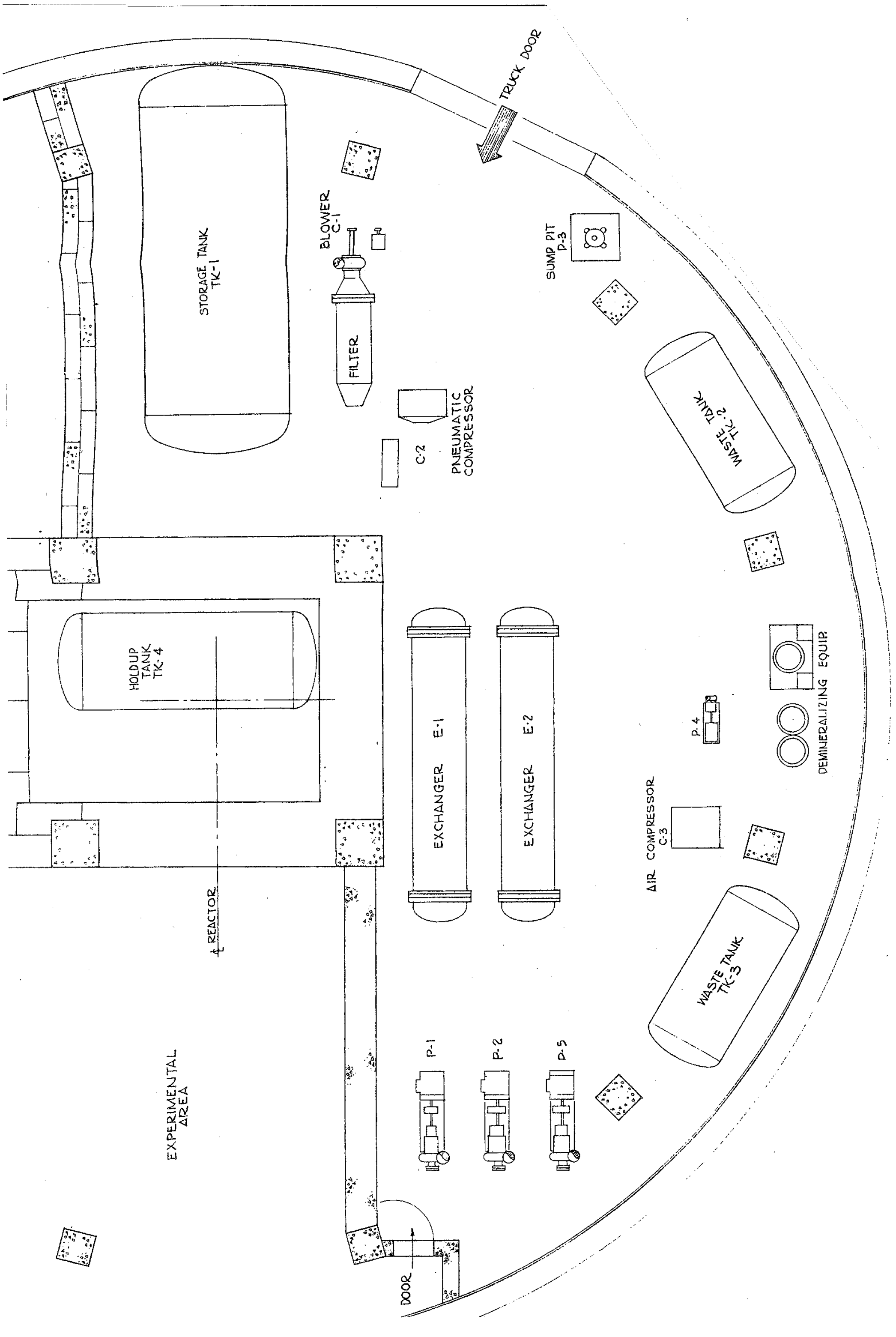

Figure 2.5. Arrangement of equipment in the operational basement area

3 Pre-project Transition Activities

After the DR-2 was finally closed down at the end of October 1975, the core was dismantled and the 35 *fuel elements*, 29 standard and six special elements, containing less than 6 kg ^{235}U, were placed in the storage rack of the reactor tank, where three spent fuel elements had already been stored. About one month later all fuel elements were transferred to the fuel storage and cutting pool of the DR-3. From here they were later sent to the US, who had supplied the 90% enriched uranium in the fuel elements. The *guide tubes* were, together with their *shim-safety rods* hanging down from the bottom of the guide tubes, placed in the storage rack. So were three *grid plate plugs*, which were also used for storage of the stainless steel screws used to attach the guide tubes to the special fuel elements.

The *beryllium reflector elements* were left in the grid plate. So was the *V-tube facility*, in which five vertical tubes for irradiation of small material samples in the core could be inserted, and two *"water holes"* used for core irradiation of large samples. The latter three components had the outer shape of fuel elements and were basically aluminium tubes with water inside.

The *regulating rod* with its extension rod and the *magnet rods* of the shim-safety rods were left hanging down from the beams, which carry the control rod drive mechanism at the top of the reactor tank. So were the *hold-down rods*, used to ensure that guide tubes (and the special fuel elements) could not be pulled out of the core when the control rods were withdrawn. Left hanging were also a tube to remove objects, which might be deposited on top of the fuel elements by the coolant flow. A few additional components were also stored in the reactor tank.

The *primary and the secondary circuits*, including the DR-2 tank, were drained for water to reduce the risk of corrosion and water leaks. The lowest point of the primary circuit, the bottom of the hold-up tank, was provided with a drainage valve so that all water could be drained. The volume of water of the primary circuit was 38 m^3. Water of the primary circuit was first transferred to the two waste storage tanks in the operational basement area of the reactor building, each with a capacity of 5.5 m^3. From here the water was moved to an emergency storage tank in a concrete cave outside the reactor containment building. This tank had a capacity of about 20 m^3. Finally the water was transferred by use of a tank car to the Risø Waste Management Plant where the water was cleaned by distillation. It was discussed whether the primary circuit should be dried, but it was decided that this was not necessary.

The *demineralizers* were in operation until the fuel had been sent to the DR-3. The resins were later regenerated and transferred as low level waste to the Waste Management Plant. The operational basement area was used for storage of reactor equipment, "fishing tools", spare parts and for some time of one of the two DR 2 archives.

To provide the necessary radiation shielding at the top of the reactor, once the water in the reactor tank had been removed, a steel plate, carrying a 5 cm thick layer of lead bricks, was placed on the top of the reactor tank.

The motor driven concrete door of the *igloo* was left in its inner position in front of the outer surface of the thermal column. The igloo was used to store various radioactive and non-active components and tools. The outer end of the igloo was closed by the two concrete blocks.

The *hold-up tank room* below the reactor was – though to a lesser extent – used to store active and non-active components. The opening to the hold-up tank room was closed by use of standard concrete blocks (61×61×61cm). No record was available indicating which components were stored in the reactor tank, in the igloo and in the hold-up tank room.

All equipment of the neutron experiments in the reactor hall was removed. In all *beam plugs*, which had been provided with a beam hole, an iron rod was inserted into the hole. In addition the vestibule boxes at the outer end of the beam tubes were, where needed, filled with lead bricks and sealed with tape. The six *S-tubes* were emptied for water and dried. Their vestibule boxes were where needed filled with lead bricks and sealed with tape.

The *sealing valves*, i.e. water filled valves in the ventilation system, was drained for water and blocked in the open position so that the hall is directly connected to the surroundings. The emergency exit of the reactor hall was drained for water.

In the late 1970'es it was decided to abandon the restart option of the DR-2 and to use the reactor hall for chemical engineering experiments. This meant that the reactor hall had to be transformed into "white" area. Therefore, a number of additional measures were carried out.

The *actuator box* at the top of the reactor with control rod drive mechanisms and the connecting cables were removed, and the thickness of the lead layer on top of the reactor was increased to 10 cm. In addition a 40 cm thick *concrete shielding plate* was placed at the top of the reactor, above the lead layer. This concrete plate with a mass of 15 tons was manufactured in the reactor hall and lifted by use of the hall crane. The concrete plate was provided with a central concrete plug which could be removed and through which measurements of the radiation from the components of the reactor tank could be performed. The vestibule boxes of the beam tubes, the S-tubes and the instrument thimbles were closed with steel plates, which were either welded to the steel faceplate on the outer surface of the reactor block or locked with padlocks. The pneumatic system was taken apart and all tubes closed. All other openings were sealed with a plastic material. The staircase to the top of the reactor was removed and so was the railing at the top of the reactor.

The interior of the primary circuit and the reactor tank was connected to the reactor basement through a air filter so that pressure differences between the reactor system and the outside were equalized through the filter. The wall at the southern part of the basement between the experimental and the operational area was moved so that the large storage tank was included in the experimental area and could be used during the chemical engineering experiments. The secondary circuit was dismantled. Free tube ends were plugged and so were a number of experimental holes in the floor. The reactor hall was provided with windows.

All equipment of the control room was dismantled and various alarm systems were deactivated. The personnel air lock of the reactor hall was de-activated so that the two doors of the air lock could be opened simultaneously.

The hold-up tank room was originally provided with a door, but it was removed and the whole opening to the room was closed by use of concrete blocks.

Since the status of the reactor after its final close-down was changed from an operating reactor to a reactor under decommissioning, a new safety documentation for the reactor had to be prepared and new "Operational Limits and Conditions" were issued by the Danish Regulatory authorities. As the situation changed, this documentation had to be modified.

After the closedown the Head of the DR-3 was made responsible for the DR-2, and he appointed, according to the new "Operational Limits and Conditions", one of his staff to be the Daily Manager of the DR-2 and another to be the Supervisor of the DR-2.

Regular inspections of the DR-2 were carried out to ensure the safe state of the reactor. In addition annual radiation surveys were performed at a number of pre-selected places in the DR-2 building to measure the decay of the activity and to detect any release of activity. The activity decreased with a "half-life" of about 6 to 8 years. Through the hole in the concrete plate at the top of the reactor a measurement of the γ-spectrum of the radiation in the reactor tank was made, and it was dominated by ^{60}Co ($T_{½}$=5.3 yr), but ^{152}Eu ($T_{½}$=13 yr) could also be observed. Based on measurements through the hole and assuming that all activity of the components in the tank was situated at the core center the activity of the components in the reactor tank was in 1977 estimated to be 0. 88 TBq (or 24 Ci).

The reactor hall was used for the chemical engineering experiments until 1995/96. After this time t was mainly used for storage of various non-active components and furniture.

4 Organization of Project

When the DR-2 project was started a Planning Committee was established, the chairman of which was the project leader. The Planning Committee was composed by three staff members from the DR-3 (the daily manager of the DR-2, the supervisor of the DR-2 and the person to be responsible for the practical work at the DR-2), two members from the Reactor Safety Group (one of which was the project leader), two members of the Waste Management Plant, two members of the Applied Health Physics Section, one member from the Safety Secretariat (the former head of the DR-2) and one member from the Building and Construction Service. The reason for having two members from most of the groups was to have both a senior staff member and one from the younger generation. The Committee met once a month.

The Planning Committee prepared the project plan and revised the safety documentation for the reactor, which was then submitted for the approval of the Danish Regulatory Authorities since the state of the DR-2 had to be changed during the project. It supervised the preparatory work, i.e. the clearing, cleaning and painting of the reactor hall and the experimental area of the basement, the modifications of the reactor block and construction of the storage facility and the measuring facility in the reactor hall.

Once the actual project work started, a Steering Group was formed. It was composed by the project leader, the daily manager of the DR-2, the supervisor of the DR-2, the person to be responsible for the practical work at the DR-2, members of the DR-3 staff to perform project work, the former head of the DR-2 and the health physicist of the project. The group met regularly to discuss the work to be carried out during the coming period according to the project plan.

The work performed in the reactor building was recorded by the staff in a logbook. This book was kept in the reactor hall. The project leader was present during all major operations, and he kept a detailed record of the work (Ref. 1). This record proved invaluable in the preparation of the present report. The work, the time of its execution and the participants in the work were recorded. So was the components removed from the reactor and the place to where they were transferred, e.g. a waste drum or the storage facility in the reactor hall. When drums with reactor components were sent to the Waste Management Plant, a letter with a list of the content of the drums was also sent to the plant

5 Preparatory Activities

5.1 Restoration of the Reactor Hall

As mentioned in section 3 the reactor hall was until 1995/96 used for chemical engineering experiments and some equipment used in these experiments, e.g. tanks, were left in the hall. This equipment had to be removed before the DR-2 project could start. Further, after the end of the chemical engineering experiments the hall had been used for storage of furniture and other items. These items had to be removed too. Next the reactor hall had to be cleaned. The floor, the reactor block and the hall walls up to a height of 2.25 m was repainted to ease decontamination should any operation during the project lead to contamination. During this period of time the reactor hall and the experimental basement area had been classified as "white area”. However, during the DR-2 project the reactor building had to be classified as “blue area” and some part, e.g. the reactor top, as “red area” due to the removal of part of the reactor shielding and the handling of radioactive components in the building. To collect any liquid spills in the reactor hall during the project, drains were established and connected to a tank in the basement, from where the water could be sent to the Waste Management Plant by use of a tank car. Drains from the reactor building to the emergency storage tanks outside the reactor building were closed.

The crane of the reactor hall, which had not been used for some years, had to be checked and approved for lifting up to 18 tons. The operation of the crane gave during the project rise to some problems, in particular the relays, but they were overcome without much difficulty.

The staircase to the top of the reactor block was reestablished. The inner and outer railing at the top of the reactor block was manufactured, but only the outer railing could be installed before the concrete shielding plate had been removed. Since the working space at the top of the DR-2 was quite limited, it was extended by erection of a scaffold, on top of which a working platform was placed. It was planned to place equipment needed for radiation measurements in the reactor tank at a table on the platform, but this option was not used very much.

The “fishing tools” used during the operation of the DR-2 for handling equipment down in the reactor tank had been stored in the operational area of the basement. These tools were checked, where needed repaired and left hanging in the reactor hall to be used when needed. They were not used very much during the project work since the use of hooks, prepared for the various tasks, turned out to be more convenient. When components in the reactor tank were handled, some of the personnel performing the work had to operate over the open tank. To prevent them from falling down into the tank they used a safety harness, which was attached to a “gallows” mounted on the top of the reactor block. The “gallows” could only be installed after the concrete shielding plate had been removed from the reactor top.

A new measurement of the total activity of the components in the reactor tank was made in 1998**.** It resulted in an estimated activity of 60 GBq (1.5 Curie). ^{60}Co still dominated the activity. Further a radiation survey was carried out in 1998 on the outer surface of the primary cooling system in the operational basement. The radiation level detected was quite low, 0.05 to 0.15 µSv/h, i.e. close to the background level. The primary circuit was opened and a smear test was performed on the inside of the main cooling tube. The measured activity was very low, around 10 mBq/cm^2. ^{60}Co was the dominating activity, but ^{137}Cs, ^{152}Eu, ^{154}Eu and ^{155}Eu were also observed.

The access to the reactor hall had to be limited to the project personnel. Therefore, the key system of the reactor building had to be changed, and the new keys were issued to a limited number of persons who were given permanent permission to enter the reactor building.

5.2 Preparation of Project Documentation

Before the start of the DR-2 project the reactor was kept in safe enclosure in accordance with the “Betingelser for drift” (Operational Limits and Conditions) issued by the Danish Regulatory Authorities. Since the project involved opening the various sealed rooms of the reactor block, a revised version of the “Sikkerhedsdokumentation for DR-2” (Safety Documentation for the DR 2), including a proposal for revised “Operational Limits and

Conditions" and a project plan had to be prepared and submitted to the Regulatory Authorities for their approval.

The "Safety Documentation for the DR 2" has the following content:

- Introduction
- Description of the plant and its surroundings
- General safety procedures
- Systems description
- Fire protection
- Accident analysis
- Radiation protection
- Organization and administrative control
- Operational Limits and Conditions

In addition it contained six appendices:

1. Calculated activity content in the materials of the DR-2
2. Material specifications for some of the materials used in the DR-2
3. Annual radiation measurements for the DR-2
4. Amounts of activity in the operational basement area of the DR-2
5. γ-spectrometric measurements at the S1 tube
6. Measurements of the radiation level at the top of the DR-2

This safety documentation (Ref. 2) was written in Danish. The document was prepared by a small working group, composed by Planning Committee members, and it was later approved by the full Committee. The work started in the autumn of 1998 and was finished during the spring of 1999. The safety documentation was then submitted to the Safety Committee of the Risø National Laboratory together with "Beskrivelse af DR 2-projektet" (Description of the DR-2 Project) (Ref. 3), which was prepared by the project leader and approved by the Planning Committee. The description of the DR-2 project was later translated into English (Ref. 4).

After approval of the Safety Committee the two documents were sent to the Danish Regulatory Authorities during the summer of 1999. The approval of the new safety documentation was received just before Christmas 1999 together with a revised version of "Operational Limits and Conditions".

According to the new "Operational Limits and Conditions" the DR-2 project has to submit semi-annual progress reports to the Danish regulatory authorities. These reports described the project status and results, changes in the plant and modifications of the reactor system, radiation surveillance, use of external work force and submission of reports (Refs. 5, 6, 7, 8, 9, 10).

During the DR-2 project the Risø National Laboratory had a contract with the IAEA on participation in a Coordinated Research Project on Decommissioning Techniques for Research Reactors. This project resulted in a number of publications (Refs. 11, 12, 13, 14, 15). A paper on the project work was also presented at the Meeting on Reactor Physics Calculations in the Nordic Countries in 2001 (Ref. 16).

5.3 Design and Construction of Various Facilities

Since it was part of the project to remove all movable, radioactive components from the reactor tank before a survey of the radiation level in the tank was performed, it was necessary to built a storage facility in the reactor hall for the radioactive components taken out of the reactor. This facility was constructed by use of concrete blocks (30.5×61×61cm). The design of this facility is shown in Figure 5.1. The available storage area is about 180×210cm. The

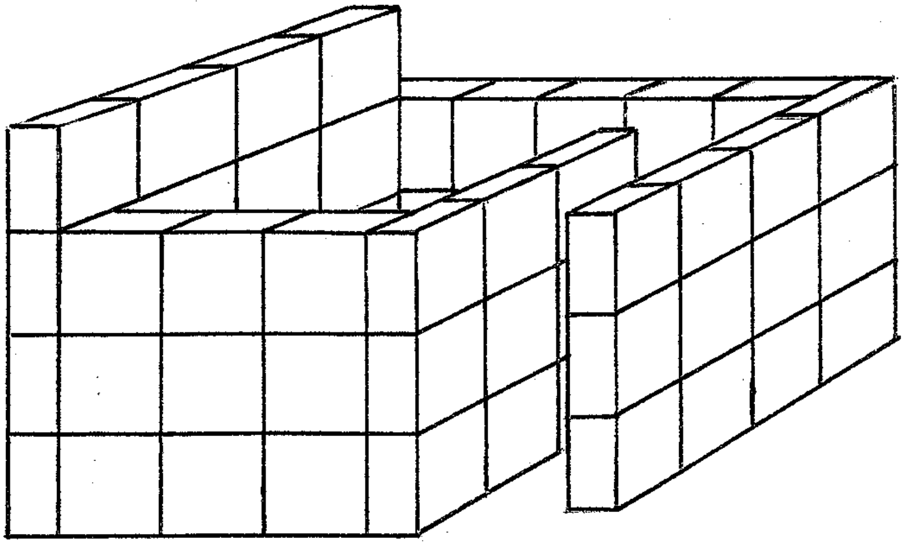

Figure 5.1. The storage facility in the reactor hall

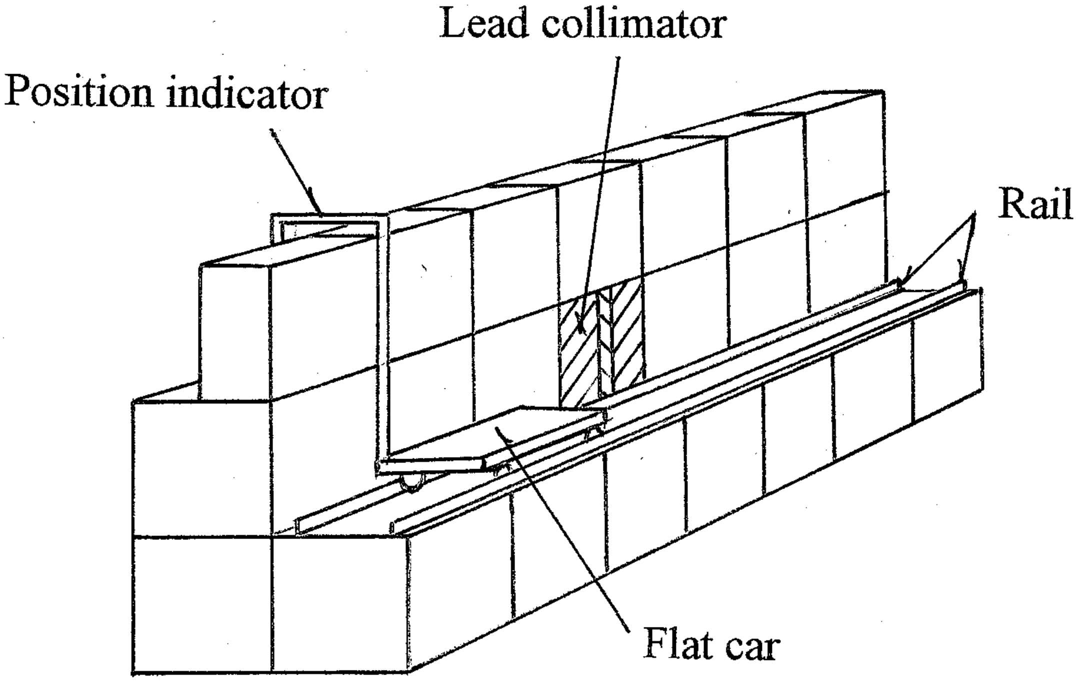

Figure 5.2. The measurement facility in the reactor hall

height of the walls is 180 cm, except towards the reactor block where it is 210 cm to reduce the radiation level at the top of the reactor

It was initially the intention to take all radioactive components out of the reactor tank, to measure the radiation level in the tank and to put the components back into the tank. However, this would have increased the radiation dose to the personnel, since later on the components would have to be taken out again and disposed of. Therefore it was decided to cut - where possible – the radioactive components so that they could be stored in the standard waste drums of Risø. Two types of drums were used, concrete lined drums for components with high activity and black drums for components with low activity. All drums have a height of 88 cm and a diameter of 59 cm. The thickness of the concrete layer of concrete lined drums is about 5 cm, and their useful volume is 70 cm high and 46 cm in diameter. The black drums have a useful volume of 210 liters. To carry out the cutting a hydraulic cutter was procured and mounted on wheels. The concrete lined drums were stored in the storage facility until they had been filled up and could be transferred to the Risø Waste Management Plant. Components that could not be cut and graphite stringers from the igloo were at the end of the project placed in the igloo.

Components with no or very low activity that were taken out of the reactor were marked for future identification and stored in plastic bags in the experimental basement area. At the end of the project they were moved to a box in the operational basement area.

Another facility, which was built in the reactor hall before the start of the project, was a facility to measure the γ-dose-rate distribution along long components taken out of the reactor. This distribution is approximately proportional to the activation-γ distribution. The design of the measurement facility is shown in Figure 5.2. It was built by use of concrete blocks (30.5×61×61cm and 61×61×61cm) except at the middle where one of the concrete blocks was replaced by a 40 cm thick lead collimator, built of lead bricks (5×10×20cm) and provided with a 6 cm wide and 50 cm high opening. One side of the facility was provided with a flat car on which not too heavy components could be place and moved past the collimator by use of a rope arrangement and a scale, while measurements were made on the other side. The distance between the component and the γ-detector was usually 100 cm. In the case of very heavy components such as beam plugs, the components had to be carried by the crane. This arrangement did introduce some inaccuracy in the measurement geometry.

5.4 Health Physics Measurements

To ensure against overexposure a health physicist, who monitored the radiation level, was always present in the reactor hall when radioactive components were handled.

Every week smear tests have been performed at 14 points in the reactor hall, in the basement, and in the changing room to ensure that the project work did not give rise to contamination of surfaces in the rooms.

During all work operations the level of air contamination was monitored by use of a continuous air monitor CAM 90-Proportional Counter and the radiation level in the reactor hall was monitored by use of a gamma remote detector RMS II Eberline.

When working in the reactor building the personnel carried thermo-luminescence dosimeters and Alnor digital dosimeters, which are provided with a visual display of the dose received. After each working day at DR-2 all participating personnel would record the dose received on a paper sheet as read from the Alnor dosimeter.

5.5 Renovation of the DR-2 Archives

When the reactor was finally closed down, two archive cupboards were prepared containing material, in particular drawings, relevant for the later decommissioning. One of these cupboards was placed at the attic of the Risø administration building, the other in the operational basement area of the DR-2. Here the remaining cupboards of the original DR-2 archive were also placed.

During the chemical engineering experiments a liquid spill occurred, which damaged some of the drawings of the original archive. Fortunately the damage was limited and little information got lost. In addition the arrangement of the drawings was not always suitable for a storage period of more than 25 years, and new, relevant material had not been added to the archives during most of these years. Finally in the new Operational Limits and Conditions it was stated that the two DR-2 archives should be identical.

For these reasons a major review of the two DR-2 archives was undertaken. It was ensured that the content of the two archives was identical and that relevant new material was included. The addition of new, relevant material is a process that continues until “green field conditions” have been reached.

The DR-2 archive at the attic of the administration building was later on moved to the DR-2 reactor hall. The DR-2 archive in the operational area of the DR-2 basement was moved twice and is now in a building near, but separate from, the DR-2. The same is true for the original DR-2 archive. Ultimately it is the intention to move the two archives to separate buildings of the DR-3 plant. The reason for keeping the two DR-2 archives in separate buildings is of course that if one of the archives is damaged e.g. by a fire the other will still be intact.

6 Examination of the Reactor Tank

6.1 Opening of the Reactor Tank

It was the intention to start opening of the reactor tank in January 2000 after the Danish regulatory authorities had approve the changes of the DR-2 system needed by the project. However, when the approval was received, a leak developed at about the same time in the reactor tank of the DR-3. Since the personnel from the DR-3 who should perform the work at the DR-2 were now needed at the DR-3, the opening of the DR-2 reactor tank was postponed. Since work on the DR-3 had the greatest priority, the work on the DR-2 project was carried out when DR-3 staff was available. This was also the case after the final closedown of the DR-3 had been decided in September 2000.

In May 2000 the concrete lid was lifted from the top of the DR-2 and placed on wooden beams and plastic sheets on the floor of the reactor hall. Part of the outer railing had to be removed during the lifting, but it was reinstalled as soon as the concrete plate had been removed. Further, the “gallows” was installed at the top of the reactor. Next the layers of lead bricks were removed.

Before the removal of the steel lid that carried the lead layers, air samples were collected in the middle of the reactor tank through a hole in the steel plate to check for any radioactivity or beryllium dust in the air. The measured radioactivity was at the background level. The measured beryllium concentration of the air was 0.8 ng Be/m^3, i.e. well below the level where monitoring becomes necessary (0.2 µg Be/m^3). Next one of the steel plates was partly removed and smear tests were performed on the tank wall at the core level, at the surface of one of the reflector elements, at the top of the thermal column and at the bottom of the tank. The measured radioactivity from the smear tests was all at background level. The cotton of the smear test of the reflector element contained 5.0 µg Be, that of the top of the thermal column 0.5 µg Be and that of the tank bottom 1.9 µg Be. All swipes were wet swipes, and the detected beryllium contamination at all surfaces was at or below the clean surface level (5µg/100 cm^2). From the removal of the steel lid and until the result of these measurements were available, the personnel working at the top used respirator masks, but this use was now abandoned except when the beryllium reflector elements were removed from the tank. Smear tests were also performed on the surface of guide tubes to check for surface contamination, but no surface contamination was found.

The steel lid was removed from the reactor top and deposited on the concrete plate in the reactor hall. As soon as the steel lid had been removed, the inner railing was installed. The tank interior was now open to visual observation. Since there was no record of which components had been stored where in the reactor, it was only at this time that the content of the reactor tank, already discussed in section 3, became known. The inspection revealed that fewer components were stored in the tank than had been expected. The "missing" components were later on found in the igloo of the thermal column, where more components had been stored than expected.

The radiation level at the top of the reactor was measured. Over the reactor tank it varied between 150 and 450 µSv/h while it was 40 to 60 µSv/h at the edge of the tank.

6.2 Removal of the Control Rods and Guide Tubes

As mentioned in section 3 the movable component in the reactor tank were stored in the storage rack or in the grid plate or left hanging down from the steel beams at the top of the reactor tank on which the control rod drive mechanisms had been situated.

The next major operation at the DR-2, which started in November 2000, was the removal of the control rods and the guide tubes from the reactor tank. It was decided first to remove the components in the storage rack of the reactor tank, i.e. the shim-safety rods, the guide tubes and the grid plate plugs. These components were the easiest to move, and it would give the personnel experience in working at the top of the reactor. The removal was expected to reduce significantly the radiation level at the top of the reactor, where much of the work had to be carried out. With experience obtained during the project it would probably have been wiser first to remove the regulation rod, which turned out to be by far the most active component.

As mentioned in section 3 the *shim-safety rods* were hanging down from the bottom of the guide tubes, which were stored in the storage rack. The magnet rods, which had carried the shim-safety rods during the reactor operation, were hanging down from the beams at the top of the reactor tank. One of the magnet rods was released, supplied with power and used to lift the shim-safety rods out of the guide tubes. Once a shim-safety rod had come out, a fork-shaped tool took over the lifting of the rod out of the reactor tank. This procedure was used to remove three of the shim-safety rods.

There were a few minor problems in removing the shim-safety rods. The magnet current had to be increased from the expected 100 mA to 150-160 mA to permit safe lifting with the magnets. Further the absorber part of the rod had a tendency to hit the bottom of the guide tube or the rack, whereby the rod became detached from the magnet, but with some manipulation the rod could be lifted up. The activity of the shim-safety rods was measured in the reactor hall as discussed in section 6.3. Next the lower, neutron absorber part of the rods was separated from the upper part containing the armature and the shock absorber by cutting.

Both these parts were deposited in a concrete lined drum. Fortunately the drum was so high that it was not necessary to cut the absorber part of the rods. They contain B_4C powder, which if the absorber part was cut, could cause contamination.

Two of the shim-safety rods demanded special treatment. One had got stuck in a calibration tool used to measure the thickness of the rods. Since the shim-safety rods are flat and since neutron capture in boron-10 produced helium-4, the pressure inside the rods and therefore their thickness increased during operation. To ensure that the rods could at all times go down into the special fuel elements, the thickness of the rods was regularly checked with this tool. Since the rod, sitting at the bottom of the guide tube had got stuck in the tool, the tool with the rod and guide tube had been placed together in the storage rack. The rod and guide tube were pulled out of the tool by fixing a hook on a wire to the guide tube and holding the tool fixed in the rack by use of a rod. After the release the rod and guide tube were placed in the storage rack and the rod removed with the magnet rod.

The reason why a second shim-safety rod demanded special treatment was that its guide tube had been bend, so that the magnet rod could not go down into the guide tube. Therefore the rod and guide tube had to be taken out as one unit. Due to the length of this component all transport had to be done by use of the crane. Once out of the reactor tank the γ-activity of the shim-safety rods and the γ-dose-rate distribution along the rods were measured at the measurement facility of the reactor hall as described in section 6.3. The upper part of the rods with the shock absorber was separated from the lower absorber part by cutting and both parts disposed of in a concrete lined drum.

Next the *guide tubes*, including the guide tube of the regulation rod, were lifted out of the reactor tank, measured and cut down into a concrete lined drum. The same procedure was used for the three *grid plate plugs*, which had been provided with threaded holes, used to store the 24 stainless bolts during refueling of the special fuel elements. These bolts were used for attaching the six guide tubes to their corresponding special fuel elements. One of the bolts was taken out, measured and stored in a small lead container.

At this point the maximum dose rate at the top of the reactor tank was 300 μSv/h.

The removal from the tank of the *shim-safety rod calibration tool* caused some difficulty since it was stuck in the storage rack and since there was no tool to lift it and its surface had no holes where a hook could be inserted. A noose was tightened around it, and after some manipulation it became loose and could be lifted. The activity of the tool was very low.

The *regulation rod* was hanging at the lower end of its extension rod, the upper end of which was fixed to one of the beams at the top of the reactor. It was lifted out of the tank. Due to its high activity the γ-dose-rate distribution along this rod could not be measured at the measurement facility in the reactor hall, and even the determination of the total activity of the rod caused some difficulty. After the measurement of the activity of the regulation rod, its absorber part was cut in two parts and deposited in a concrete lined drum. The radiation around this drum was rather high, so to reduce it the five *magnet rods* and six *hold-down rods* were cut into pieces and dropped on top of the regulation rod. The activity of the magnet rods and the hold-down rods was very low, so the reason for cutting them and depositing them in the drum was only to use them as shielding material.

Most of the lifting and transport of the components was carried out by use of a hook connected to a rope which via a pulley on the crane could be operated from the hall floor, by use of carrying rods or even by hand transport if the activity was sufficiently low. The "fishing" tools used during reactor operation were not used so much as expected, since the use of these tools gave problems with respect to lifting height.

After the removal of the regulation rod the dose rate at the top of the reactor had decreased to 150 μSv/h.

6.3 Measurement Procedure

When a component was lifted out of the reactor tank, its radiation level was measured at the top of the reactor tank, usually at a distance of 1 m, to get a measure of its γ-activity. The measurement was carried out by use of a RO-20 Eberline γ-rate meter (ion chamber), which was placed over the concrete of the reactor top, while the component was hanging over the reactor tank.

If the component was radioactive, a measurement of its activity was carried out in the reactor hall by use of a Canberra C-10 γ-spectrometer with a Ge-detector. During the measurement the component was hanging freely in the air at a well-defined distance, the size of which depended on the activity of the component. By use of the Genie2k programme and the measured γ-spectrum the radioinuclides involved were identified and their activity calculated. With the same geometry a dose rate measurement was also performed with a Automess Szintomat 6134A rate meter (scintillation counter).

When the γ-dose-rate distribution along a component was to be measured, it was placed on the flat car of the measurement facility in the reactor hall and moved past the lead collimator, where the Automess Szintomat 6134A rate meter measured the dose rate distribution. This distribution is roughly proportional to the induced γ-activity distribution of the component. The distance between the detector and the component varied with the dose rate, but was usually 1 m.

The results presented in this report are given in the units of the instruments with which the measurements were made.

6.4 Removal of the Grid Plate Components

It was feared that corrosion might make it difficult to remove some of the components inserted in the grid plate, but this was not the case. Only one component gave rise to difficulties, as discussed below. In all other cases the components were easily extracted.

The first component of the grid plate to be removed was the *V-tube facility*. It consisted of an aluminium tube with the same cross section as a fuel element. Inside the tube it could accommodate five vertical irradiation tubes. It was lifted out of the reactor tank, measured and cut down into a concrete lined drum.

Next, an aluminium tube with the same outer dimensions as the fuel elements, a so-called *"water hole"*, was removed. It had a circular opening at the top. A hook at the end of a wire was placed around the bar across the opening at the top and the hook was pulled upwards. However, only a cylinder inserted in the top of the tube was lifted with the hook. The main aluminium tube of the "water hole" remained in the grid plate, but it was lifted up afterwards without difficulty. The reason for this unexpected feature of the "water hole" is unknown. From the results of section 6.6 it is seen that the activity of this "water hole" was quite low, so presumably it had only been irradiated in the core during a short period of reactor operation, but it was nevertheless cut down into a concrete lined drum.

The lifting of the *second "water hole"*, also an aluminium tube with the same outer form as a fuel element, gave rise to some difficulty. It had at the top at two opposite sides a hole, in which a hook could be inserted. The first hooks used were not strong enough to permit the lifting of the "water hole", which obviously - for unknown reasons - had got stuck in the grid plate. Hammering on the outer sides of the aluminium tube with a long rod and wobbling it with a rod inside the hole to loosen it had no effect. It was necessary to use a stronger hook and a special tackle that could apply the necessary force (60 kg) to the "water hole", before it finally jumped out of the grid plate. A dynamometer was used to control the force applied. After the removal the "water hole" was measured and cut down into a concrete lined drum.

The removal of the *reflector elements* was similar to that of other components in the grid plate with a few exceptions. During the work all personnel at the top of the reactor used respirator masks, as mentioned in section 6.1. The reflector elements were one by one lifted by insertion of a hook into one of the holes of the stainless steel top piece of the elements. At the top of the reactor tank the activity of the elements was measured at a distance of one meter. The elements were then lowered down to the floor of the reactor hall where they were put into plastic bags. Two of the elements were measured in the measurement facility in the reactor hall (R-58 and R-60). An attempt was also made to determine the β-activity of the beryllium elements. At one of the elements a radiation level of 25 mSv/h was measured with a monitor placed on the surface of the element and without the β-filter while 18 mSv/h was measured with the same geometry, but with the β-filter. However, too much importance should not be placed on these measurements.

Before the removal of the reflector elements an attempt was made to loosen one of the stainless steel bolts, which connects the top piece of the element to the beryllium part. It was done with the tool, which has been used to remove and insert the bolts connecting the special fuel elements to the guide tubes. However, the bolts could not be loosened without damaging the "screw driver". Therefore the attempt was abandoned. A new attempt was made on element R-52 in the reactor hall, but due to the high radiation level and difficulties in getting the screw loose, the removal of the bolt would have resulted in too large personnel doses, and the attempt was stopped. A final attempt was made on R-60 with the element placed behind concrete blocks, except for the top piece. Here it proved possible to remove all the four bolts and the top piece. The activity of the bolts, the top piece and the beryllium block were measured separately. The top piece and the beryllium block were placed in one of the stainless steel containers, while the bolts were placed in a separate lead container. It may be noted that according to the available drawings the top pieces were made off aluminium, but actually they were made of stainless steel.

After the measurements all reflector elements in their plastic bags were deposited in two stainless steel containers, six elements in each. These containers had been made for the purpose. They were later sent to the Waste Management Plant.

After the removal of the reflector elements the radiation level at the top of the reactor above the tank had been reduced to 75 µSv/h.

6.5 Removal of other Components

A number of other components, usually not radioactive, were removed from the reactor tank. One was a *round steel disk,* another a smaller, crescent shaped steel plate. Both were the result of the cutting long before the project of a hole in the steel lid. It was this hole that had been used to obtain air samples down in the reactor tank (cf. section 6.1). These steel pieces had after the cutting dropped down on the grid plate. They were lifted out of the tank by use of a strong permanent magnet.

Another component to be removed was the *suction tube* used to remove any objects that was deposited on the inlet (top end) of the fuel elements. The suction tube was at the top of the reactor connected to a plastic hose, which was removed by cutting. When it was cut, a small amount of water came out.

A third component was a *double tube* that had been used in connection with measurements of the water height of the reactor tank. Due to its length and place in the tank it was difficult to get out, and it was somewhat bent during this operation. Care was taken that the double tube did not hit the reflector elements during its removal.

A fourth component to be removed was a *sphere* resting on the top of the thermal column. It had presumably been used in connection with the equipment for measuring the water level of the reactor tank. All these components were found to be non-radioactive and were stored in plastic bags in the experimental area of the basement.

The final component to be removed was an *aluminium tube* that had been sitting in a vertical hole in the thermal column, where the abandoned pneumatic facility had originally been placed. The purpose of this tube was to improve the natural circulation of the water in the hole, i.e. act as a chimney. This tube contained a significant amount of activity and was consequently cut down into a concrete lined drum.

During the work in the reactor tank there was a number of minor problems, e.g. problems with the relays of the crane and with the ventilation system, that after some modifications started to blow dust into the reactor hall. However, these problems were all solved without too much difficulty, even though they caused some delays in the work.

Samples of the various materials removed from the reactor tank were collected for later analysis at the Waste Management Plant for radionuclides with long half-lives.

The removal of all movable parts of the reactor tank was accomplished at the beginning of February 2001.

6.6 Measurement Results

The results of the measurements of the activity of the control rods and the guide tubes are given in Table 6.1.

Table 6.1. Activity of Shim-Safety Rods and Guide Tubes

	Absorber Part (MBq ^{60}Co)	Guide Tube (MBq ^{60}Co)	Total (MBq ^{60}Co)
Shim-Safety Rod SR(E)	114	741	855
Shim-Safety Rod SR(D)	76	557	633
Shim-Safety Rod SR(C)	122	496	618
Shim-Safety Rod SR(B)	103	614	717
Shim-Safety Rod SR(A)			919
Regulation Rod SR(RR)	23.000	871	24,000
Total			27,750

From Table 6.1 it is seen that the activity of the *regulation rod* dominates the activity of the control rods. The only radionuclide identified was ^{60}Co.

In Figure 6.1 the γ-dose rate distribution of the *shim-safety rods* is given as measured in the measurement facility of the reactor hall. The γ-dose rate distribution along a component is roughly proportional to the activity distribution, as seen by the detector. At the bottom end of the rods the activity curve increases with height (except for SR(A)). The reason is that the bottom piece is made of aluminium only, but higher up the absorber part of the rods contains two lead filled stainless steel tubes, which gets activated in spite of the neutron absorption of

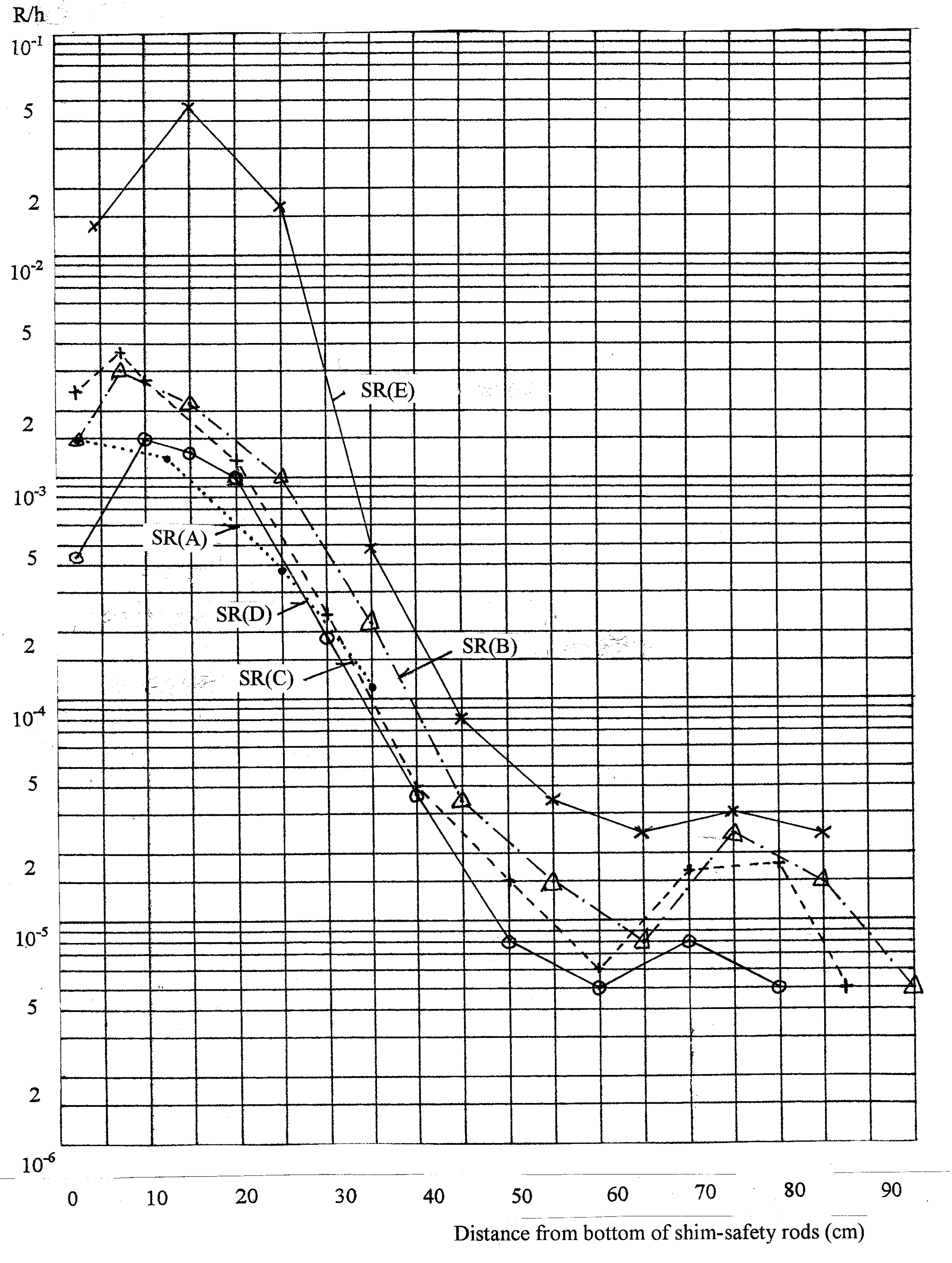

Figure 6.1. γ-dose rate distribution along the shim-safety rods as measured in the measurement facility

the surrounding B_4C powder. Since only the lower part of the shim-safety rods were inserted into the core during reactor operation, the radiation level goes through a maximum after which it decreases with height until it gets close to the background level. The curve for SR(A) is only given up to a height of 35 cm from the bottom of the rod, since higher up the measurements start to be affected by the guide tube from which it could not be separated. The shim-safety rods were 73 cm long (excluding the extension rod at the top), of which the absorber part was 65 cm.

Figure 6.1 gives the γ-dose rate distribution curves along the five shim-safety rods. According to Table 6.1 the activities of the shim-safety rods are about the same. Consequently it would be expected that the dose rate distribution curves would also be similar. As is seen from Figure 6.1 this is not the case, since the dose rate level of the rod SR(E) is at the bottom end an order of magnitude higher than that of the other rods. The reason for this difference is not known.

In Figure 6.2 the γ-dose rate distribution of the *guide tubes* is given as measured in the measurement facility. Due to the flange at the bottom of the guide tubes and the holes higher up the mass of the tubes per unit length vary with the distance from the bottom. Nevertheless the activity decreases roughly exponentially, as would be expected, with the height above the bottom end. It is seen that at a distance of about 60 cm the radiation level reaches the background level. The length of the guide tubes was about 102 cm.

Table 6.2 presents the measured activities of the grid plate plugs, a single bolt from the grid plate plugs, the V-tube facility, the water hole with insert and the water hole without.

It is seen from Table 6.2 that the activity of the listed components all was fairly low. The only radionuclide identified was ^{60}Co. From the activation distribution of the grid plate plugs and from Table 6.2 it is clear that the activity of the grid plate plugs originate almost completely from the stainless steel screws.

To avoid too much manipulation with the *reflector elements* the activity and the γ-dose rate distribution were only measured for two beryllium reflector elements. However, the radiation from the reflector elements in the distance of one meter was measured for all elements at the top of the reactor. The result of these measurements are given in Table 6.3

Table 6.2. Measured γ-Activities of Grid Plate Plugs and "Water Holes"

	MBq
Grid plate plug (6 bolts)	36
Grid plate plug (9 bolts)	50
Grid plate plug (9 bolts)	43
V-tube facility	23
"Water hole" with insert	2
"Water hole" without insert	44
Total	198
(A single bolt	6.8)

In Table 6.3 "Type" indicates whether the elements are made of solid beryllium (solid), are provided with a ¾" diameter water hole (3/4" hole) or are provided with a 2" diameter hole, filled with a beryllium cylinder (2" hole). The grid plate was provided with six by eight element positions, of which the 12 reflector elements were placed in the six positions at each end of the grid plate. "Position" in Table 6.3 indicates whether a reflector element was placed in a corner position of the grid plate (Corner), in one of the two central positions (Central) or between these two positions (Middle). Two radionuclides, ^{60}Co and ^{137}Cs, were identified for

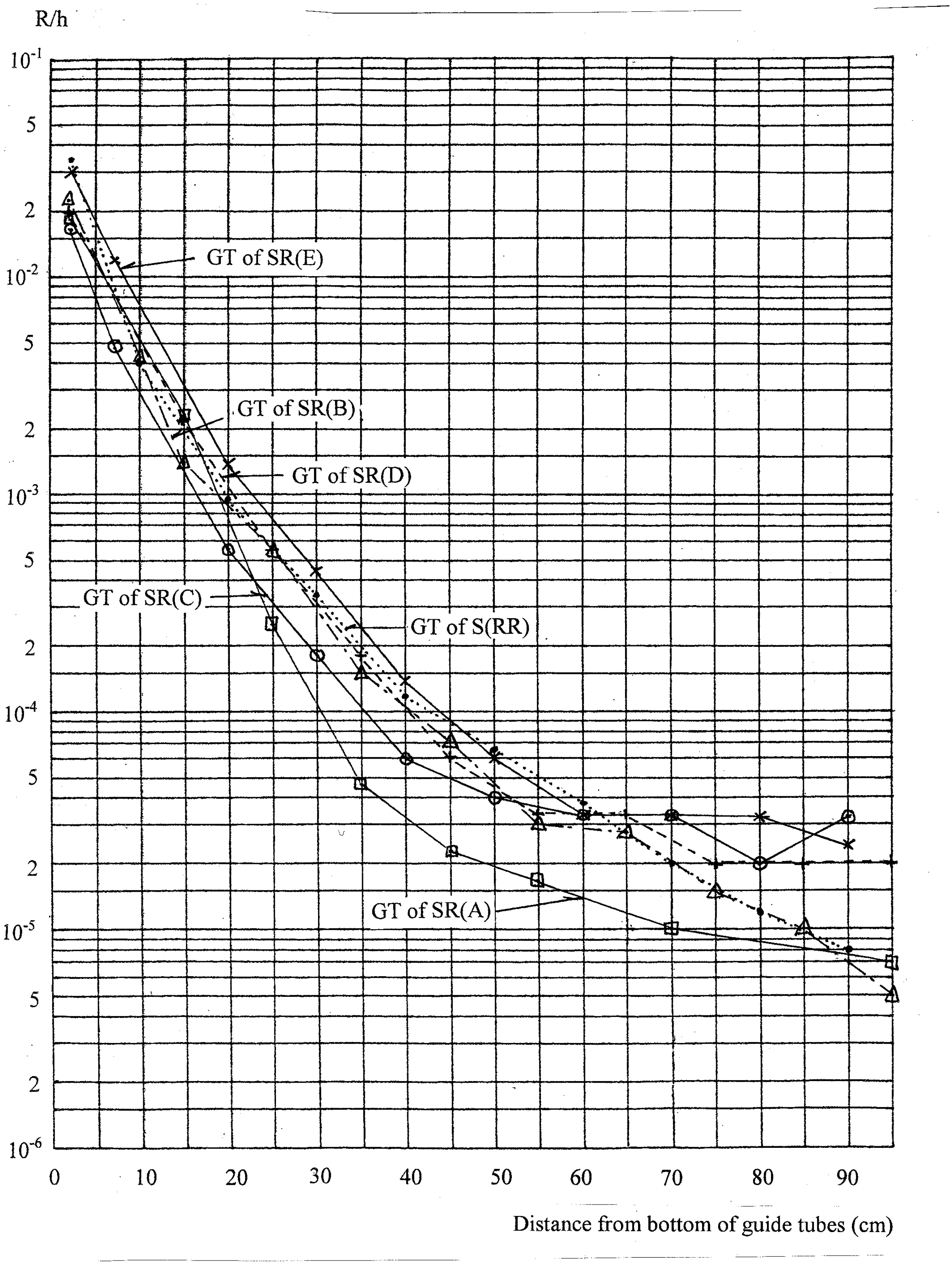

Figure 6.2. γ-dose rate distribution along the guide tubes as measured in the measurement facility.

the two reflector elements for which the activity was determined by a γ-spectrum measurement. The ^{137}Cs nuclides could originate from fission in uranium impurities in the beryllium or they could have been deposited on the surface by the reactor water. The ^{60}Co originates presumably from iron impurities in the beryllium. The last column of Table 6.3 gives the dose rate measured in one meter distance from the reflector elements at the top of the reactor tank.

Table 6.3. Measured activities of the Beryllium Reflector Elements

Element	Type	Position	MBq ^{60}Co	MBq ^{137}Cs	μSv in 1 m
R-58	Solid	Corner	770	43	500
R-60	Solid	Corner	809	49	550
R-52	2" hole	Central			500
R-54	¾" hole	Middle			600
R-53	2" hole	Central			470
R-55	¾" hole	Middle			500
R-59	Solid	Corner			400
R-50	2" hole	Corner			450
R-61	Solid	Middle			550
R-56	¾" hole	Central			750
R-51	2" hole	Middle			550
R-57	¾" hole	Central			600

In the case of reflector element R-60 the four stainless steel bolts were removed and the activity of the four screws (56 MBq), that of the stainless steel top piece (235 MBq) and that of the beryllium part (518 MBq ^{60}Co and 49 MBq ^{137}Cs) was measured. These figures demonstrate that the stainless steel part of the top piece and the bolts add significantly to the activity of the element, but that the activity of the beryllium itself makes the largest contribution. From the data of table 6.3 it has been estimated that the total γ-activity of all reflector elements was about

10 GBq

In Figure 6.3 the γ-dose rate distribution along the two reflector elements R-58 and R-60 is given. At the top end the activity of element R-58 the radiation level is higher than for R-60, since the stainless steel top piece and the four stainless steel screws had been removed from R-60 before the measurement. The length of the top piece was 6.4 cm, while beryllium part of the reflector elements was 73 cm.

After the reflector elements had been placed in the two stainless steel containers, the radiation level at the outer surface of the containers was measured to 35-40 mSv/h. In 1 meters distance it was 1.6-2 mSv/h.

Table 6.4 gives a review of the activity of all the radioactive components removed from the reactor tank. It is seen that the total activity of the components removed is close to one Curie. This activity represents the major part of the activity of the components in the reactor tank. The result agrees well with the activity estimate based on the measurement performed in 1998 (cf. section 5.1).

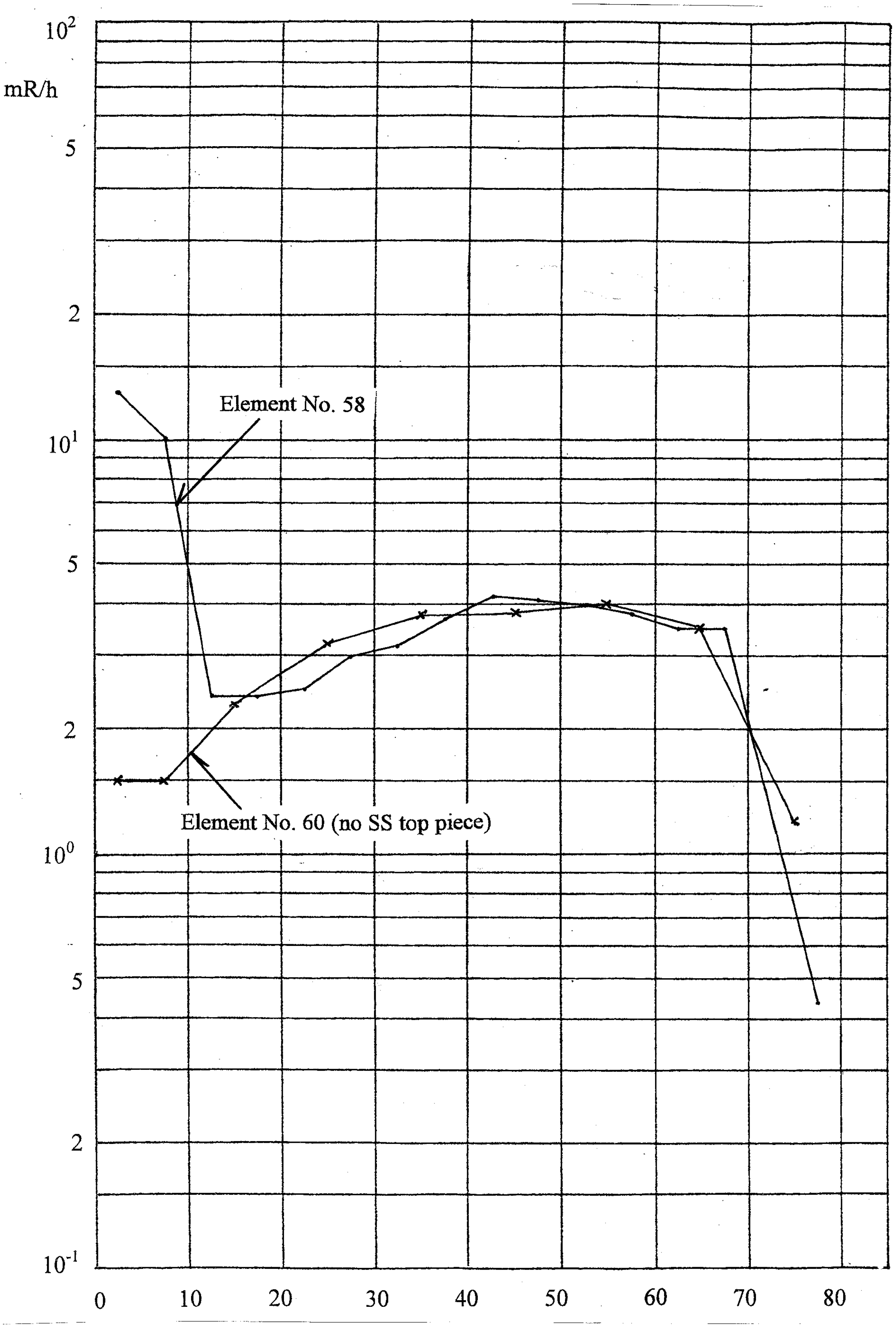

Figure 6.3. γ-dose rate distribution along two beryllium reflector elements as measured in the measurement facility

Table 6.4. Activity of Components Removed from the Reactor Tank

	Activity GBq
Shim-Safety Rods	3.75
Regulation rod	24.00
Plugs and water holes	0.20
Reflector elements	10.00
Total	37.95

These components and some further components from the hold-up tank room and the igloo (see section 7 and 8) were cut into smaller pieces, loaded into drums and transferred to the Waste Management Plant. During the DR-2 project a total of four concrete lined drums (high activity components), two stainless steel containers with the 12 reflector elements, five stainless steel boxes with waste from the Hot Cells, and two black drums (low activity components) were sent to the Waste Management Plant. In addition a collection of material sampled was also sent to this plant. One not yet full black drum remains in the igloo.

6.7 Determination of the Remaining Radiation in the Reactor Tank

After all movable components had been removed from the reactor tank a number of thermoluminescence dosimeters were placed at various positions in the reactor tank and left there for 16 days, after which they were taken out and measured. The γ-dose rates in the tank due to the remaining activity are presented in Figures 6.4 and 6.5. Note that the two fuel elements and guide tubes shown in Figure 6.4 in the grid plate and the two fuel elements in the storage rack had of course been removed long before these measurements.

From these figures it is seen that the radiation level in the former core region is around 25-50 mSv/h. It is highest in front of the thermal column (49 mSv/h), but also quite high at the grid plate (39 mSv/h). The high dose rate in front of the thermal column is presumably due to the unexpectedly high γ-activity of the graphite stringers (see section 8.3), but the activity of the lead of the lead nose does also contribute (see section 8.3). The rather high value near the grid plate is presumably due to the stainless steel pins in the grid plate, but also its significant mass of aluminium including impurities. The dose rate decreases with distance from the core, but it is noted that the dose rates on the thermal column side of the tank are higher than on the opposite side. The reason for this difference is again believed to be the activity of the graphite.

7 Examination of the Hold-up Tank Room

After the examination of the reactor tank had been terminated, it was the plan to continue with the examination of the igloo in front of the thermal column and the column itself. However, since the experimental basement area was needed for the storage of heavy water drums from the DR-3, but also needed for the examination of the hold-up tank room, it was decided to examine the hold-up tank room first.

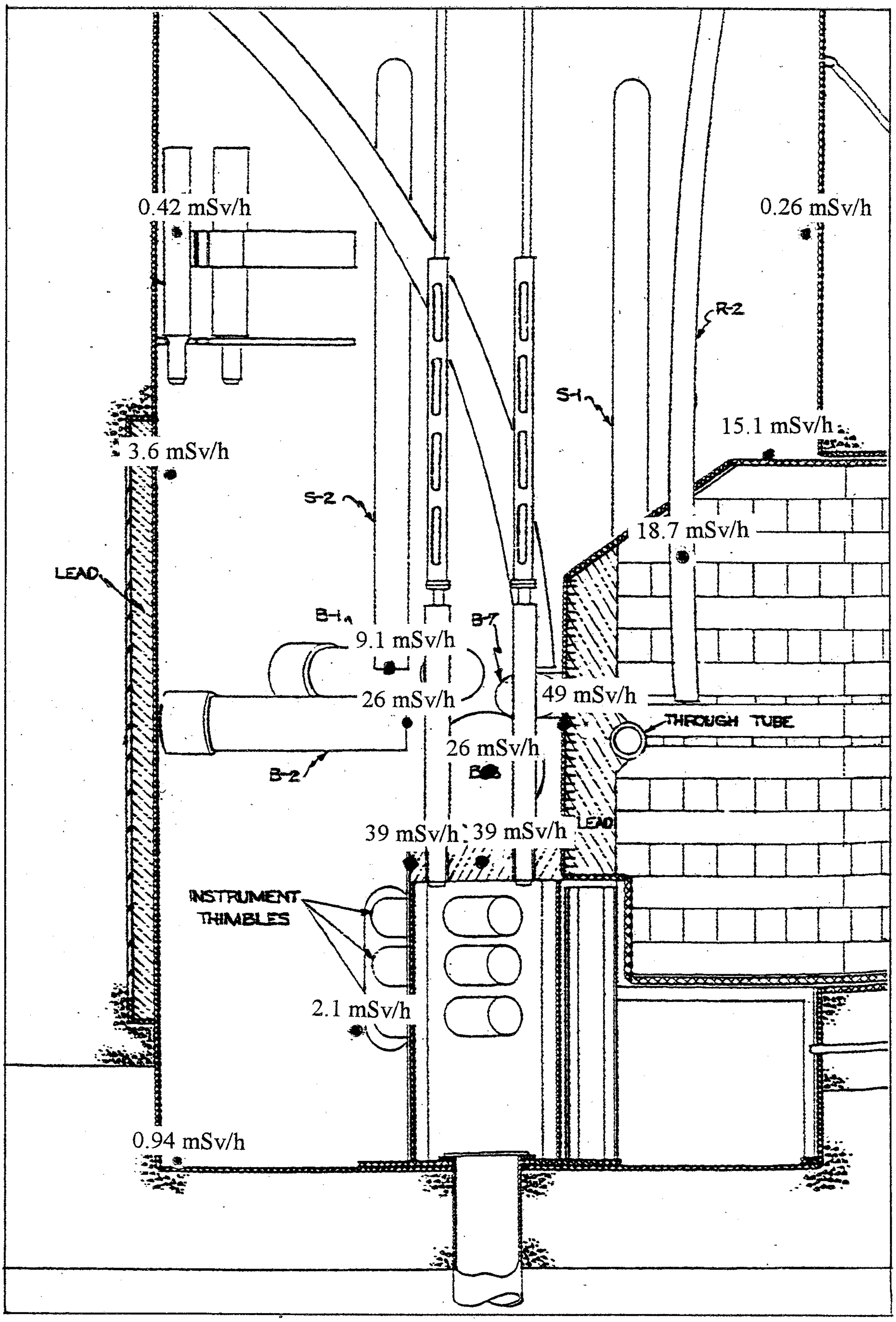

Figure 6.4. Vertical cross section of the reactor tank giving the γ-dose rates measured with thermo-luminescence dosimeters over a period of 16 day

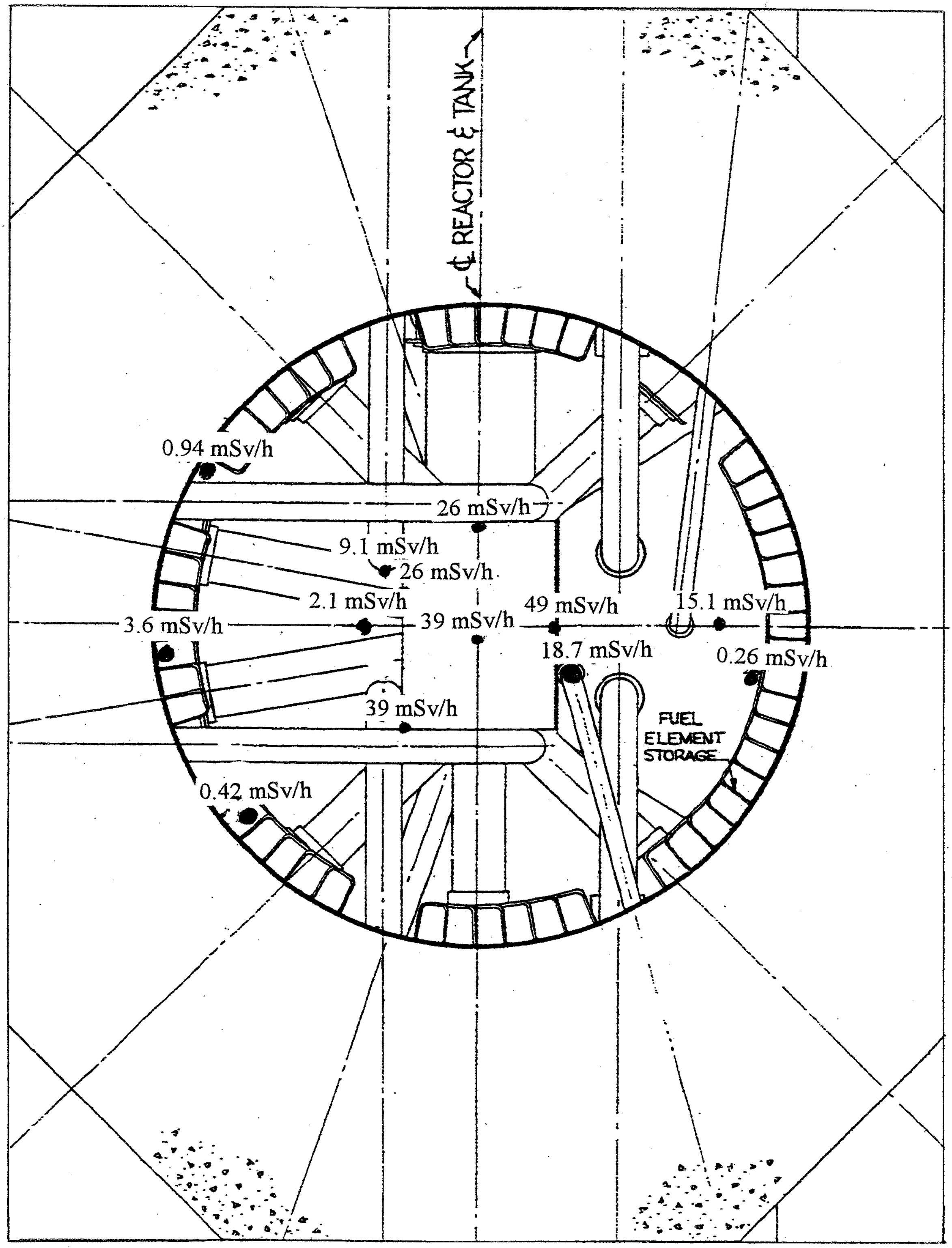

Figure 6.5. Horizontal cross section of the reactor tank giving the γ-dose rates measured with thermo-luminescence dosimeters over a period of 16 days .The thermal column is seen to the right

The hold-up tank room is situated directly below the reactor block and contains the hold-up tank (cf. Figure 2.3 and 2.5). The purpose of this tank was to ensure that the short-lived activities of the coolant, produced when the coolant passes down through the core, have decayed before the coolant reaches the pumps and the heat exchangers of the primary circuit in operational basement area.

The concrete blocks in front of the hold-up tank room were removed so that the room could be entered. It was known that contaminated glove box components from the Hot Cell facility had been stored in the hold-up tank room. These components were stored in five flat stainless steel boxes (about 1.5×1.5×0.3m) with a volume of 0.58 m^3. The boxes were taken out into the experimental basement area and the radiation level at the outside measured. The results of these measurements are given in Table 7.1 together with the data given on the plate of the boxes. Afterwards the containers were sent to the Waste Management Plant.

Table 7.1. Radiation levels on the surface of Hot Cell boxes

	Radiation level May 2001 µSv/h	Plate information: Radiation level R/h	(mSv/h)	Date	Container weight
Box No.1	50	4.5	(= 45)	01-03-1977	500 kg
Box No.2	25	0.016	(= 0.16)	01-03-1977	400 kg
Box No.3	150	3.5 R/h	(= 35)	01-03-1977	800 kg
Box No.4	120	7 R/t	(= 70)	01-03-1977	560 kg
Box No.5	80	0.175 R/h	(= 1.75)	16-10-1978	490 kg

In addition to the five boxes the room contained two major components. One was a heavy, flat box (about 2×1×0.5m), wrapped in paper and plastic sheets. On the box "Left coil outwards" was written. The radiation level at the surface of the box was measured to be 70-80µSv/h at one of the ends and 2µSv/h at the other. The component originates from a system of magnetized cobalt mirrors used to produce a beam of polarized thermal neutrons. A description of the system is given in Ref. 17. Since the box, below referred to as "the magnet box", is big, heavy and radioactive, it has been left in the hold-up tank room.

The other major component was a beam chopper (?), presumably used in connection with a beam experiment. Its upper part was active, but not very much (<4µSv/h). The shutter was moved to the storage facility in the reactor hall. From here it was at the end of the project moved to the igloo.

In addition to the five boxes and the two major components mentioned above the hold-up tank room contained a number of smaller components, often of unknown origin or use. The major part of these was not radioactive. The radioactive components that were too large to fit into the waste drums were moved to the storage facility in the reactor hall, from where they were later transferred to the igloo. The non-active or possibly slightly radioactive parts were in plastic bags stored in the experimental basement area awaiting release measurements. The remaining parts were after further investigation all found to be slightly radioactive and deposited in black drums (no concrete lining). These drums were later sent to the Waste Management Plant.

At the end of the examination of the hold-up tank room the wall of concrete blocks were partly rebuilt (the upper row of concrete blocks was not installed) to prevent non-authorized access to the room. The only movable component left in the room is the magnet box.

The examination of the hold-up tank room was started in March and terminated in June 2001.

8 Examination of the Igloo and the Thermal Column

8.1 The Igloo

The igloo in front of the thermal column had been used in a somewhat unorganized way for storage of slightly radioactive components, e.g. five of the original beam plugs, ion chambers, an underwater television camera from the reactor tank, irradiation tubes used in the V-tube facility (cf. section 6.4) and in the reflector elements, graphite stringers (used in the thermal column), various tools etc. In some cases the use of these components could be identified, in some cases not.

The igloo was opened for one day in June 2000 to get a first idea of its content by removal of one of the two concrete blocks in front of the entrance to the igloo. At that time the radiation level at the entrance was 25-35 μSv/h. The actual examination of the igloo and the thermal column was started in June 2001, when the two concrete blocks were moved outwards towards the wall of the reactor hall in such a way that they minimized the γ-radiation outside the reactor building. At this time the radiation level at the entrance was measured to be 22 μSv/h, while the maximum radiation level at the wall of the reactor building was 0.18 μSv/h.

The examination of the components of the igloo followed a procedure similar to that used for the reactor tank and for the hold-up tank room. The components were taken out one by one, and their activity – if any – was measured with a β-sensitive rate meter. If no activity could be measured they were sent to another building for more accurate measurements. If they were clearly, but not significantly, active, they were stored in the reactor hall for further examination. If they contained significant amounts of activity, they were placed in the storage facility of the reactor hall. After the additional examinations the active components were cut into pieces and stored in either concrete lined drums or black drums, depending on their activity. If they were too large for the drums and could not be cut, they were stored in the storage facility of the reactor hall. If they were only very slightly radioactive or nor at all, they were stored in plastic bags in the experimental basement area. Material samples were taken and sent to the Waste Management Plant for later analysis for radionuclides with long half-lives.

The γ-dose rate distributions along the tubes of the V-tube facility (3/4”) and along vertical tubes (5/4”), which had been inserted in reflector elements with 2” holes, were measured. The result of these measurements is shown in Figure 8.1

The 3/4” tube distributions give a measure of the vertical flux distribution of the reactor core and the top reflector, since these tubes went down to the bottom of the core. Note that the core flux does not have its maximum at the middle of the core since the control rods, coming in from above, will push the flux maximum downwards.

The activity of two of the 16 graphite stringers in the igloo was measured. All graphite stringers that had been stored in the igloo were arranged in six parcels, wrapped in plastic sheets with 1, 2 or 4 stringers per parcel. The parcels were transferred to the storage facility in the reactor hall. To make the transport of the parcels easier, they were provided with a rope handle. These stringers had not been permanently installed in the thermal column, but had been used for irradiation purposes. The result of the activity and dose rate measurements on two graphite stringers is given in Table 8.1.

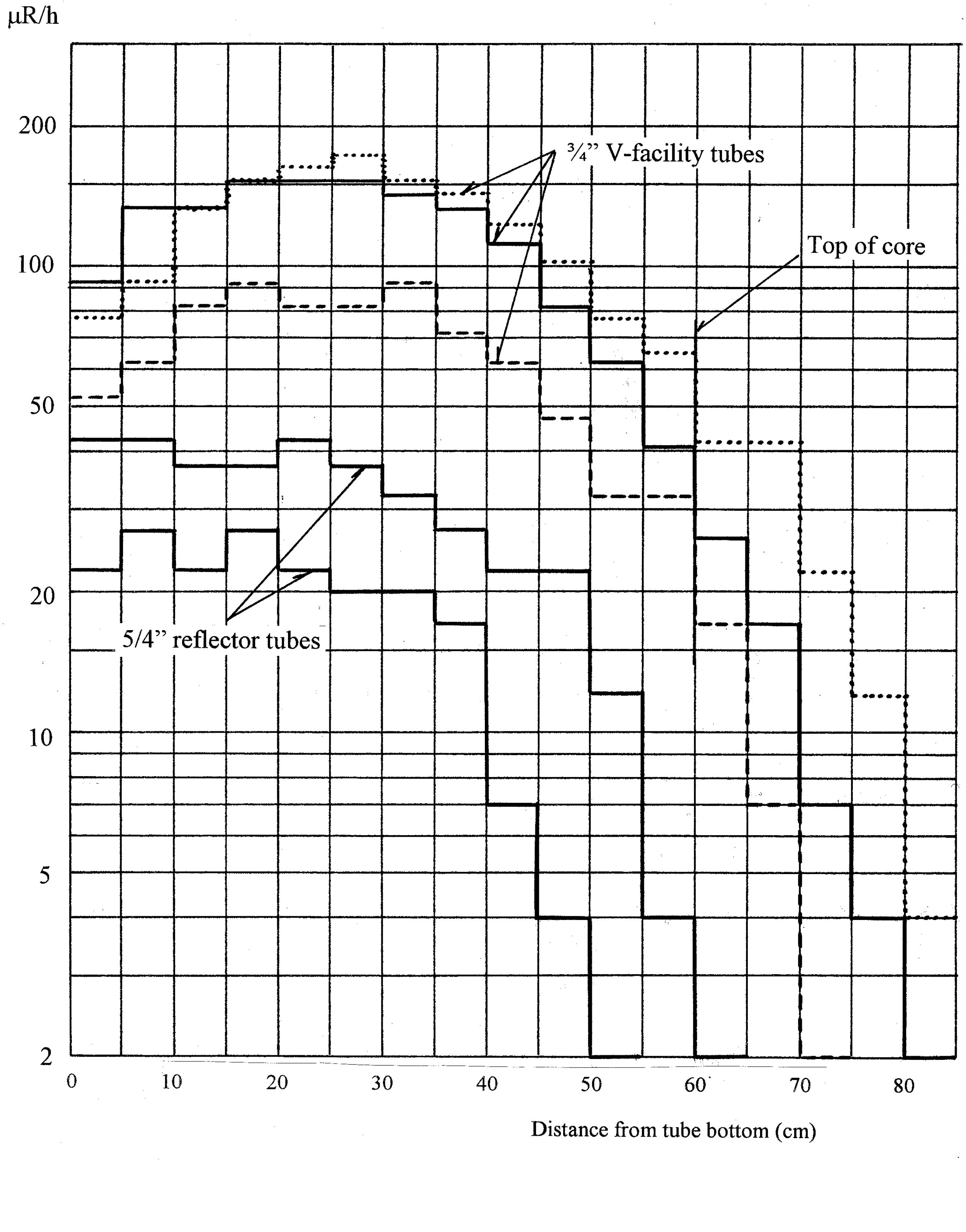

Figure 8.1. γ-dose rate distribution along V-facility tubes and the irradiation tubes of the reflector elements

Table 8.1. Activity of two Graphite Stringers Stored in the Igloo

	Radiation at surface (µSv/h)	Radiation in 1 m (µSv/h)	^{152}Eu activity (MBq)	^{154}Eu activity (MBq)	^{60}Co activity (MBq)
Graphite stringer No. 1	-	20	45.6	6.25	0
Graphite stringer No. 2	400	15	33.6	4.42	0.312

Five of the original, concrete filled beam plugs from Foster Wheeler were stored in the igloo on small cars. The dose rate at the hot end of these plugs was found to vary between 10 and 60 µSv/h. They were used initially in the reactor, until they were replaced by new plugs, which were provided with neutron channels to permit beam experiments outside the reactor block. Their activities are given in Table 8.2.

Table 8.2. Activity of Five Original Beam Plugs

	^{60}Co activity (MBq)	^{40}K activity (MBq)	^{133}Ba activity (MBq)	^{152}Eu activity (MBq)	Radiation at hot end (µSv/h)
Beam plug No.1	0.155	0.203	0	0	30
Beam plug No.2	0.175	0.193	0	0	32
Beam plug No.3	0.0369	0.177	0	0	10
Beam plug No.4	0.0887	0.189	0.0542	0	14
Beam plug No.5	0.268	1.65	0.0462	0.0350	60

The diameter of beam plug No. 1, 3 and 4 was 212 mm and that of No. 2 and 5 was 170 mm.

8.2 The Thermal Column

After all components had been removed from the igloo, the movable shielding door was activated with only minor problems, and the door moved outwards until it came out of the igloo. Here the floor of the hall had been repaired and painted with epoxy painting, and the door got stuck due to the higher level of the repaired floor. To permit the door to move further out, the floor painting in front of the igloo was removed over the necessary area. After the paint removal the door could move further out. The igloo was vacuum cleaned, and then there was free access to the outer surface of the thermal column, which is shown in Figure 8.2. The thermal column consists of graphite stringers. Most of these has a cross section of 10.2×10.2 cm and their length varied between 40 and 75 cm. The density of the graphite is around 1.6 g/cm^3 so the mass of the stringers varies from about 7 to 13 kg. The total mass of the graphite in the thermal column is about 4 tons.

Firstly an attempt was made to remove the central stringer (position 8,7), one of the five stringers which could be assessed through the movable concrete door, and which were all closed with a lead plug at the outer end of the thermal column. When this plug was removed at position (8,7) it turned out that there were no graphite stringers behind the plug. The same was found to be true for position (9,2) and (9,5). The reason for the missing stringers is undoubtedly that most irradiations in the thermal column were performed in the inner stringer in its inner position and with the outer stringer removed to allow rapid removal of the inner stringer. The missing stringers are without any doubt those found in the igloo.

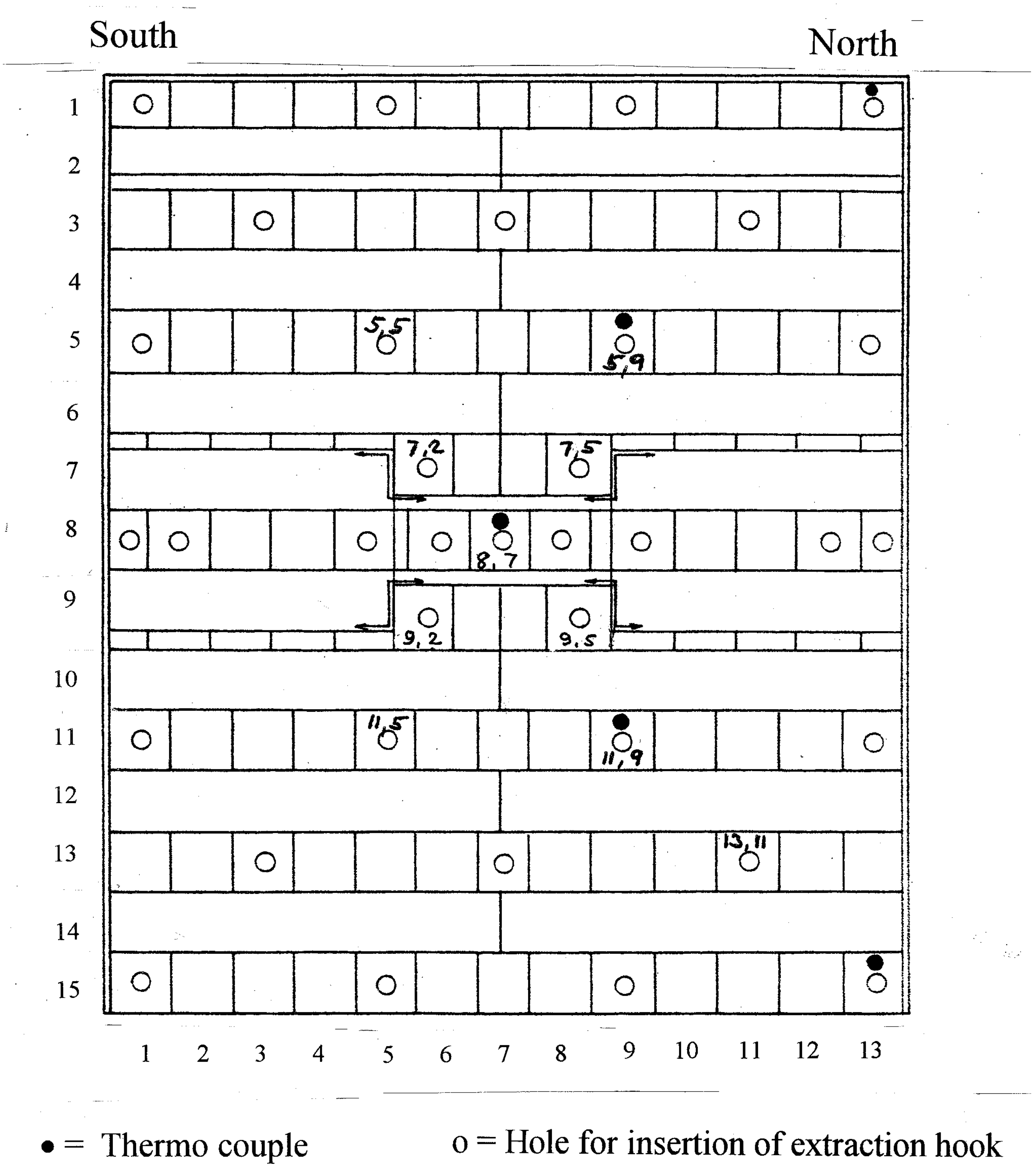

Figure 8.2. Front face of thermal column. Approximate dimensions: 130×160 cm

However, in position (7,5) there were two graphite stringers, and they were, after the lead plug had been removed, pulled out by use of a steel rod, which at the end was provided with a hook. This steel rod had been stored in the igloo. The outer stringer was 40 cm long, the inner 65 cm. The inner was provided with holes for irradiation boxes. The activity of the two stringers and the activity distribution along the stringers was measured after which they were reinserted in the thermal column.

The same procedure was followed with the stringers of position (5,5), where the outer was 75 cm long and the inner 45 cm, position (5,9) where the outer was 75 cm long and the inner 60 cm, position (13,11) where the outer was 75 cm long and the inner 60 cm, and position (7,2) where the outer was 40 cm long while the inner was 65 cm.

At two positions, (11,5) and (11,9), it was only possible to get the outer stringers out. In the case of position (11,5) it was 75 cm long, while for (11,9) its length was 50 cm.

Graphite samples were taken by cutting off a corner of both the inner and the outer end of both stringers of position (7,5). The same done for the two stringers of position (5,5)

To get some idea of the γ-activity of the lead nose of the thermal column, a drilling device was built, mounted on a "sledge", that could be moved through the holes of one of the positions, when the stringers had been removed. The drill was sitting at the end of a long rod. At the other end of the rod was mounted a drilling machine. The cuttings were collected on a tray. At position (5,5) two lead samples were obtained and at position (7,2) one lead sample was taken. An aluminium sample was obtained by drilling at the end of position (13,11).

In the stringers of (5,9) a thermo couple had been placed. It was removed and its activity and γ-dose rate distribution measured.

8.3. Thermal Column Measurements

The measured activities of the graphite stringers are presented in Table 8.3. "n.m." means not measured.

The result of the activity measurements of Table 8.3 was a surprise. The dominating europium activities were unexpected. It had been expected that there would be a limited amount of γ-activity from ^{60}Co. Presumably the europium activities are due to impurities in the graphite. Since all the stringers listed in table 8.3 have been pulled out regularly during the operation of the DR-2, the europium of the stringers could be due to surface contamination while the stringers were out of the thermal column. That this is not the case was demonstrated by taking out one of the stringers of the top layer of the thermal column, which have never been taken out before. A γ-spectrum measurement on this stringer revealed that it contained europium also. The ^{152}Eu has a rather complex γ-spectrum with γ-lines in the range from 0.12 to 1.41 MeV, while ^{154}Eu has γ-lines from 0.72 to 1.27 MeV.

It should be noted that the radiation level involved during the work at the thermal column was quite modest so the emptying of the thermal column of graphite should not give rise to major concern. Respirator masks were not used during the extraction and reinsertion of graphite stringers due to the limited amount of work and the absence of graphite dust. But the use of masks may well be advisable when the all graphite stringers are to be finally removed.

The activities recorded for the inner stringers are, as should be expected, larger than for the outer except for ^{154}Eu for position (7,5) where the value of the outer stringer seems too high. It should be noted that the length of the graphite stringers varied from about 40 to about 100 cm and that the measured activities given in Table 8.3 have not been corrected for the length (mass) of the stringers.

Table 8.3. Activity of Graphite Stringers

	^{60}Co (MBq)	^{152}Eu (MBq)	^{154}Eu (MBq)	Dose rate in 1 m (µSv/h)	Length of stringer (cm)
Inner stringers:					
Position (7,2)	0.0560	15.8	1.81	8	65
Position (7,5)	0.456	17.2	1.91	7	65
Position (5,5)	0.124	18.7	3.55	7	40
Position (5,9)	n.m.	n.m.	n.m.	8	55
Position (13,11)	0.0772	19.4	1.45	10	60
Outer stringers:					
Position (7,2)	0.0284	6.64	0.844	5	40
Position (7,5)	0.0456	4.92	1.97	4	40
Position (5,5)	0.0928	8.16	0.195	5	75
Position (5,9)	0.108	12.4	0.876	7	59
Position (11,5)	0	18.5	1.33	7	75
Position (11,9)	0	8.92	1.45	6	75
Position (13,11)	0	12.4	0.412	5	75

It was to be expected that the highest activities would be found in the central parts of the thermal column, where the neutron flux should be the highest, while the activity should be lower at the outer regions. This does not seem to be the case, possibly because irradiation experiments involving strong neutron absorbers in the five central positions, i.e. (8,7), (7,2), (7,5), (9,2) and (9,5), have distorted the flux distribution.

When comparing the values of Table 8.3 with those of Table 8.1, the two stringers of Table 8.1 could well be two of the inner stringers missing in position (8,9), (9,2) or (9,5).

As in seen from Table 8.3 and 8.1 ^{152}Eu is the dominating activity. A rough estimate of the total γ-activity of the thermal column was obtained in the following way. The thermal column contains about 200 stringers in both the outer and the inner part. Averaging the activity values for the outer and inner stringers of Table 8.3 yields 18 MBq for the inner stringers and 10 MBq for the outer. Thus the total activity of the graphite should be about 6 GBq. This is probably an overestimation since it does not take into account the lower neutron flux along the sides of the thermal column. So probably

4 GBq (or 0.1 Curie)

is not an unreasonable figure for the activity of the graphite of the thermal column.

β-activity measurements of ^{14}C and ^{3}T were not part of this project, but samples were taken to permit such measurements. Results of measurements on these samples are reported in Ref. 18.

The γ-dose rate distributions along the graphite stringers are shown in Figure 8.3, 8.4, 8.5 and 8.6. The outer ends of the outer stringers were all at the same plane (the outer surface of the thermal column) except for position (7,5) and (7,2), which ended at the lead plug. For this reason the γ-dose rate curves starts at the outer surface of thermal column (or at the inner end of the lead plugs) and the distance values increase in the negative direction of the x-axis.

If the europium contamination had been uniform over the stringer volume, the dose rate curves should have varied linearly on a semi-logarithmic scale. This is hardly the case for most of the stringers. For both stringers of position (7,5), (7,2) and (5,5) of Figure 8.3 and 8.4 the γ-dose rate curves goes through a maximum, while it for the inner stringer of position

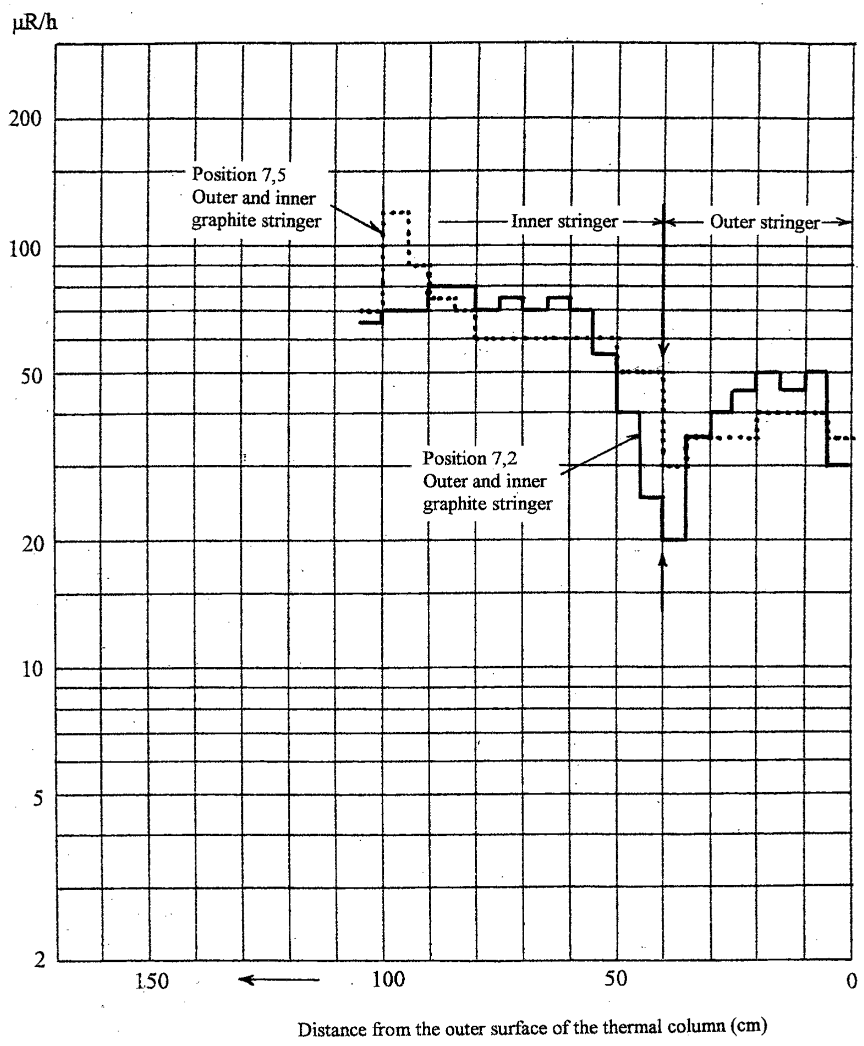

Figure 8.3. γ-dose rate distribution of the graphite stringers of position (7,2) and (7,5) from the outer end of the outer stringers and inwards

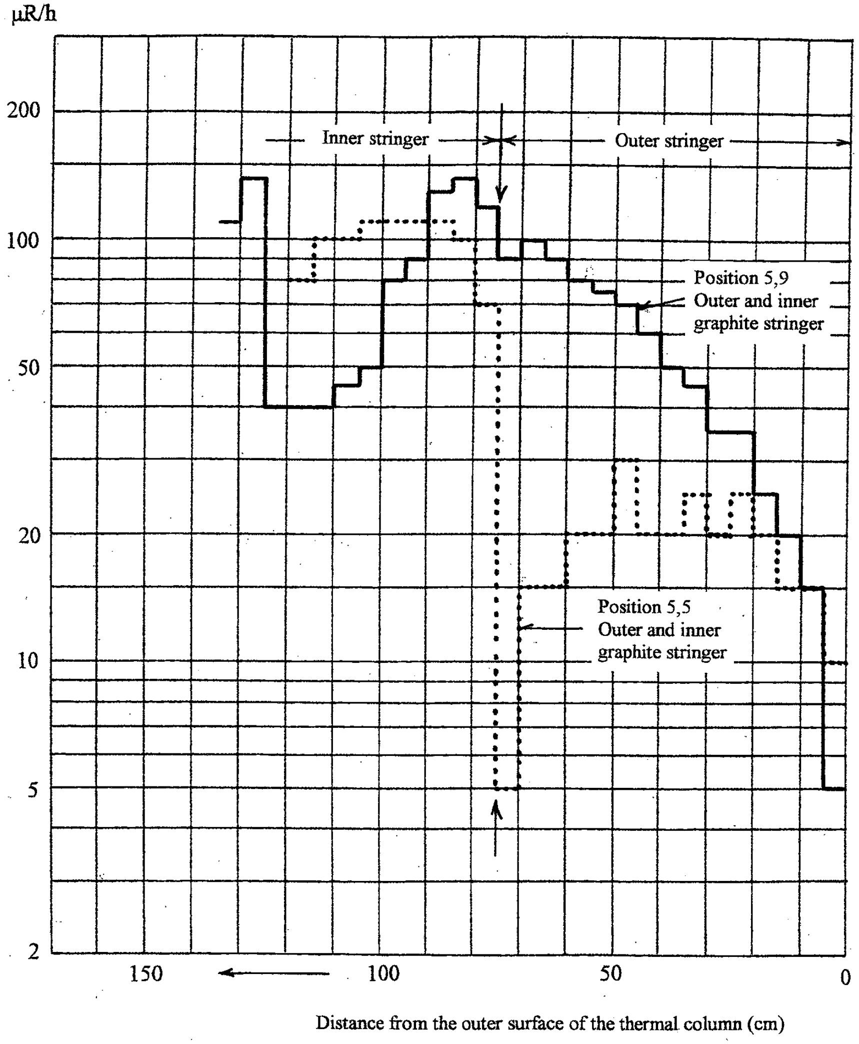

Figure 8.4. γ-dose rate distribution of the graphite stringers of position (5,5) and (5,9) from the outer end of the thermal column and inwards

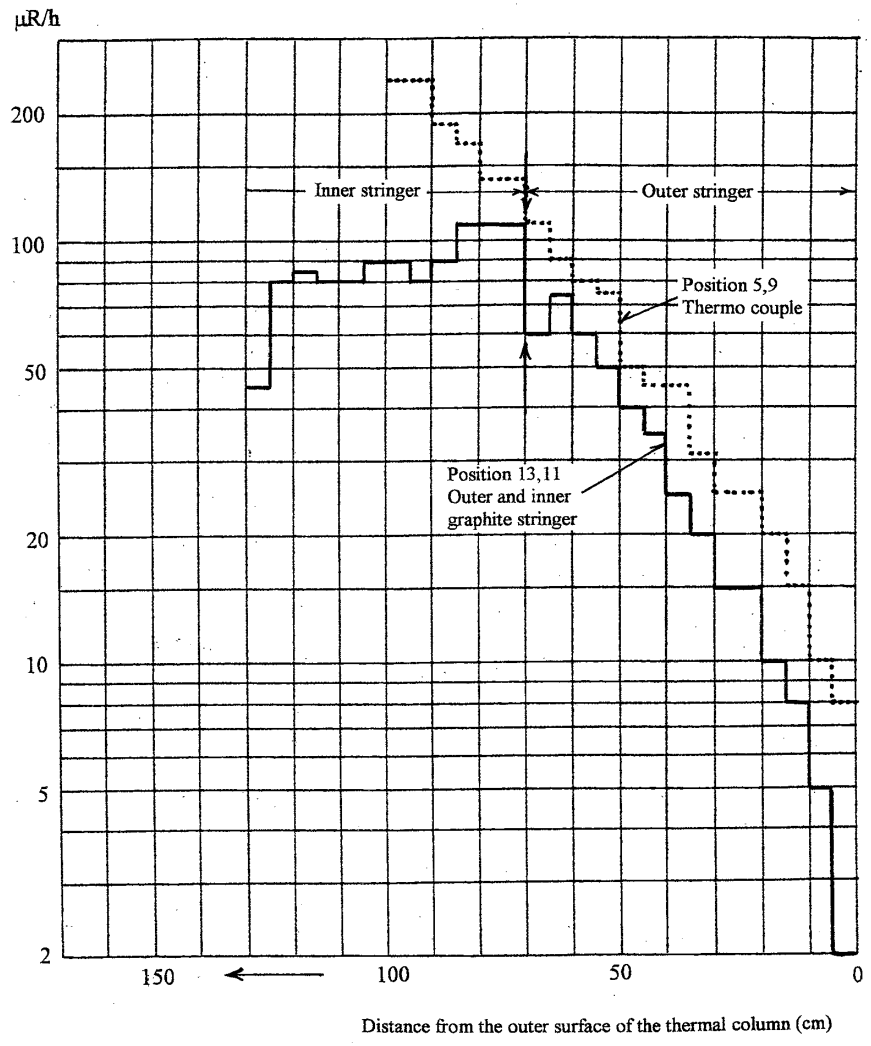

Figure 8.5. γ-dose rate distribution of the graphite stringers of position (13,11) and of the thermo couple of position (5,9) from the outer end of the thermal column and inwards

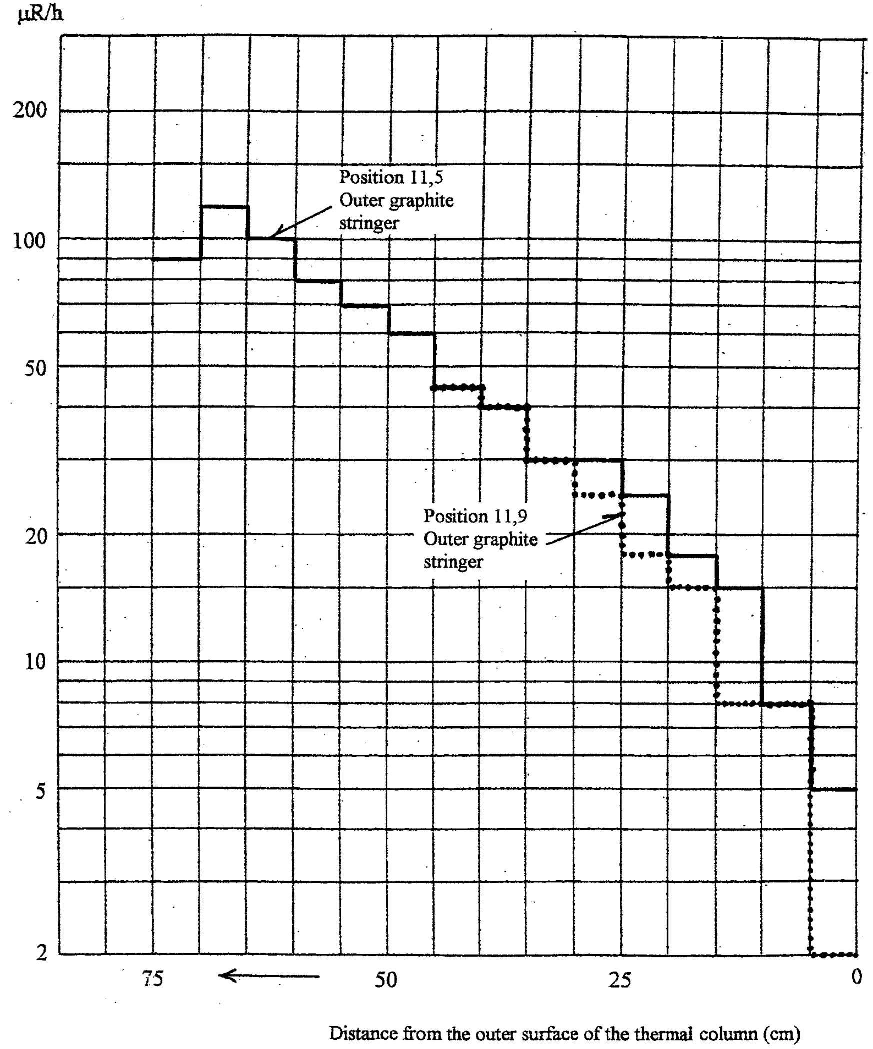

Figure 8.6. γ-dose rate distribution of the outer graphite stringers of position (11,5) and (11,9) from the outer end of the thermal column and inwards

(5,9) of Figure 8.4 goes through a minimum. In other cases such as the outer stringers of position (13,11), (11,5) and (11,9) of Figure 8.5 and 8.6 the γ-dose rate curves are reasonably close to be linear. Note that the γ-dose rate distribution curve of the thermo couple of position (5,9) is very close to a straight line. The total activity of the thermal couple was 17.6 MBq ^{60}Co.

The reason for these very different variations of the dose rate curves is probably non-uniform content of europium in the graphite stringers.

As mentioned in section 8.2 three lead samples and one aluminium sample was drilled out of the nose of the thermal column. The result of the activity measurements of these samples is given in Table 8.4.

Table 8.4. Activity of Lead and Aluminium Samples

	Mass (g)	^{60}Co Bq	^{108m}Ag Bq	^{60}Co (Bq/g)	^{108m}Ag (Bq/g)
Lead sample 1	6.885	1790	569	260	83
Lead sample 2	1.717	193	2090	112	1220
Lead sample 3	2.390	83.5	1140	35	480
Aluminium sample	0.945	868	0	920	0

The amount of lead in the lead nose of the thermal column is about 1 ton, so the total activity of the lead nose is

about 0.1 GBq ^{60}Co and about 0.5 GBq ^{108m}Ag

^{60}Co has two γ-lines of 1.17 and 1.33 Mev, both with a yield of 100%. ^{108m}Ag has three γ-lines of 0.4, 0.6 and 0.7 MeV, each with a yield of 70%.

Both the activity of the lead nose and of the graphite will contribute to the radiation level at the core region. However, their contribution will be reduced by the shielding effect of the lead nose.

The removal of components from the igloo and the examination of the thermal column were finished in October 2001.

It should be mentioned that when the graphite stringers are taken out of the thermal column for disposal, it may be worth to consider, whether at least the inner part of the stringers should be annealed, e.g. at 350 ^{o}C, to remove most of the Wigner energy of the graphite. Annealing experiments could be made on the stringers that are at present stored in the igloo.

9 Examination of the Beam Tubes, the S-Tubes and the Instrument Thimbles

9.1 Beam Tubes

The examination of some of the *beam tubes* was started in October 2001. The steel plates that covered the vestibule boxes and that were welded to the faceplate on the surface of the reactor block were removed from B-3, from B-5 and T-1 and from B-8 and T-2. Any shielding material in the vestibule boxes was removed, and so was cooling tubing and other loose components. Remaining water in the tubing of the beam plugs was drained and the vestibule boxes cleaned.

The *B-5 beam plug* was pulled out without difficulty by use of a lever and a rope. Once the outer end of the plug was outside the surface of the faceplate, a belt hanging down from the hook of the crane was put around the plug to support it. Using the crane to lift the plug slightly so that it left the bottom of the beam hole without touching the ceiling the plug was pulled out. The belt was gradually moved inwards on the plug until it reached the center of gravity of the plug, which was situated about 75 cm from the outer end of the plug. Carried by the crane, the activity of the plug was measured to be:

B-5: 36 MBq ^{60}Co

The activity of the plug was concentrated at its inner end, where the radiation level at the surface of the plug was 600 μSv/h, while it was 30 μSv/h in a distance of 1 meter. The γ-dose rate distribution along the plug was determined by use of the measurement facility of the reactor hall with the plug hanging in the belt from the hook of the crane and moved by the crane past the collimator. The results of these measurements are given in Figure 9.1.

The same procedure was followed for the *B-3 beam plug*, which was somewhat more difficult to pull out. Unfortunately the result of the activity measurement got lost, but it is undoubtedly close to that of B-5 since the γ-dose rate distributions are quite similar. The radiation level in a distance of 1 meter from the inner end of the plug was 15μSv/h, somewhat lower than for B-5. The γ-dose rate distribution along the B-3 is given in Figure 9.1.

While the plugs were out of the reactor block an attempt was made to pull out the two *beam hole liners*. First the bolts of the liner were removed. Then bolts were introduced in two threaded holes in the end flange of the liner and by turning these bolts the liner could be moved a little outwards. The following outward movement was achieved by use of a lever and a rope. A belt, hanging down from the crane to carry the liner once it was sufficiently far out of the beam hole, was used here too. Once the liner had been extracted, dose rate measurements were performed.

This process was accomplished successfully for the *liner of B-3*, though with some difficulty, since the liner was hard to get out. The activity of the liner was found to be

Liner of B-3: 57 MBq ^{60}Co and 0.64 MBq ^{137}Cs

The ^{137}Cs may have been deposited on the outside of the liner by the tank water or the ^{137}Cs may originate from fission of uranium impurities in the aluminium liner. The γ-dose rate at a distance of 1 meter from the inner end of the liner was measured to be 26 μSv/h.

The result of the γ-dose rate measurement is shown in Figure 9.1.

The attempt to extract the *liner of B-5* was not successful. It was moved a bit outwards, but with great difficulty. Since it would have to be reinserted after the measurements and since there was some doubt whether this would be possible, the attempt to extract the liner was abandoned.

An attempt was made to pull the *beam plug of B-8* out of the reactor, but with the force available the attempt was not successful. B-8 was never used for an experiment, but to avoid leaks the nose piece of B-8 was early during the operation of DR-2 replaced by one of a better design. However, the outer part of B-8 is that supplied by Foster Wheeler.

As mentioned in section 2.3 the DR-2 has eight beam holes, five 6" holes (B-1, B-2, B-3, B-4 and B-5), two 4" holes (B-6 and B-7) and one 13" hole (B-8). From the measurements discussed above it is estimated that the total activity of the eight beam plugs and liners is

around 1 GBq (or 0.03 Ci)

This value is quite uncertain since it depends on the design of the plugs, which again depends on the experiments performed and also on the time the plugs were in the reactor. The liners have not been changed so they have been in the reactor all the time.

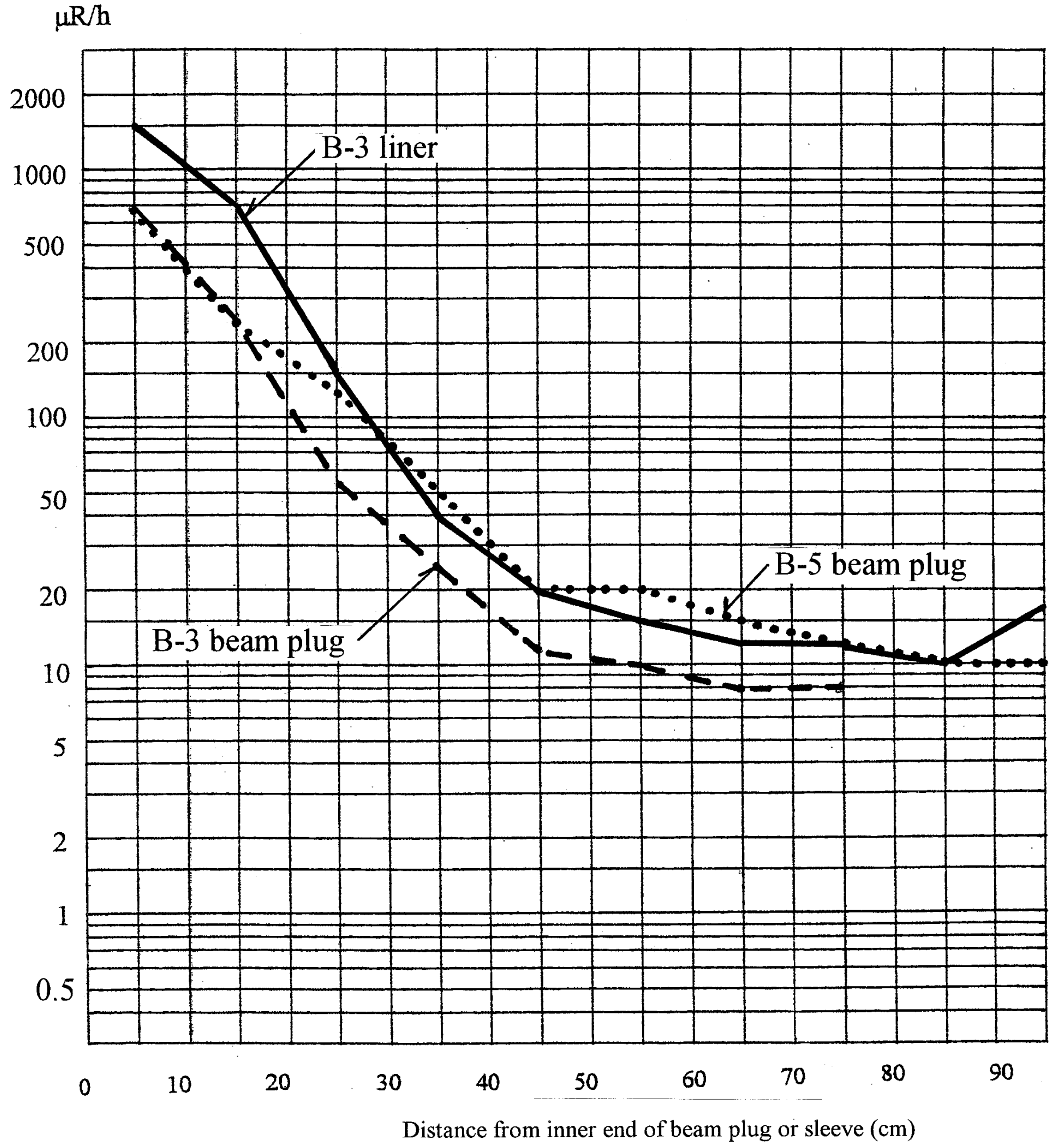

Figure 9.1. γ-dose rate distribution along beam plugs B-5 and B-3 and the liner of B-3.

It is seen from Figure 9.1 that at a distance of about 70-80 cm from the inner end of the plugs and the liner the γ-dose rate reaches the background level of the reactor hall (about 10 μR/h). In this connection it is of interest to note that this length is about the same as the distance from the core to the reactor tank wall, which for B-3 is about 75 cm and for B-5 is about 65 cm.

The DR-2 was provided with a *through-tube*, T-1-2, which penetrated the thermal column. It was opened in both ends and beam plugs at both ends (T-1 and T-2) were extracted and measured. The plugs consisted of an outer and an inner part. T-1-2 had been used for a pneumatic system to inject and extract samples for short irradiation. This system, a long tube arrangement, was taken out, and its activity measured. The central, thicker part of the pneumatic system was cut into a black drum while the outer parts were stored in the experimental basement area. Afterwards the T-plugs were reinserted. The results of the activity measurements on the through-tube components are presented in Table 9.1.

Table 9.1. Activity of Through- Tube Components

	^{60}Co (MBq)	^{152}Eu (MBq)	^{137}Cs (MBq)
T-1, outer shielding plug	0.82		0.003
T-1, inner shielding plug	0.45		
T-2, inner shielding plug	0.20		
Pneumatic tube system	2.41	0.16	0.04

9.2 S-Tubes

The S-2 irradiation tube was covered by a steel plate, which was welded to the faceplate. The plate was removed by grinding. The S-2 tube was provided with a double isotope irradiation tube. Initially it was difficult to move the S-2 tube, but pulling the isotope tube somewhat out and pressing it towards the S-tube made it possible to move the S-tube so far out that a rope could be placed behind its top flange. After that the S-tube, hanging in a robe attached to the hook of the crane, was taken out with no further difficulties, measured and reinserted. The activity of the S-2 tube was 13 MBq ^{60}Co. The dose rate at the surface of the bottom end of the S-tube was 600 μSv/h. The γ-dose rate distribution of the S-2 tube is shown in Figure 9.2. The activity of the double isotope tube was 0.59 MBq. The radiation level at the surface of the bottom end of the isotope tube was 30 μSv/h. The lower part of the isotope tube was disposed of in a black drum, the upper part was stored in the experimental basement area. When the double isotope tube had been removed from the S-2 tube there were no further loose parts in the tube.

The S-5 irradiation tube was covered by a steel hatch, which was locked with a padlock. The lock was cut with a saw. The extraction of the S-5 tube caused some difficulties initially. It proved necessary to cut part of the railing in front of the S-5 tube to get it out, but after that the S-tube was successfully pulled out. The S-5 tube contained a thin tube, which could not be pulled out. There were no loose parts in the tube. The S-tube was measured and reinserted. The activity of the S-5 tube was 11 MBq ^{60}Co and 0.5 MBq ^{137}Cs. The γ-dose rate distribution of S-5 is shown in Figure 9.2.From the measurements of the two S-tubes it can be estimated that the total activity of the six S-tubes is

about 0.1 GBq

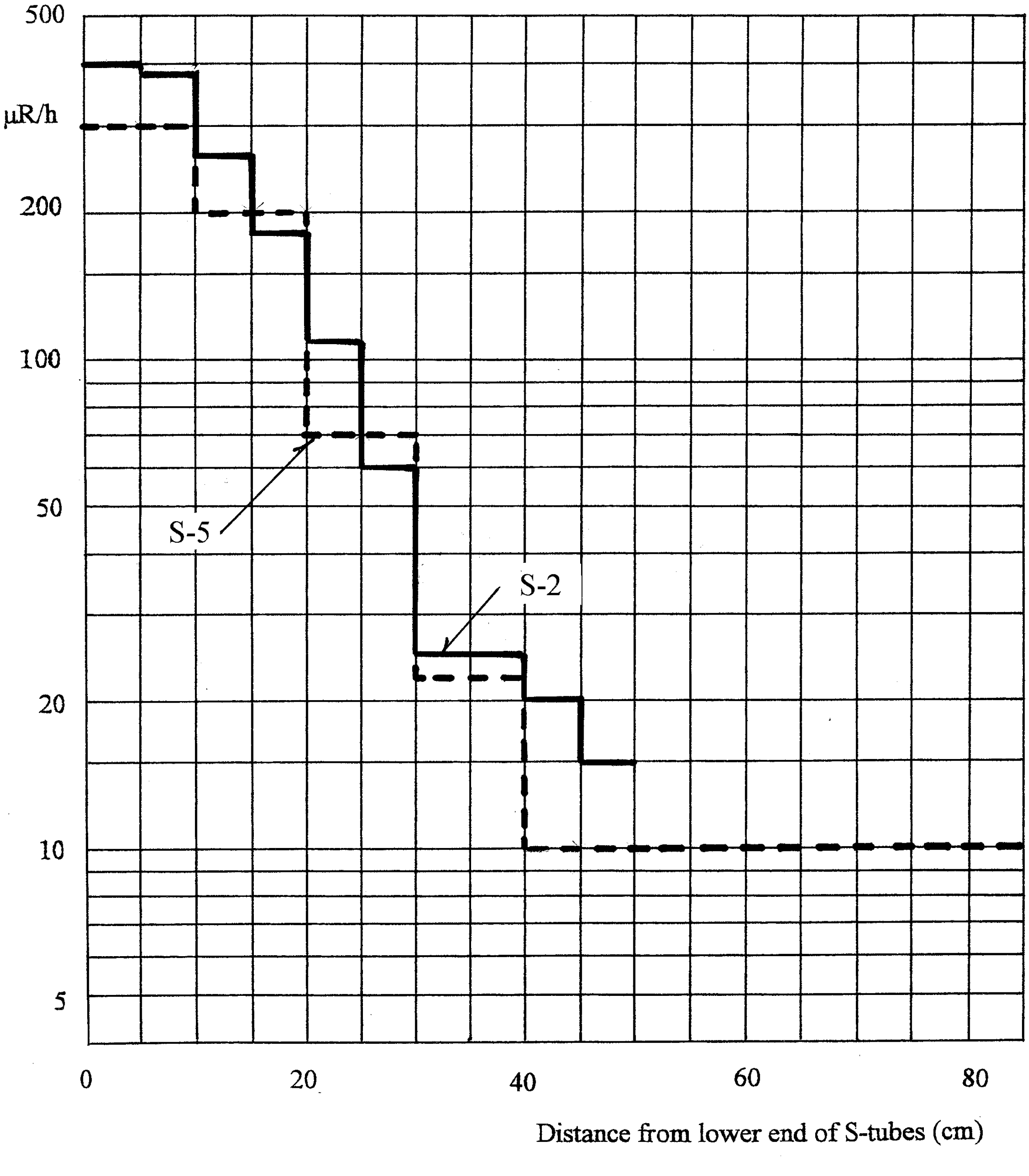

Figure 9.2. γ-dose rate distribution along the S-2 and S-5 tubes.

9.3 Instrument Thimbles

Removal of the steel plate covering the entrance to the southern instrument thimbles gave access to the three southern instrument thimbles, the upper, the middle and the lower thimble. The shielding plugs of the lower and middle thimbles had not been fully inserted, after the ionization chambers had been removed. They were difficult to get out, since they were covered by a significant layer of rust. It is believed that this rust was formed due to a small water leakage, presumably from the reactor tank through the concrete shield down to vestibule box of the southern instrument thimble. Such a leak may also have developed at the northern instrument thimbles. The upper plug, which had been fully inserted, was not rusty and was the easiest to get out.

As expected all ionization chambers were removed and transferred to the igloo when the reactor was finally closed down. The dose rate of the shielding plugs of the lower and middle thimble was at the background level of the reactor hall (0,1 μSv/h=10 μR/h). The upper plug was connected to an arrangement for the movement of the fission chamber during operation. The activity of this component was measured to be 0.51 MBq ^{60}Co, 0.31 MBq ^{137}Cs and 0.12 MBq ^{133}Ba. The activity was concentrated in the inner 60 cm of the 3 m long component. While the shielding plugs were out the dose rate in the three instrument thimbles was measure by use of a XETEX instrument with the detector at the end of telescope rod. The result is shown in figure 9.3. It should be noted that under the grid plate, measurements in the lowest thimble gave the highest dose rate and the highest thimble the lowest dose rate, though the difference is not large. This might indicate that there in a radiation source at the bottom of the tank, e.g. under the thermal column, where any lost object can not be seen from above.

Figure 9.3 demonstrates that the dose rate is highest under the grid plate (i.e. in the inner 40 cm). Then it decreases very rapidly. The reason for this decrease is that due to too high γ-sensitivity of the ionization chambers during start-up, it was necessary to place a U-shaped lead shield (with the "legs" downwards) around the instrument thimbles to reduce the γ-radiation. This was done both around the southern and the northern thimbles. It may be noted the radiation level just outside the grid plate is significantly higher for the highest thimble than for the two others. The reason may be that the lead shielding has been activated. Around the wall of the reactor tank, the radiation level increases somewhat due to the disappearance of the lead shield, but decreases again out through the concrete shield of the reactor block. After 70 to 80 cm of concrete it reaches the "background level". The reason for the high value of this "background level", 15-25 μSv/h, is that it is composed by two components: The radiation from the reactor tank out through the instrument thimbles and the background level in the concrete.

The examination of the beam tubes, the S-tubes and the instrument thimbles was concluded in December 2001.

10 Examination of the Concrete Shield

10.1 Activation Measurements through Beam Tube

While the liner was removed from the beam hole B-3 a measurement was made of the variation of the γ-dose rate inside the beam hole from the inner end near the tank wall to the outer end in the vestibule box. It was done by use of the XETEX telescope instrument. The

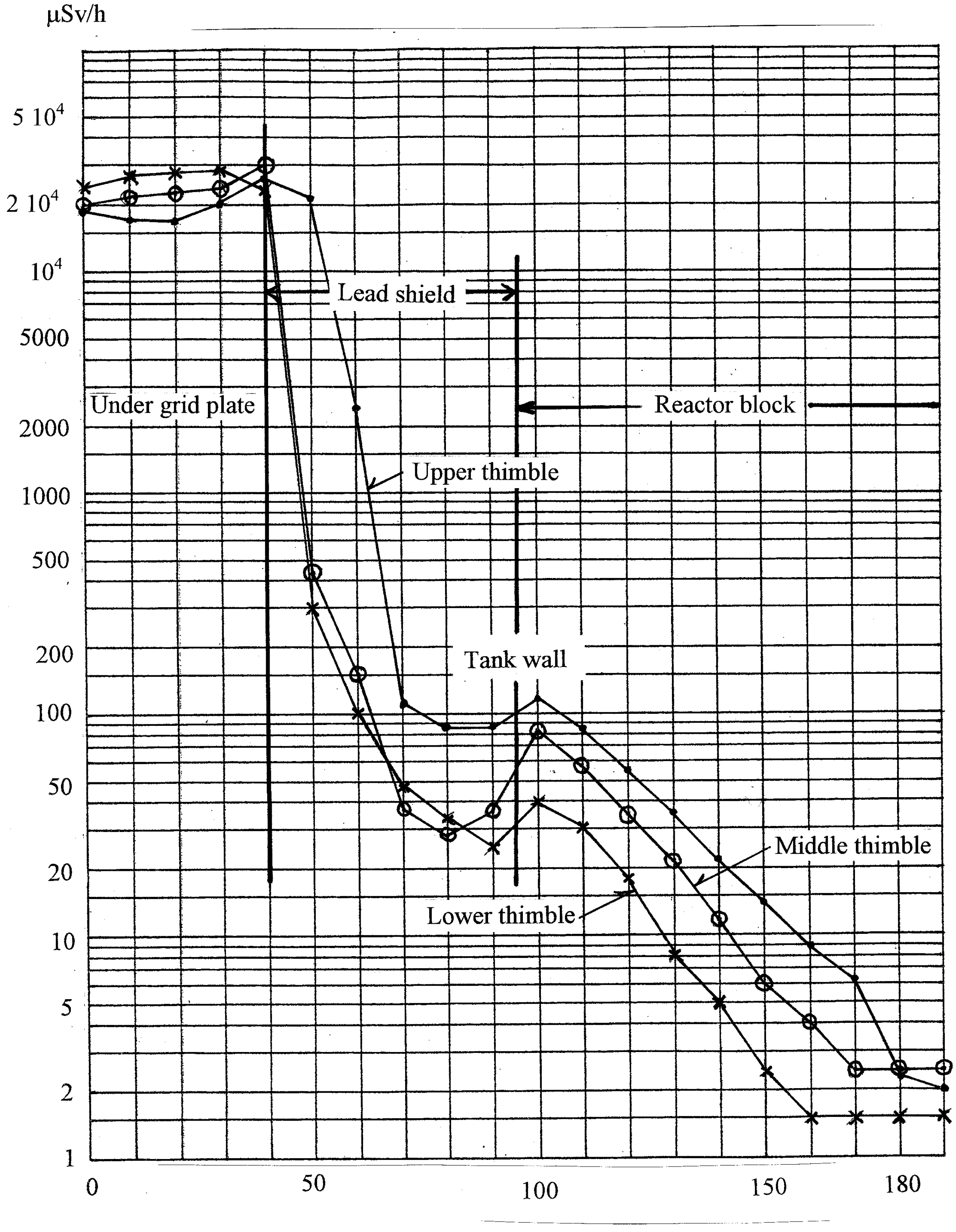

Figure 9.3. γ-dose rate distribution in the three southern instrument thimbles.

first measurement was carried out without any attempt to shield for the radiation from the active components inside the reactor tank. To reduce the effect of these components an attempt was made to lower a 30×60×60cm concrete block down into the reactor tank by use of the crane to cover the inner end of the B-3 beam hole. However, the concrete block turned out to be too large. Next a metal bucket with lead bricks was lowered down into the tank until it covered the inner end of the B-3 beam hole. Then measurement was repeated. The result of both measurements is given in Figure 10.1. While the dose rate has certainly been reduced after the introduction of the bucket with the lead bricks, it is doubtful how effective it was in cutting off all radiation from the active components in the reactor tank.

10.2 Cored Boreholes through the Reactor Block

In order to determine the activation of the reactor tank, the lead layer around the tank and the concrete shield two cored holes were drilled from the outer surface of the concrete to the reactor tank, roughly at the level of the center of the reactor core. The diameter of the cores was about 2.5 cm and the total length 2 m. The places where the drillings were carried out were chosen so that tubing in the concrete was not cut by the drillings. Before the drilling could start, holes were cut in the faceplate and a steel plate construction was welded on to the faceplate to fix the drilling machine in the right direction.

The drilling through the concrete proceeded as planned. The diameter core samples were taken out gradually and placed on a steel angle according to their position in the reactor block. The only difficulty experienced was the drilling through the lead layer. It took about the same time to drill through 2 m concrete and through 6 cm lead.

After the holes had been drilled, the γ-dose rate distribution along the cores was measured. It had been planned to use the measurement facility in the reactor hall for these measurements. However, it turned out that the activity of the cores was so low that the dose rate measured in the facility was at background level. In the facility the distance between the sample and the detector is typically 1 m. Instead an ad-hoc facility was built by use of lead bricks with a distance between the cores and the detector of only 5 cm and a collimator width of 4 cm. With this set-up meaningful measurements could be made. The results of these are presented in Figure 10.2.

It is seen from Figure 10.2 that the γ-dose rate decreases exponentially until the background level (in this case 12 μR/h) is reached. This level is reached about 60 cm into the concrete shield from the outer tank wall.

The activity of the various samples obtained from the drilling was measured. The results are presented in Table 10.1, starting at the tank wall and moving out into the concrete shield.

The numbering of the borehole samples starts from the inner wall of the reactor tank and increases with the distance from this wall.

The high value of the ^{60}Co activity of the aluminium sample of the outer wall of bore hole A is probably due to the fact that the sample contained the inner end of a thermocouple. The same is likely to be true for the high ^{108m}Ag activity of the same sample. In some of the measurements naturally occurring radionuclides were detected. They have not been included in Table 10.1.

The drilling of the cored borehole and the measurements on the cores were performed from November 2001 to January 2002.

Additional measurements, not part of this project, on the borehole core material are reported in Ref. 19.

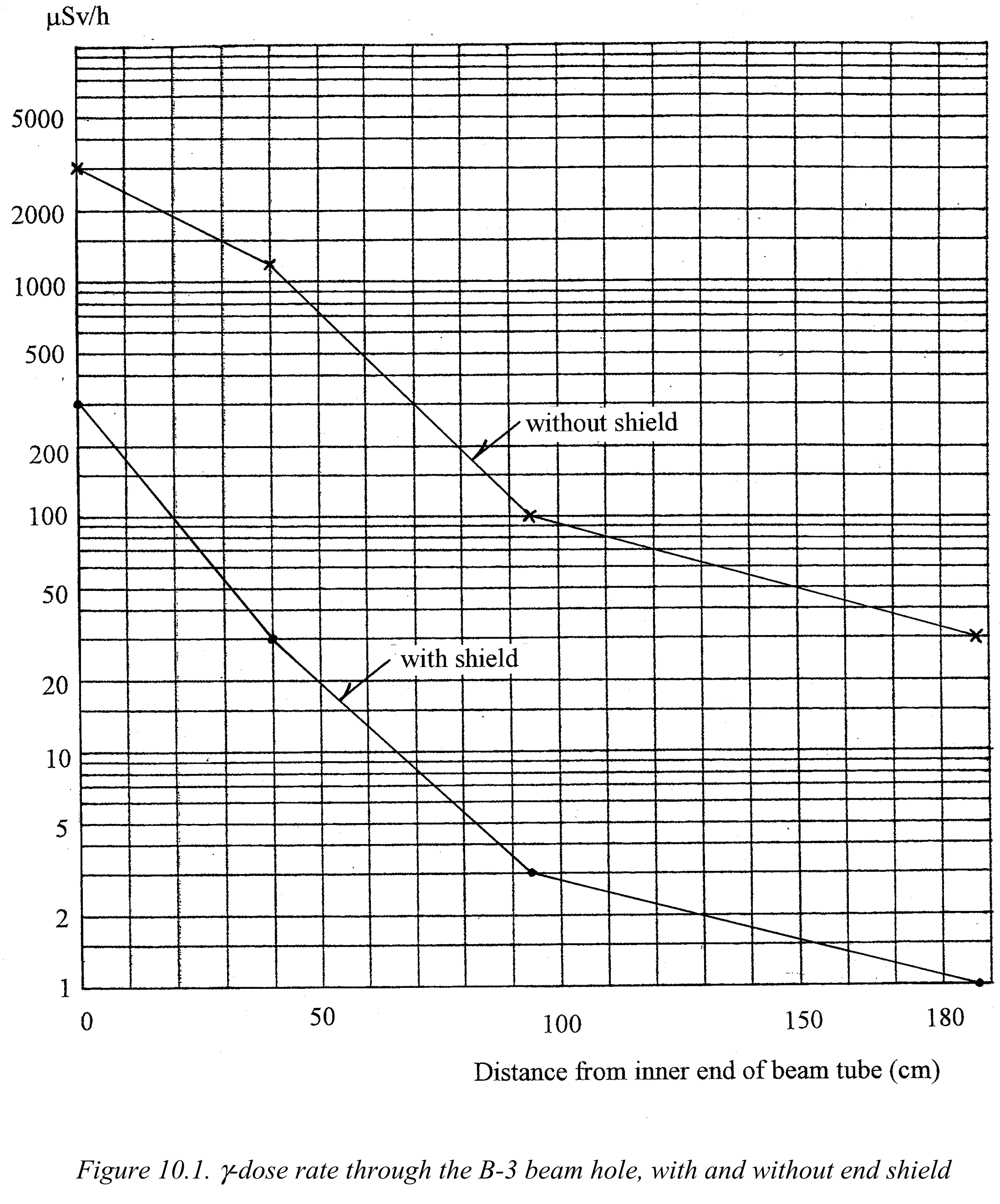

Figure 10.1. γ-dose rate through the B-3 beam hole, with and without end shield

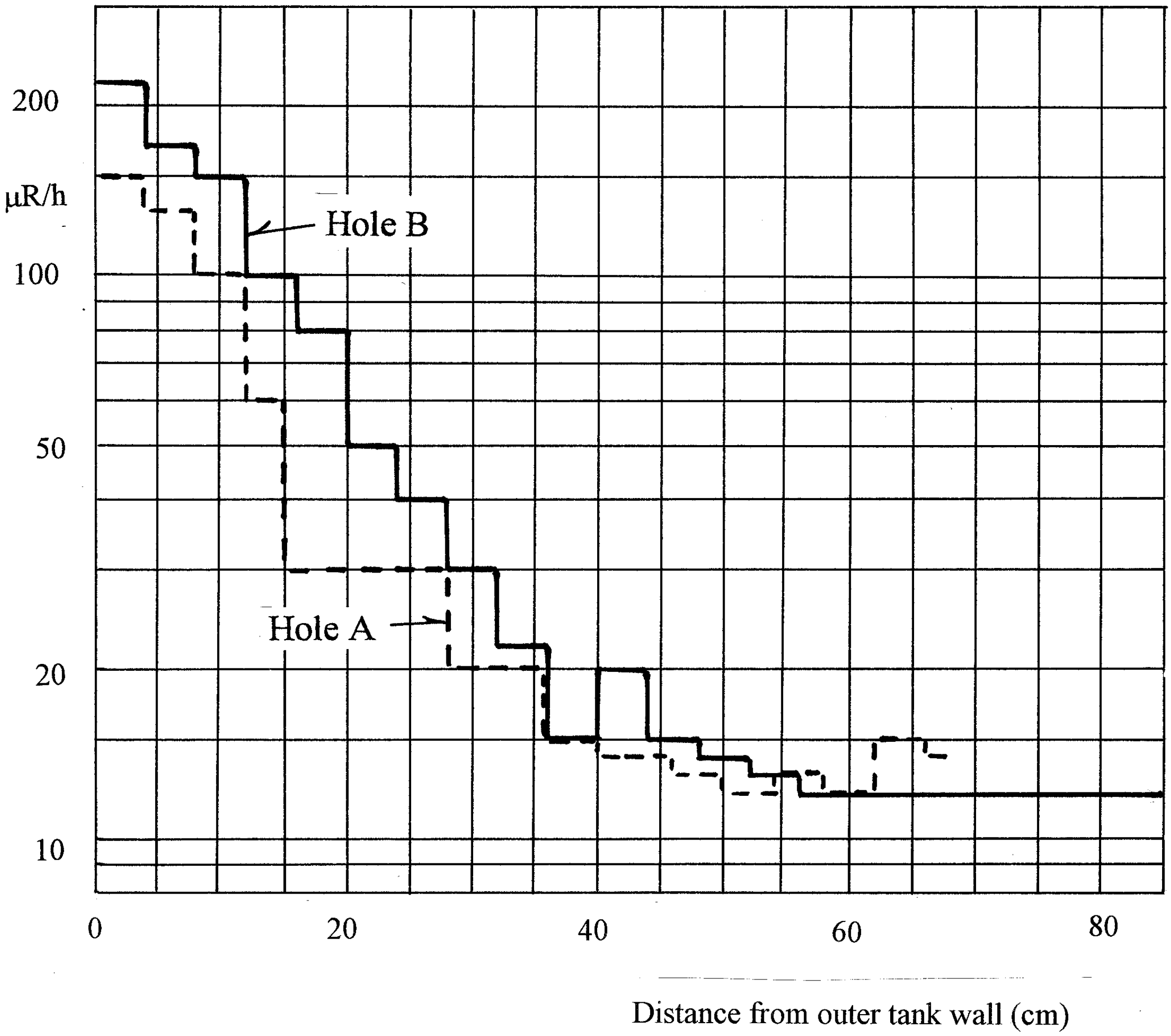

Figure 10.2. γ-dose rate distribution along the borehole cores outwards through the concrete shield

Table 10.1. Activity of Bore Hole Samples

Bore hole A

	Material	Length (cm)	Weight (g)	^{60}Co (Bq)	^{137}Cs (Bq)	^{108m}Ag (Bq)
Tank wall (A1)	Al	1.3	20	266	49	0
Lead layer (A2)	Pb	9.0	694	102	84	66
Outer wall (A3)	Al	1.2	25	5200	118	588

Sample	Material	Length (cm)	Weight (g)	^{60}Co (kBq)	^{133}Ba (kBq)	^{152}Eu (kBq)	^{154}Eu (kBq)
A-4	Concrete	17.5	535	4.0	150	40	0
A-5	Concrete	11	334	0	32	3.8	0
A-6	Concrete	27	792	0	15.4	6.9	0
A-7	Concrete	28	849	0	2.3	0	0

Bore hole B

	Material	Length (cm)	Weight (g)	^{60}Co (Bq)	^{137}Cs (Bq)	^{108m}Ag (Bq)
Tank wall (B1)	Al	1.3	20	297	79	0
Lead layer (B2)	Pb	3.5	206	88	61	45
Lead layer (B3)	Pb	5.5	303	101	64	61
Outer wall (B4)	Al	1.2	23	293	80	0

Sample	Material	Length (cm)	Weight (g)	^{60}Co (kBq)	^{133}Ba (kBq)	^{152}Eu (kBq)	^{154}Eu (kBq)
B-5	Concrete	10.5	312	2.2	123	63	4.3
B-6	Concrete	29	839	0.6	64	32	4.7
B-7	Concrete	28	856	0	8	0	0

10.3 Measurements in Vertical Holes in the Concrete Shield

The reactor block of DR-2 is provided with 13 vertical steel tubes, which extend from the reactor top down through the concrete shielding to about 25 cm above the bottom of the reactor tank. Seven tubes are placed on a row in the north westerly directions from the reactor tank. Another six tubes are placed on a row in the south westerly direction from the tank. These tubes were used to measure the activation of the concrete. However, it must be recalled that the dose rate in the tubes is due both to the activation of the concrete and to the radiation from the reactor tank components.

The tubes in the north westerly direction are named NV1, NV2, ...NV7 while those in the south westerly direction are named SV1, SV2, ...SV6. The horizontal distances of the tubes to the inside of the reactor tank wall are:

Tube	NV1	NV2	NV3	NV4	NV5	NV6	NV7	SV1	SV2	SV3	SV4	SV5	SV6
Distance (cm)	24	52	84	112	142	172	202	44	72	98	127	156	186

From February 4 to March 6, 2002 long plastic tubes with thermo-luminescence dosimeters at predetermined distances were irradiated in tube NV1, NV2, NV3, NV4, NV5, SV1, SV2, SV3, SV4, SV5, and SV6 for 30 days. In each tube six dosimeters were placed on plastic tubes along the region of the core, i.e. from 596 to 721 cm below the reactor top. The core was situated at a depth of around 640 to 700 below the reactor top. Analysis of the results revealed that in NV4, NV5, SV3, SV4, SV4, SV5 and SV6 the dose rate was negligible, while the dose rate in NV1, NV2, NV3, SV1, and SV2 went through a maximum. Since the dose rate of NV1 and SV1 were unexpectedly high at the lowest and highest dosimeters additional measurements were made for these two tubes at lower and higher heights than those of the first measurements. The supplementary measurements were performed from June 24 to September 9, 2002.

The result of all these measurements is shown in Figures 10.3 and 10.4. The maximum of the dose rate shown in Figure 10.3 around 6.5 m is due to activation of the concrete. In Figure 10.4 the attenuation of the γ-radiation out through the concrete shield is shown. It drops off almost exponentially as was to be expected. It is seen that at a distance of 80 cm from the outer tank wall the dose rate flattens out, i.e. reaches the "background level" in the concrete, which includes the contribution from active components in the tank.

The increase of the dose rate at the very bottom of the NV1-tube and the increase above the core level of that same tube was a surprise. Therefore it was decided to make an extra series of measurements in NV1 and SV1 from a depth of 521 cm and upwards. The results of all measurements in NV1 and NV2 are presented in Figure 10.5. In order to understand the curves of Figure 10.5 it is useful at the same time to consider Figure 10.6, which gives a vertical cross section of the tank and the NV1-tube. The peak dose rate of curve NV1 and SV1 around 6.5 m, i.e. around the center of the core, is due the activation of the concrete as mentioned above. For NV1 there is another maximum at the bottom of the tube. This maximum is believed to be due to the fact that at this depth of the tube, γ-radiation from the activated graphite at the bottom of the thermal column can reach the tube without being attenuated by the lead shield of thermal column and of the reactor tank (cf. Figure 10.6). The SV1 curve does not show a maximum at the bottom of the tube.

The NV1-curve has also a maximum above the core, though smaller than the maximum below. Here again the maximum is believed to be due to the fact that around a depth of 5.5 m from the reactor top γ-radiation from the top of the thermal column can reach the NV1-tube without having to penetrate the lead shield of the column and the tank. The reason why the maximum below the core is larger than the maximum above may well be that more graphite can be "seen" below the lead shield than above. The SV1-curve does not exhibit a maximum, only a bulge around 5.5 m, presumably due to the better shielding of the SV1-tube due to a thicker layer of concrete.

Finally the NV1-curve shows a minimum around 4 meters from the reactor top and a maximum around 3.25 m from the top. The reason for this maximum may well be that at close to 4 m below the reactor top the concrete shield material changes from heavy to ordinary concrete. Also a S-tube (S-3) enters the tank close to NV1. This reduces the efficiency of the shielding. SV1 may also have a maximum here, but due to low dose rate level the accuracy of the experimental points is rather poor.

It should be mentioned that when the plastic tubes with the dosimeters of the second measurement series were removed from the vertical tubes, it was noted that the plastic tubes were contaminated with both β- and α-emitting radionuclides. To investigate the origin of this radiation a number of smear tests were taken at various depths of some of the vertical steel tubes. It turned out that the origin of this radiation was naturally occurring radionuclides, ^{214}Bi and ^{214}Pb, from radon decay. This may indicate that the vertical steel tubes at some points have been corroded through so that radionuclides from the concrete could enter the tubes.

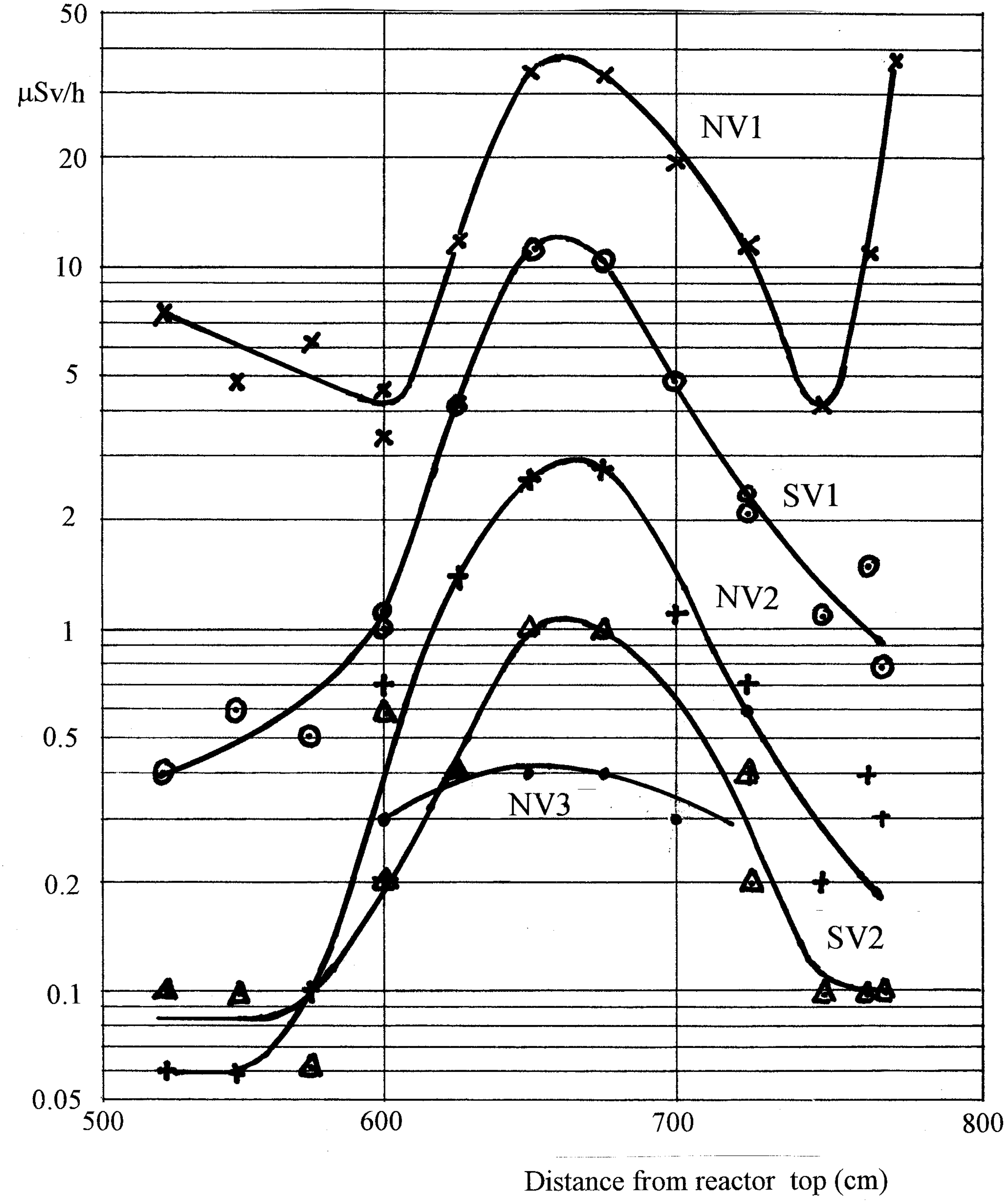

Figure 10.3. γ-dose rate in the vertical tubes of the reactor block. Dose rate versus distance from reactor top

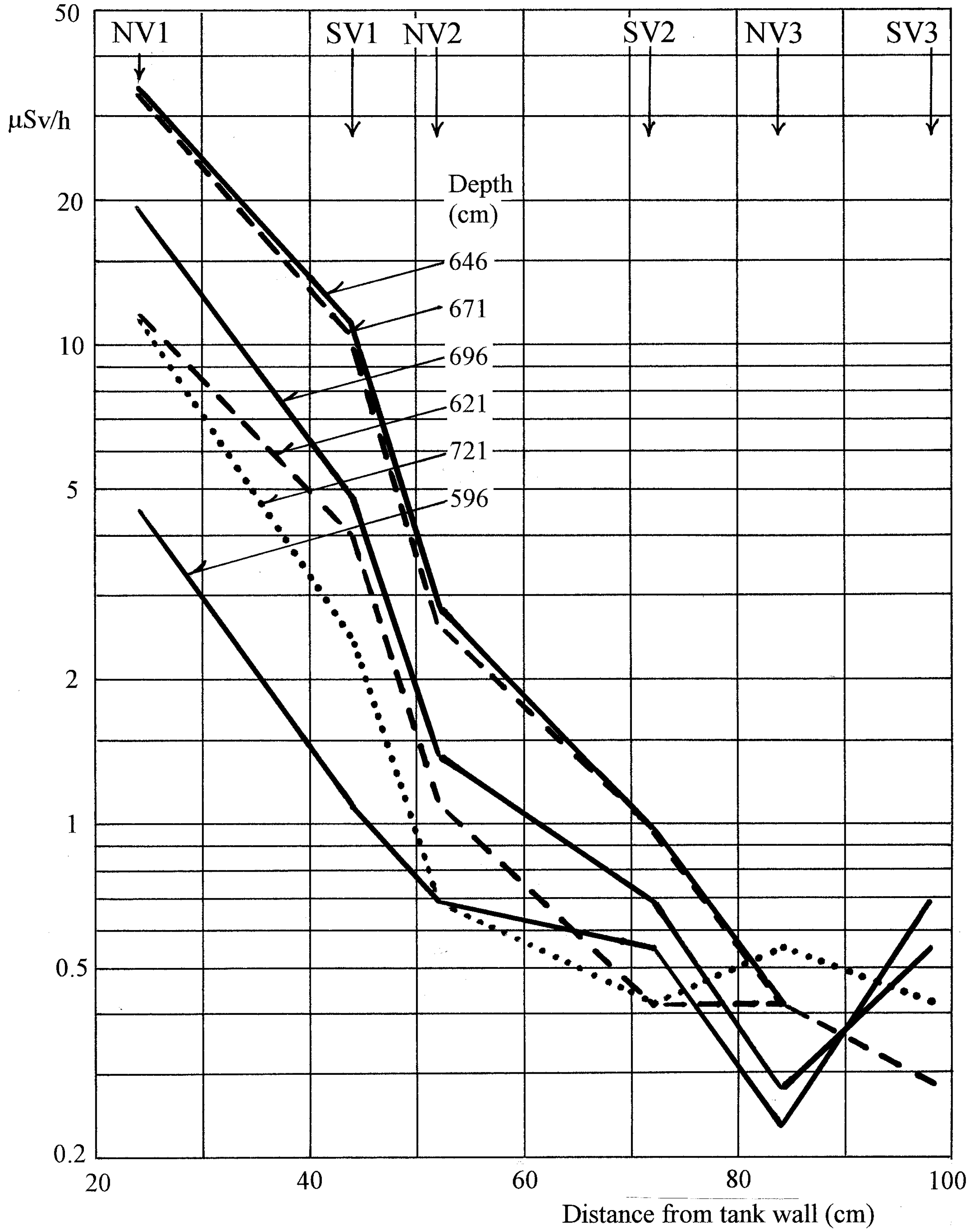

Figure 10.4 γ-dose in the vertical tubes of the reactor block. Dose rate versus distance from tank wall

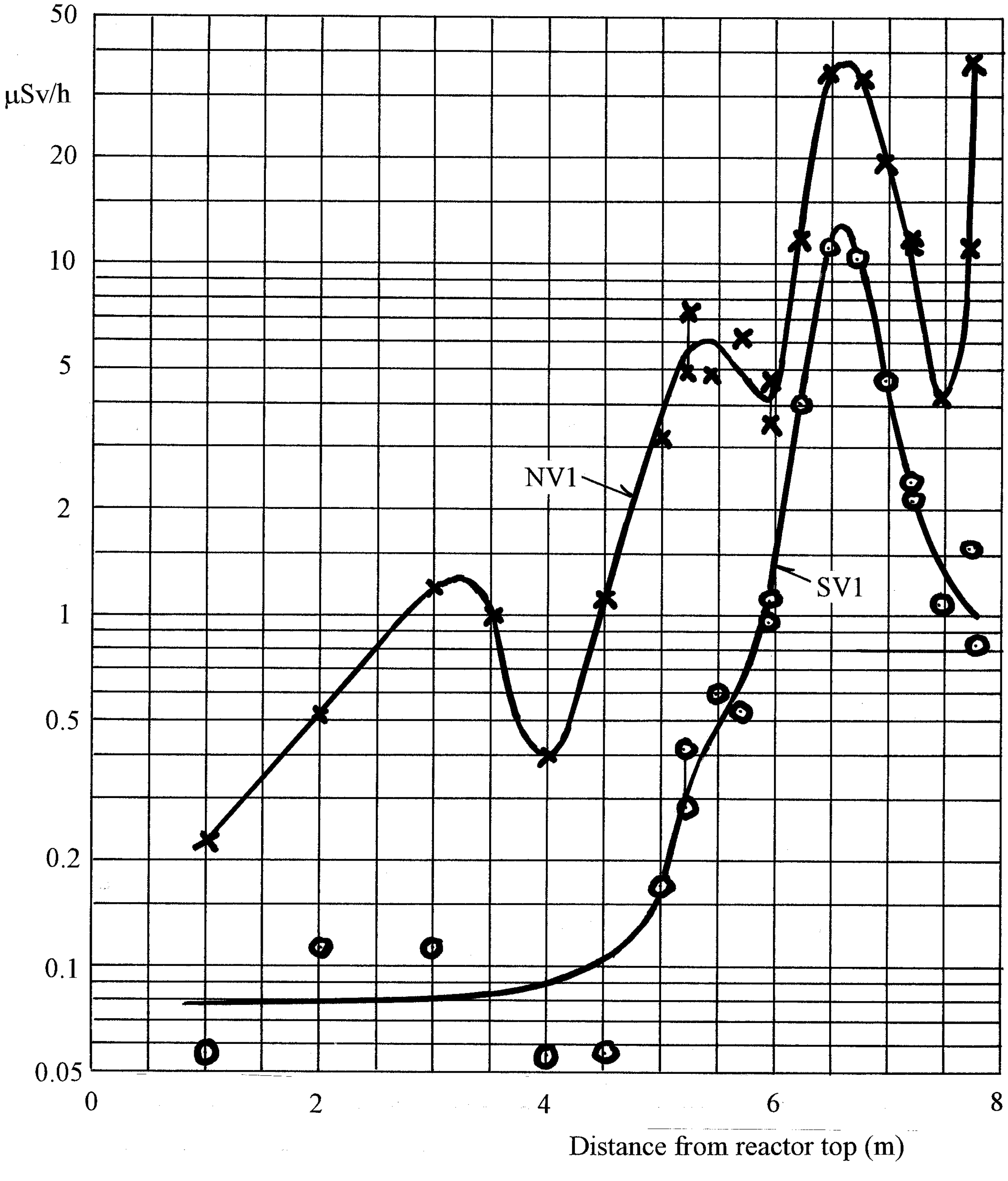

Figure 10.5. γ-dose rate in NV1 and SV1. Dose rate versus distance from reactor top.

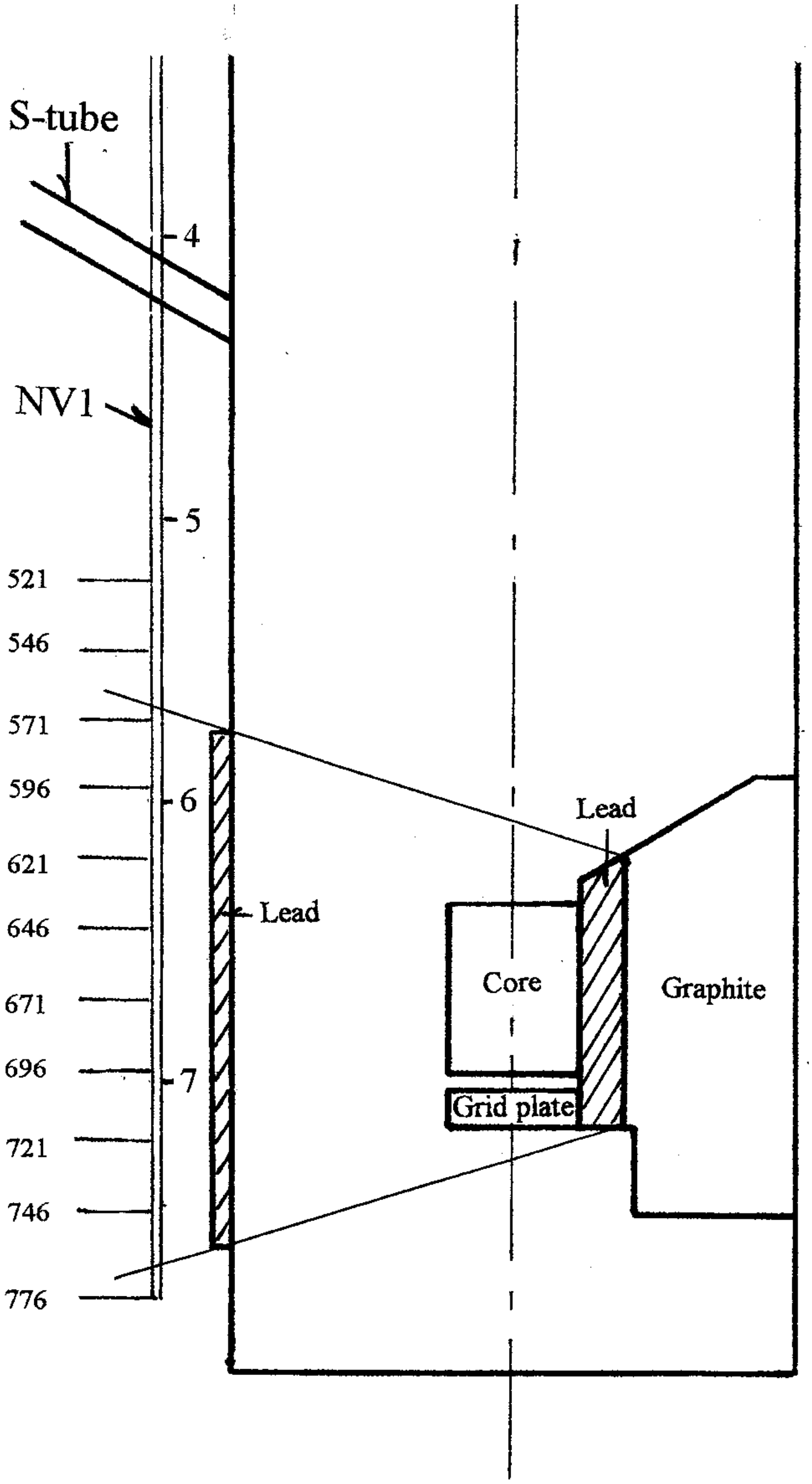

Figure 10.6. Vertical cross section of the reactor tank and the NV1-tube.

11 Remaining Activity

As mentioned in section 6.6 four concrete lined drums, two stainless steel containers with reflector elements and two black drums, containing a total activity of about 40 GBq, had been sent to the Waste Management Plant at the end of the project. This removal of radioactive components, primarily from the reactor tank of the DR-2, reduced the radiation level in the reactor significantly. However, some activity still remains.

From the results presented above it is seen that the amount of activity remaining in the DR-2 is modest. A review of the estimated activities is given in Table 11.1.

Table 11.1. Activities Remaining Today in the DR-2

Thermal column (graphite)	4 GBq ^{152}Eu
Thermal column (lead nose)	0.1 GBq ^{60}Co and 0.5 GBq ^{108m}Ag
Beam plugs and sleeves	1 GBq ^{60}Co
S-tubes	0.1 GBq

A component, which may well make a significant contribution to the total activity and for which it has not been possible to make a separate measurement, is the grid plate. It was situated close to the core and it contains not only a significant amount of aluminium, but also some stainless steel (bolts and fuel element guide pins). The lead shield around the instrument thimbles may also make a not insignificant contribution. The reactor tank, its lead shield and the concrete shield will of course also contribute to the activity, but it is estimated that this contribution is of the order of 0.1 GBq. A guesstimate of the total remaining activity of the DR-2 is

5-10 GBq (or 0.15-0.3 Ci)

It should be emphasized that the activities discussed above are activation-γ activities only. There are also β-activities, in particular in the graphite (^{14}C), and there may also be some tritium.

12 Radiation Doses Received

As mentioned in section 5.4 the personnel working in the reactor building carried thermoluminescence dosimeters and Alnor digital dosimeters. The latter are provided with a visual display of the dose received. After each working day at DR-2 all participating personnel would record the dose received as read from the Alnor dosimeter on a paper sheet. Based on these sheets the total dose received by the personnel could be obtained.

In Table 12.1 the doses received by the staff during the project are given for the various working periods. The first column gives the working periods, the second the working days of the periods, the third the total man days and the fourth the total dose received by the staff members during the periods.

Table 12.1 Doses Received during the Project

Period	Working days	Man-days	Total staff dose (µSv)
31/5-8/6 2000	4	7	47
15/6-7/12 2000	12	65	2696
9/1-1/2 2001	7	34	1795
14/2-3/9 2001	11	53	290
5/9-17/9 2001	6	26	254
17/9-1/11 2001	6	16	206
5/11-28/11 2001	8	34	73
28/11 01-5/2 02	9	35	52
24/6-10/7 2002	4	17	76
2/9-3/0 2002	2	7	3
Total	69	294	5462

From Table 12.1 it is seen that the total dose received by the staff was

5,5 mSv

and that the major part of the doses received by the staff occurred during June 2000 to February 2001. This is the period when the components of the reactor tank were taken out and disposed of. Since the reactor tank contained the most active components this result was expected. During the remaining part of the project the doses received tended to decrease.

It should be pointed out that man-days does not necessarily mean full man-days. Often work was only carried out in the morning. It may also be noted that work at DR-2 was only carried out if no other tasks, e.g. at DR-3, were given higher priority.

The individual doses to the staff members varied significantly from member to member, depending on the number day he or she worked on the project and on the type of work performed. In Table 12.2 the distribution of the doses on the staff is presented

Table 12.2. Distribution of the Total Radiation Doses to the Project Participants

Dose Range (µSv)	Number of staff members
0-50	15
50-200	4
200-400	1
400-600	1
600-800	3
800-1000	1
1000-1200	1
Total	26

Many of the staff members worked only on the project for a few days, and only a few of the members were responsible for the work involving the most active components.

13 Lessons Learned

During the course of a project experience is always gained. Some times the experience confirms that the procedures used were the right ones, some times that they can be improved. In the DR-2 project most of the work went according to the plans and there were only a limited number of surprises. Nevertheless a number of lessons were learned and the more important lessons are listed below.

A. Removal of the most active parts first.

When planning the removal of the radioactive parts in the reactor tank it was decided to start with the components left in the storage rack above the core. The reason for this decision was that these components were most easily accessible and would give personnel experience in working at the top of the reactor. In addition it was believed that the rack also contained some the most active components and that their removal would reduce the radiation level at the top of the reactor significantly.

It was well known that the regulation rod would also be quite active, but it was not foreseen that its activity would be so domination as is evident from Table 6.1. In hindsight it is clear that the regulation rod should have been removed first. This would have reduced the radiation doses for those working at the reactor top. As a general rule one should if possible remove the most active components first. Hereby the radiation level is reduced as early as possible.

B. Use of respirators

When opening the reactor tank the personnel used respirator masks to be protected against radioactive and beryllium dust. This dust was not believed to be a problem, but the respirators were used “to be on the safe side”. Later on it turned out that respirators were not needed and the use of respirators was abandoned.

The graphite stringers of the thermal column turned out to be more active than expected. Since only a few were taken out and measured, and since there was very little graphite dust, the personnel who handled the stringers was not instructed to use respirator while working with the graphite stringers inside the igloo. It may be debated whether they should have, but the use of respirators would probably be reasonable when the all graphite stringers are removed from the thermal column.

C. Documentation of the work performed

It is of the greatest importance for the management of the project that a detailed record is kept of who did what work at which time and of where which components are placed. This record must be kept by somebody, who is used to write, preferably the project leader or his deputy. The record of a given day must be written immediately after the work has been carried out, and for the same reason the project manager or his deputy should be present at all major project operations.

During the DR-2 project the project leader was present during all major operations and wrote the entries in his project diary at the end of the day. It included a record of the movements of all components taken out of the reactor. Also digital pictures were taken of all major operations. In addition the personnel kept a logbook in the reactor hall, but it was not very detailed.

The results of the measurements were recorded and kept by the health physicist responsible for the measurements or in a few cases the project leader. Even though this arrangement worked quite well during the project, it may be asked whether there should be two records, e.g. one at the health physicist and one at the project leader. The risk that some data gets lost is always larger if only one record is kept. This also applies to the records of the daily readings of the Alnor dosimeters.

D. Component accounting systems

The number of components to be handled was significant, of the order of 200. The components came from the reactor tank, from the hold-up tank room and from the igloo. They had to be moved around in the reactor building – some times even outside the building to be more accurately measured in another building. The active components were – if they could be cut - disposed of in waste drums which when filled were sent to the Waste Management Plant. If they could not be cut, they were stored in the storage facility and ultimately transferred to the igloo. The non-active components were put into plastic bags and marked with an identification code.

A record of which components were placed where was kept in the diary of the project leader. This record was brought up to date every time components were moved. This system seemed to work quite well, but it must be admitted that some times the identification of one of the smaller, active components could give rise to problems. For example "Small Al-tube" is not a very unique definition of a component. To reduce personnel doses and to avoid contamination the identification code was only applied after a components had been found non-active or possibly slightly active. The active components were – if at all possible - cut into drums and therefore not identified by a special code, only given a more or less unique name.

E. Archives

It is important to ensure that archives containing all information relevant for the decommissioning are maintained until the facility has been finally decommissioned. At the DR-2 two archives, which were kept at separate locations, were established shortly after the final shut-down of the reactor. Unfortunately nobody was appointed to ensure that the archives were kept in a proper state and that new relevant information was included in the archives. For this reason a considerable effort had to be made at the start of the DR-2 project to bring the two archives up to the required level.

It is of great importance that one person is appointed to be responsible for the maintenance of the archives.

14 Some Considerations on the Dismantling of the DR-2

As mentioned in section 1 it was initially the intention to include planning of the dismantling of the DR-2 in the project, but this planning was transferred to the planning of the decommissioning of all nuclear facilities at Risø. However, since it is unavoidable that some thoughts were given to the ultimate dismantling of DR-2 during the project, a short review of these thoughts are presented below.

In the operational basement, in the hold-up tank room and in the igloo a number of components, some of which are somewhat radioactive, have been stored. It is not expected that the removal and disposal of these components will give rise to any major difficulties.

During the DR-2 project the primary circuit was opened and smear tests made on the inner surface of the tubing. The detected surface concentration was 6 mBq/cm^2 for ^{60}Co, 1 mBq/cm^2 for ^{137}Cs and 1 mBq/cm^2 for ^{152}Eu and ^{154}Eu. Further, the radiation level along the tubing of the primary circuit was measured, and it was found to be at or slightly above the background level. Thus the dismantling of the primary circuit should be straight forward. The primary circuit includes the hold-up tank.

It will have to be decided whether decontamination of any contaminated parts of the primary circuit should be carried out or they should be considered radioactive waste.

It should be mentioned that south of the DR-2 are some earth-covered tanks, which were used in connection with the transfer of contaminated water from the DR-2 to the Waste Management Plant. These tanks were **not** examined during the DR-2 project and may still be contaminated. It would be reasonable to examine the state of these tanks fairly soon.

Assuming that the planned waste containers are available it would be reasonable to start the actual dismantling of the DR-2 with the unloading of graphite stringers from the thermal column and placing them into containers used only for graphite. The graphite stringers in the plastic wrapped parcels in the igloo should of course also be placed into these containers. The graphite stringers next to the core have been exposed to irradiation of fast neutrons. It should be considered whether these stringers have accumulated so much Wigner energy that they will have to be annealed before disposal. The boral plates of the igloo and the thermal column should be removed.

Next the beam plugs and liners are pulled out one by one, and the inner, active part of these components cut off and disposed of, while the outer, inactive part of the plugs are reinserted in the beam hole. Whether the outer, inactive part of the liners should also be reinserted depends on how difficult this reinsertion is. The removal of the beam plugs and liners include the through tube, which penetrates the thermal column. The cutting may be performed at the DR-3 or in the reactor hall of the DR-2.

The S-tubes are pulled out and the lower active part is cut off and disposed of. The upper, inactive part may be reinserted.

The welding that connects the aluminium casing of the graphite of the thermal column, to the rectangular channel protruding from the reactor tank, is removed. After the removal it should be possible to pull/push the casing box with its lead nose out into the igloo, provided the through tube has already been removed. From the igloo the casing is transported to dismantling.

When this has been done, there is free excess through the igloo to the inside of the reactor tank, and the grid plate is removed. The two lead shields around the instrument thimbles are lifted out of the reactor tank by use of the crane. Finally the square coolant channel below the grid plate and the instrument thimbles are cut out of the reactor tank. When this has been accomplished the remaining activity of the reactor is quite small.

At this stage it should be considered whether the lead shield on the outside of the reactor tank should be removed by cutting it up from the inside of the tank or whether the cutting up of the lead shield should await the removal of the concrete shield.

A major task is the dismantling of the concrete shield of the reactor block. There are various methods for concrete dismantling, e.g. sawing into blocks, chopping into smaller pieces or use of small amounts of explosive. The various methods should be evaluated with respect to feasibility and price and the best method(s) selected. The upper part of the concrete is not active, but it may contain tubing the inside of which has been contaminated. As seen from the results given in section 10 the active part of the concrete is approximately a zone 200 cm high and 70-80 cm deep around the core position. Parts of the concrete has to be considered radioactive waste and parts can be considered ordinary waste. The distinction between these two parts depends on the release criteria to be used.

15 Conclusions

The DR-2 project was carried through as foreseen in Ref. 2 (or 3) with only few changes. The most important change was the decision that the most active components, taken out of the reactor, should not be returned to it, but sent, in proper containers, to the interim storage at the Waste Management Plant at Risø. This change has significantly reduced the radiation level in the reactor and will make its dismantling easier. The execution of the project took longer time than originally planned due to the close-down of the DR-3.

Few surprises were experienced during the project. One was the europium activity of the graphite of the thermal column. Another was the other than expected distribution of active components stored in the reactor tank, igloo and hold-up tank room. A list of where all the components found in the DR-2 have gone is given in Ref. 1. This list includes the components now stored in the reactor rooms.

The distribution of the remaining γ-emitting activities of the reactor has been established. The dismantling of the reactor may be started as soon as the work plan of the dismantling work has been prepared, permission to perform the work has been given and the final containers for the radwaste are available. The dismantling work will be straightforward, and there will be little if any need for use of remote handling or use of robots. One important decision to be made by the authorities is the establishment of the release criteria for reactor materials. It will greatly affect the volume of radwaste. This is in particular true for the concrete of the reactor block.

16 References

1. P.L.Ølgaard: DR-2-projektet: DR-2 dagbog. Juli 2002

2. Sikkerhedsdokumentation for DR-2, Juli 1999, 77 sider

3. Beskrivelse af DR 2-projektet, Apr. 1999, 8 sider

4. Description of the DR 2-Project, June 1999, 6 pages

5. Halvårsrapport for DR-2-projektet for 1. halvår af 2000, august 2000, 4 sider

6. Halvårsrapport for DR-2-projektet for 2. halvår af 2000, februar 2001, 4 sider

7. Halvårsrapport for DR-2-projektet for 1. halvår af 2001, juli 2001, 3 sider

8. Halvårsrapport for DR-2-projektet for 2. halvår af 2001, februar 2002, 3 sider

9. Halvårsrapport for DR-2-projektet for 1. halvår af 2002, september 2002, 2 sider

10. Halvårsrapport for DR-2-projektet for 2. halvår af 2002, marts 2003, 2 sider

11. P.L.Ølgaard: Technical Aspects of Research Reactor Decommissioning Experience from the DR-2. Paper presented to the IAEA Research Co-ordination Meeting on

Decommissioning Techniques for Research Reactors", Feb. 1998, Mumbai, India, 16 pages.

12. P.L.Ølgaard: Progress Report on the DR 2 Decommissioning Project. Paper prepared for the IAEA RCM, Feb. 2000, Taejon, Republic of Korea, 11 pages.

13. P.L.Ølgaard: Recordkeeping Aspects of Decommissioning. Paper presented to the IAEA RCM, Feb. 2000, Taejon, Republic of Korea, 6 pages.

14. P.L.Ølgaard: The DR-2 decommissioning project, Denmark. In: Decommissioning techniques for research reactors. Final report of a co-ordinated research project 1997-2001. Page 65 to 78. IAEA-TECDOC-1273. Feb. 2002.

15. P.L.Ølgaard: Denmark: Record Keeping for the Decommissioning of the DR 2 Reactor. In: Record Keeping for the Decommissioning of Nuclear Facilities: Guidelines and Experience. Tech. Rep. Series No. 411, IAEA, Wien 2002.

16. P.L.Ølgaard: Nuclear Decommissioning at Risø and the DR-2-project. Paper presented to the Meeting on Reactor Physics Calculations in the Nordic Countries, May 2001, Roskilde, Denmark, 9 pages.

17. K.Abrahams, W.Ratynski, F.Stecher-Rasmussen and E.Warming: On a System of Magnetized Cobalt Mirrors Used to Produce an Intense Beam of Polarized Thermal neutrons. Nucl. Instr.and Meth. 45 (1966) 293-300.

18. K. Brodersen: Interpretation of measurements on graphite from DR2 and methods for estimating integrated flux. Risø Decommissioning, March 2003, 29 pages.

19. K. Brodersen: Sample preparation and γ-spectroscopy of heavy concrete from DR2. Risø Decommissioning, May 2003, 10 pages.

Annex 1. Photo Series

During the project more than 300 digital color photos were taken of the various tasks performed, of the various facilities built, of the equipment used and of the components taken out of the reactor, measured and disposed of or stored. A selection of these photos is presented in this annex in chronological order. They should serve as an illustration to the work described in this report and in Ref. 1.

Diskettes with all the photos taken are available from Erik Nonbøl of the Radiation Research Department at Risø National Laboratory.

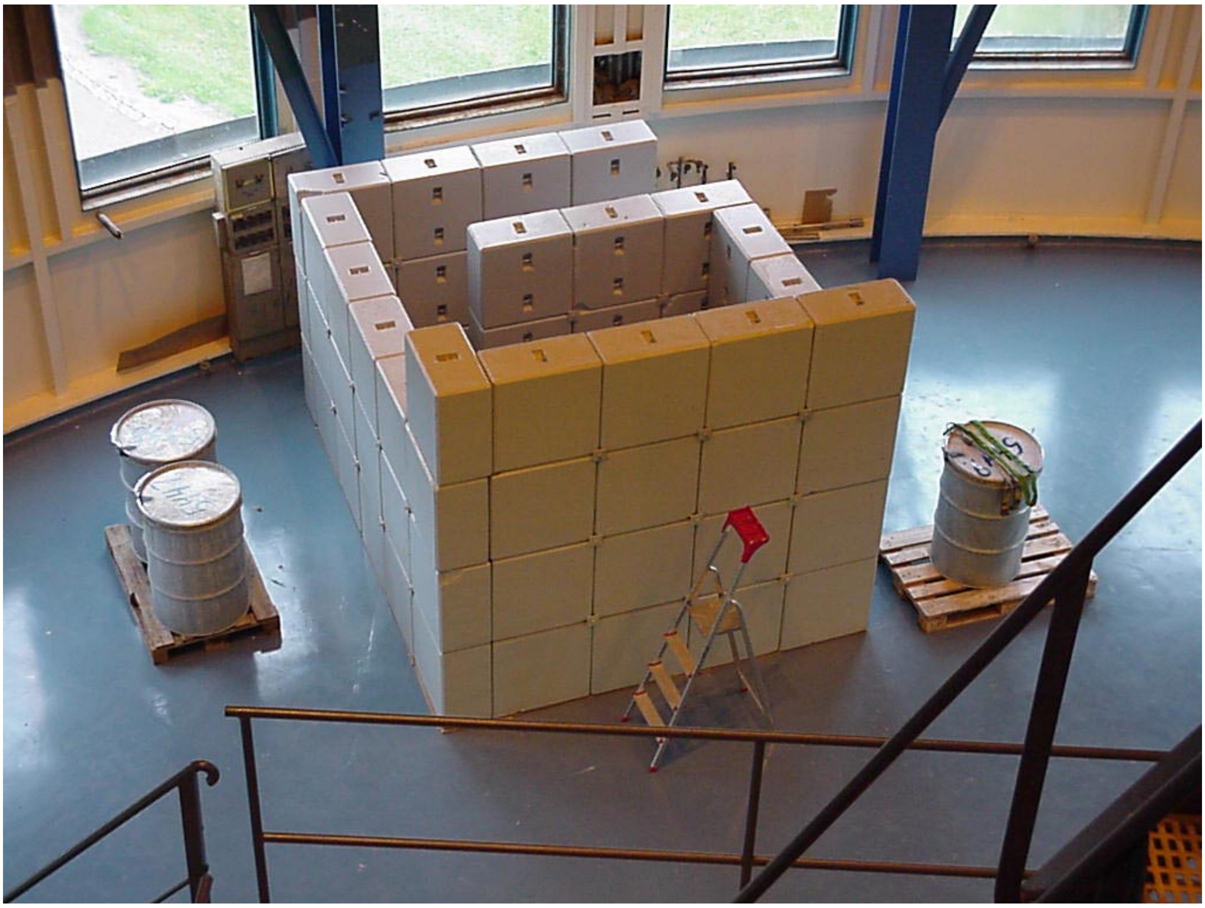

Figure A1. The storage facility in the reactor hall as seen from the reactor top.

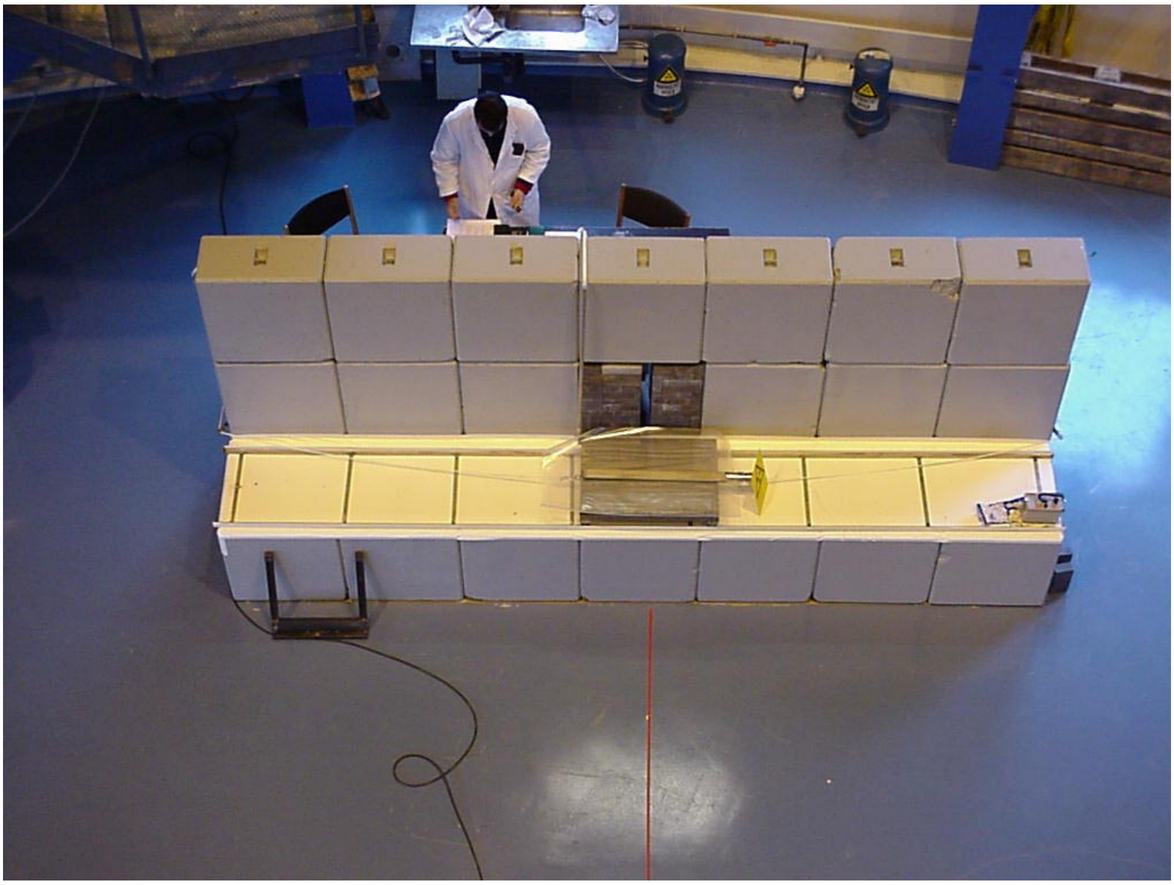

Figure A2. The measurement facility as seen from the reactor top.

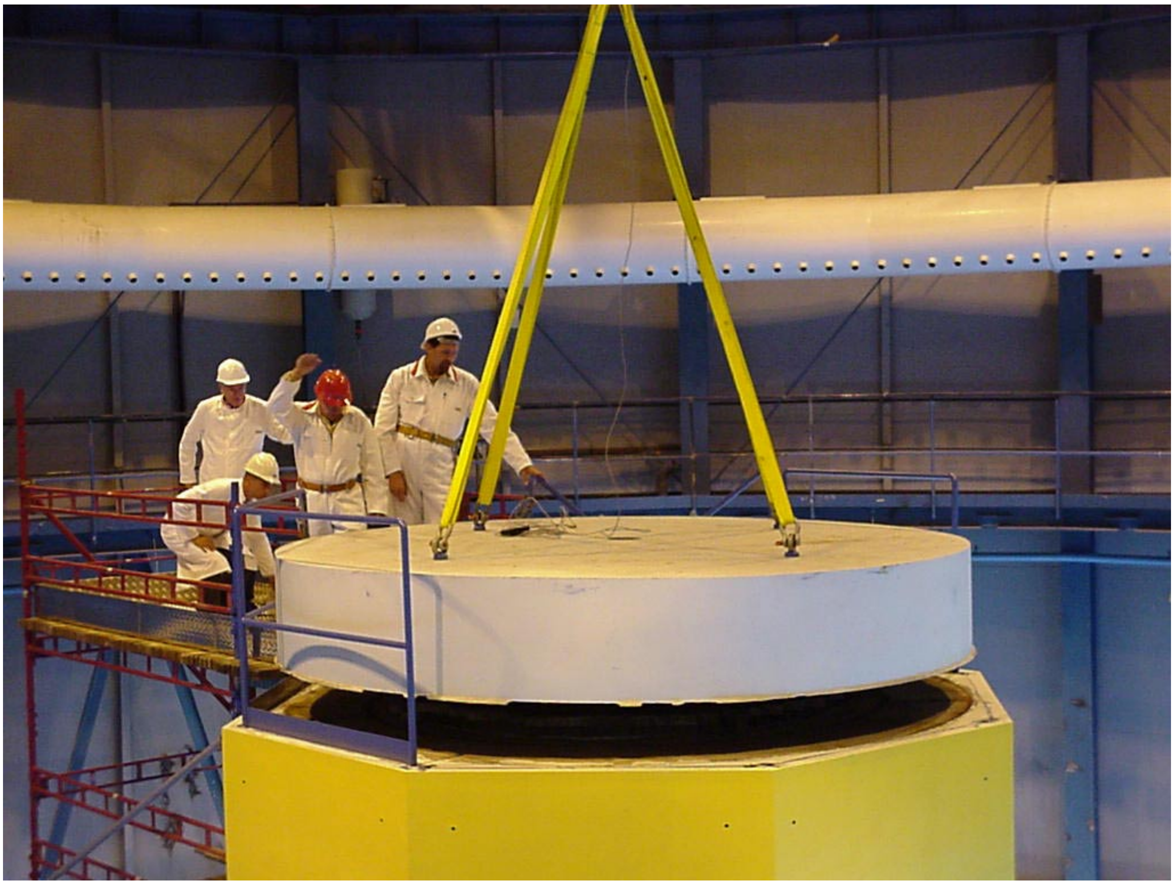

Figure A3. The concrete lid is lifted from the reactor top.

Figure A4. Vacuum cleaning of the lead brick layer below the concrete lid.

Figure A5. Removal of lead bricks and collection of air samples in the reactor tank.

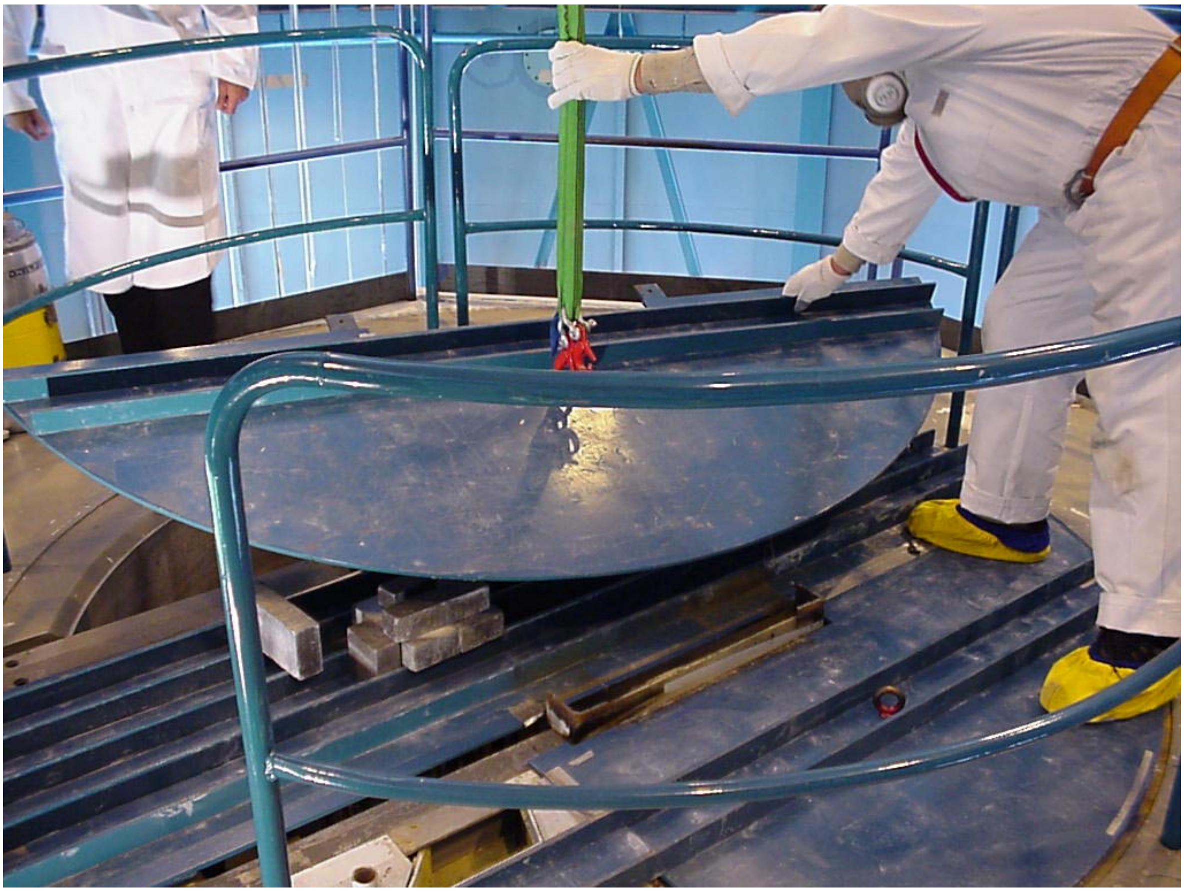

Figure A6. The lifting of the steel lid from the reactor top.

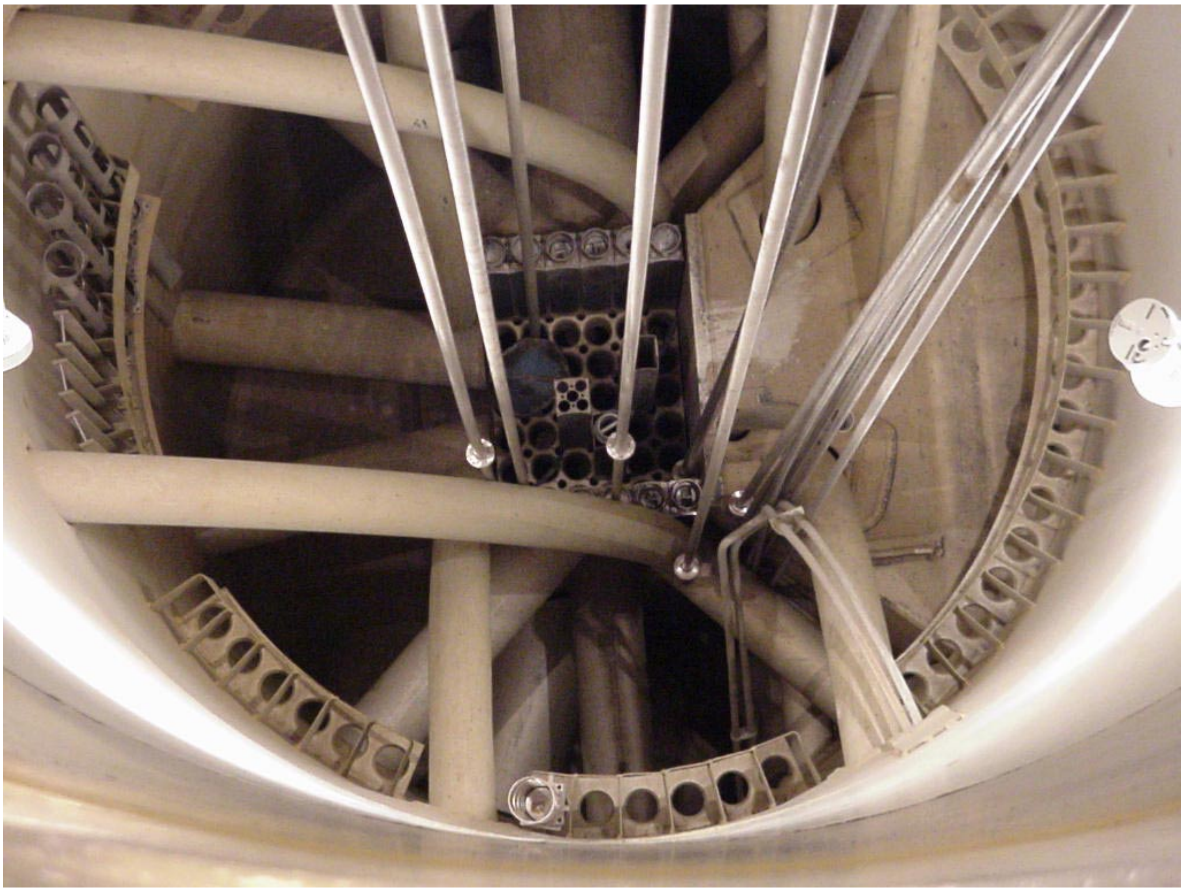

Figure A7. The interior of the reactor tank.

Figure A8. The project leader with respirator mask.

Figure A9. Smear tests are taken in the reactor tank.

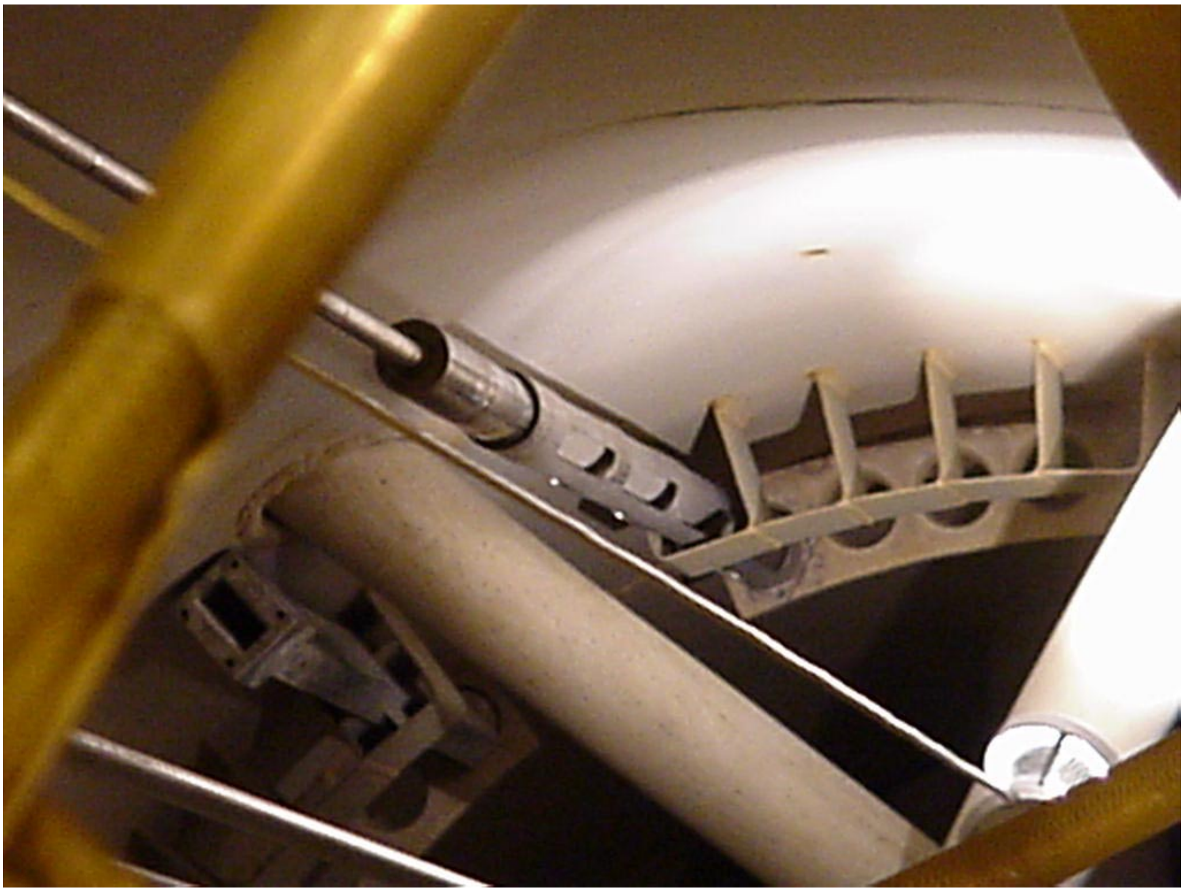

Figure A10. A magnet rod is lifting a shim safety rod out of a guide tube.

Figure A11. A control rod is lifted out of the reactor tank with the fork shaped tool.

Figure A12. γ-spectrum measurement of a shim-safety rod at the measurement facility.

Figure A13. Cutting the armature and shock absorber off a shim-safety rod.

Figure A14. Calibration tool with stuck shim-safety rod and guide tube. Magnet rod on top.

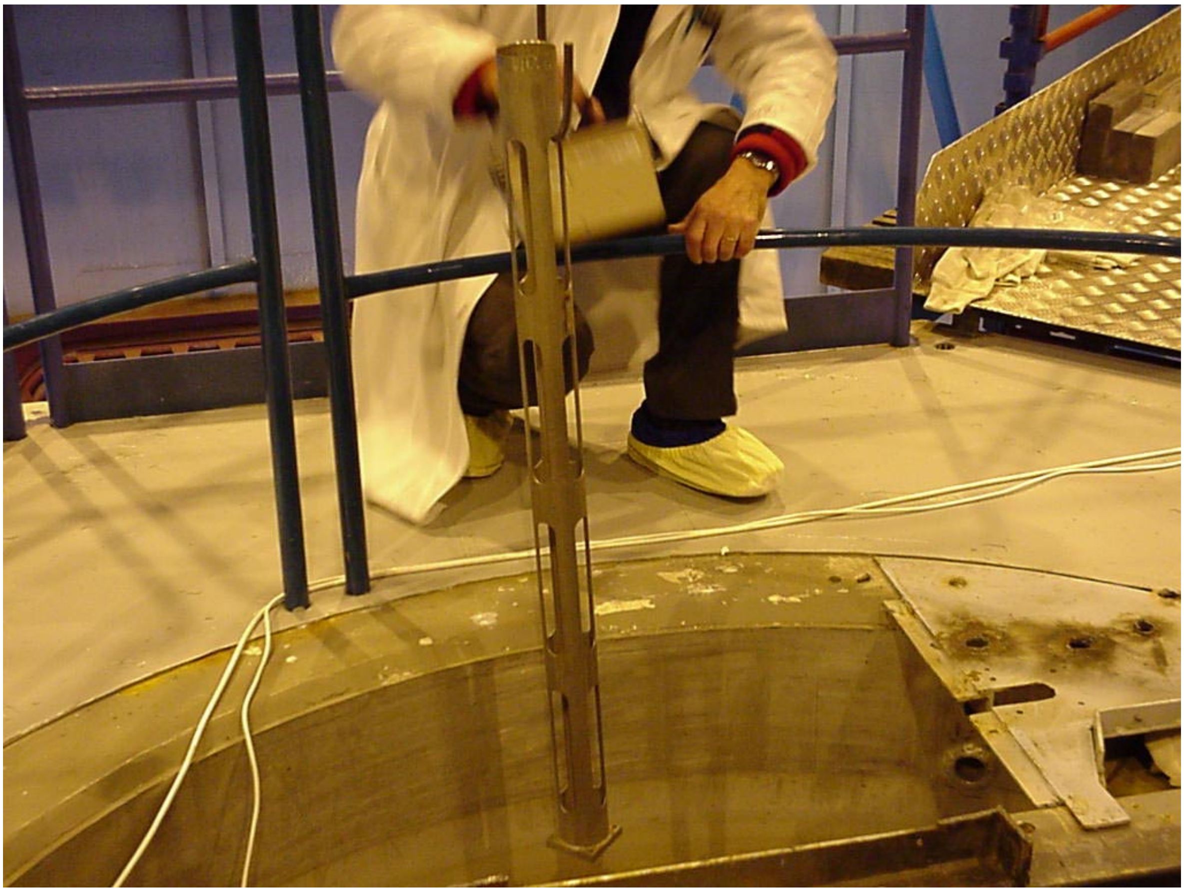

Figure A15. Lifting a guide tube out of the tank and measuring it at the reactor top.

Figure A16. Cutting a guide tube down into a concrete lined waste drum.

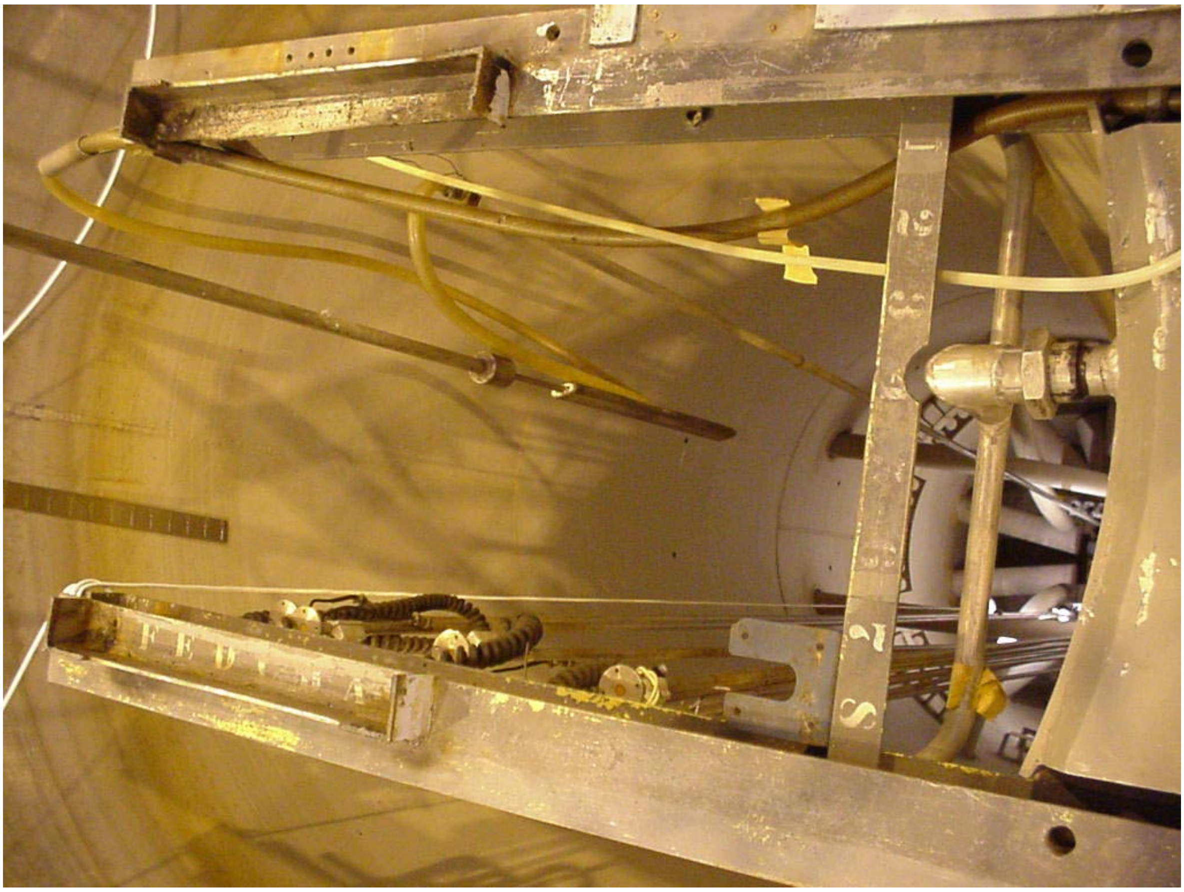

Figure A17. The regulation rod is lifted out of the reactor tank.

Figure A18. The regulation rod is cut down into a concrete lined drum.

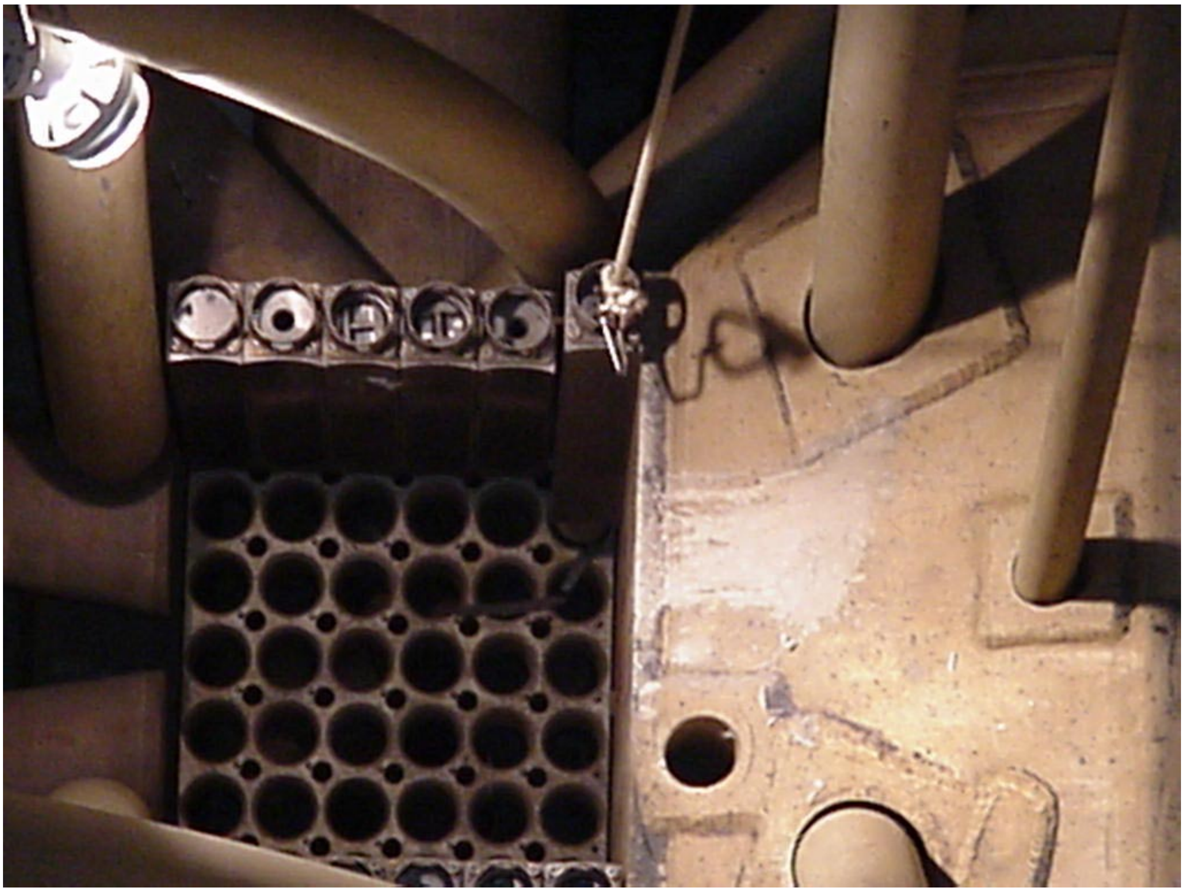

Figure A20. The first beryllium reflector element is lifted out of the reactor tank.

Figure A19. The concrete lined drum No. 4549 is full.

Figure A21.The two stainless steel containers for the beryllium reflector elements.

Figure A22. Screws are removed from the top of reflector element No. 60.

Figure A23. γ-dose rate distribution measurement for a reflector element in measurement facility.

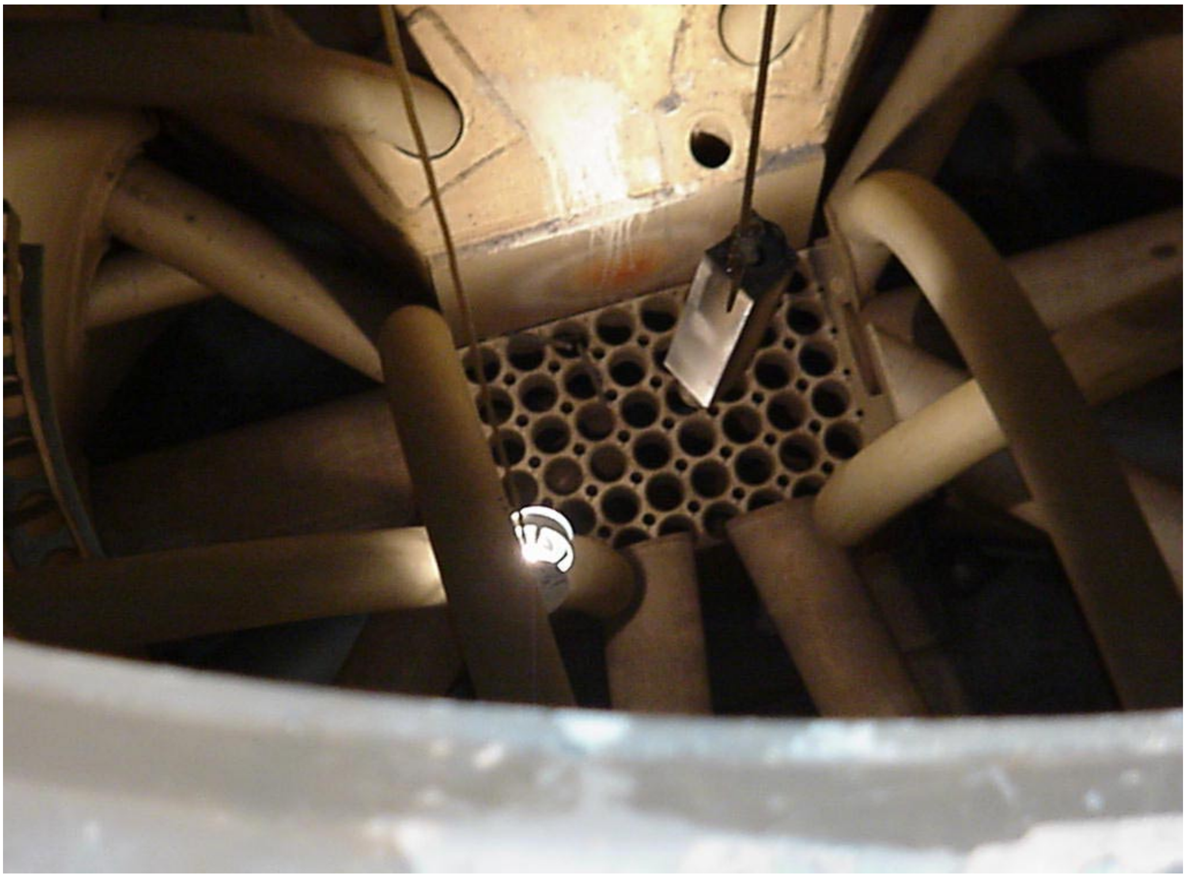

Figure A24. The last movable component in the reactor tank, a reflector element, is leaving.

Figure A25. A look into the hold-up tank room. Note the five boxes from Hot Cell and the long magnet on the floor.

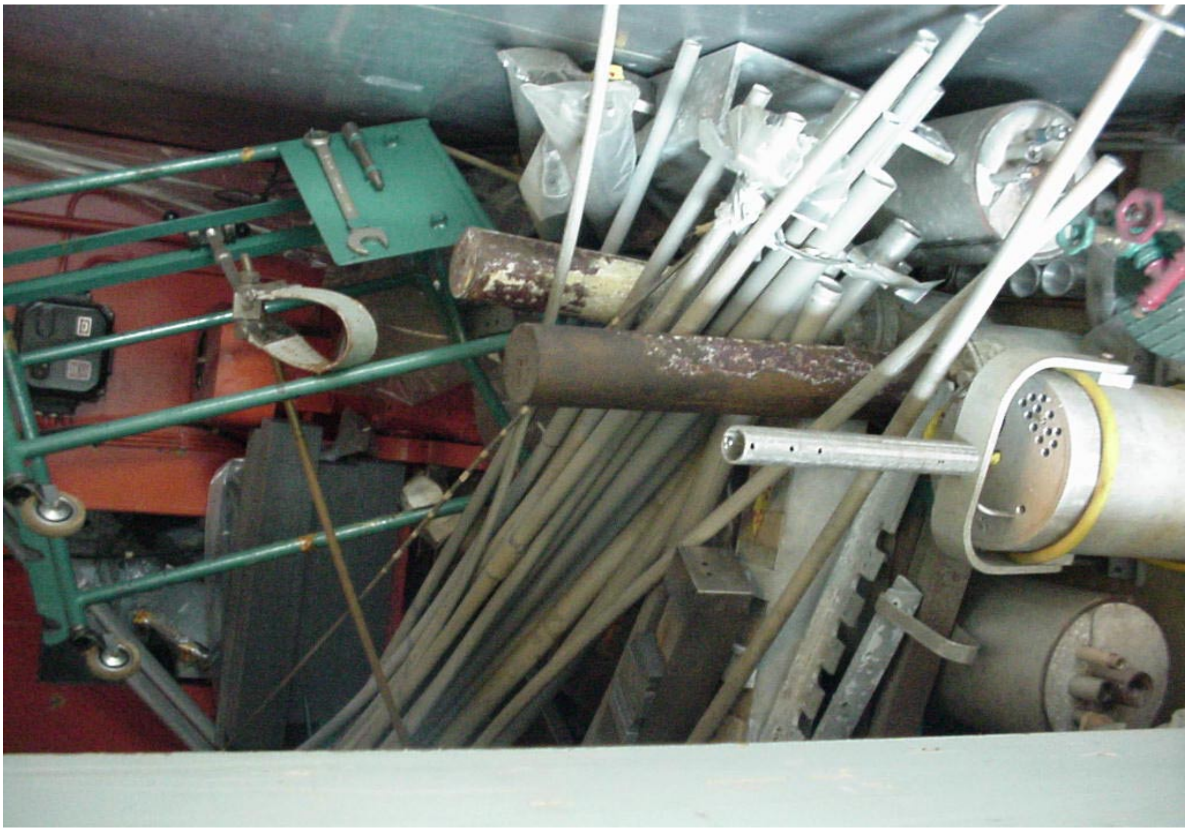

Figure A26. A first look into the igloo.

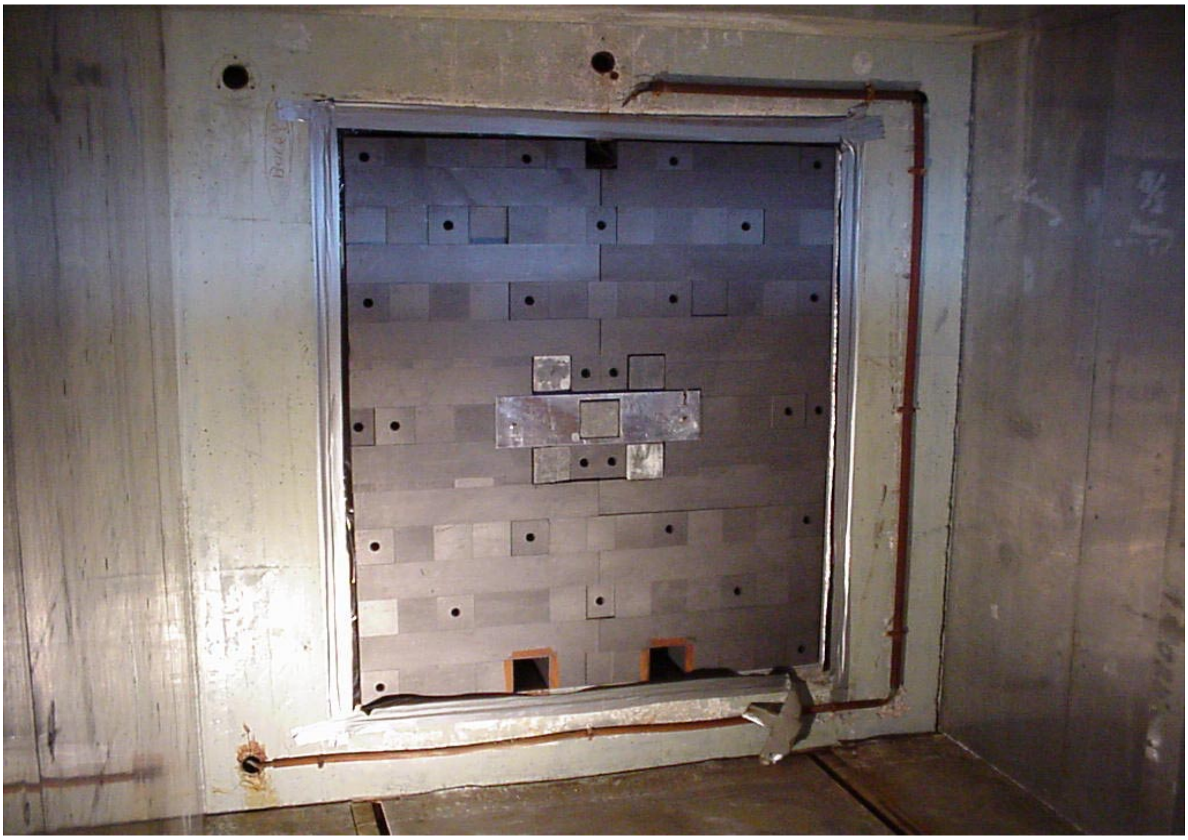

Figure A27. The outer surface of the thermal column in the igloo.

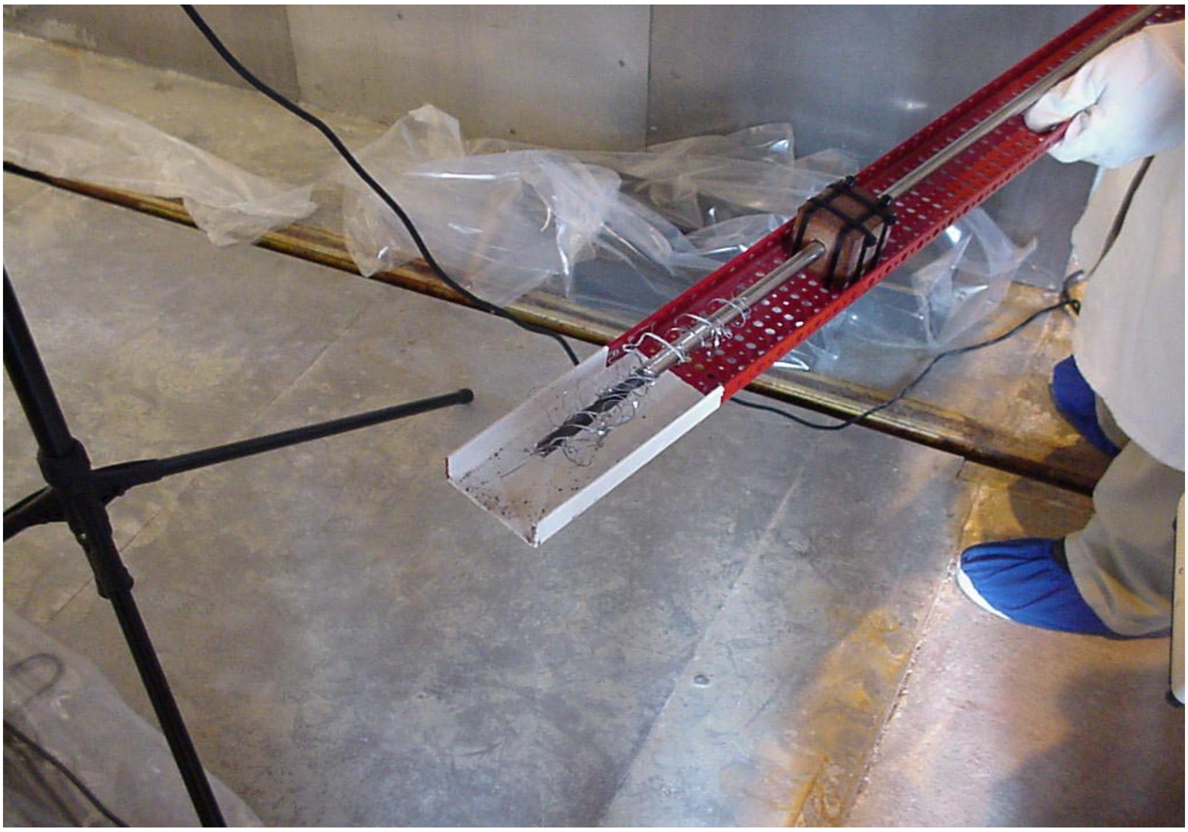

Figure A28. The drilling device for taking lead and aluminum samples at the wall at the inner end of the thermal column.

Figure A29. Removal of a steel plate in front of a beam tube.

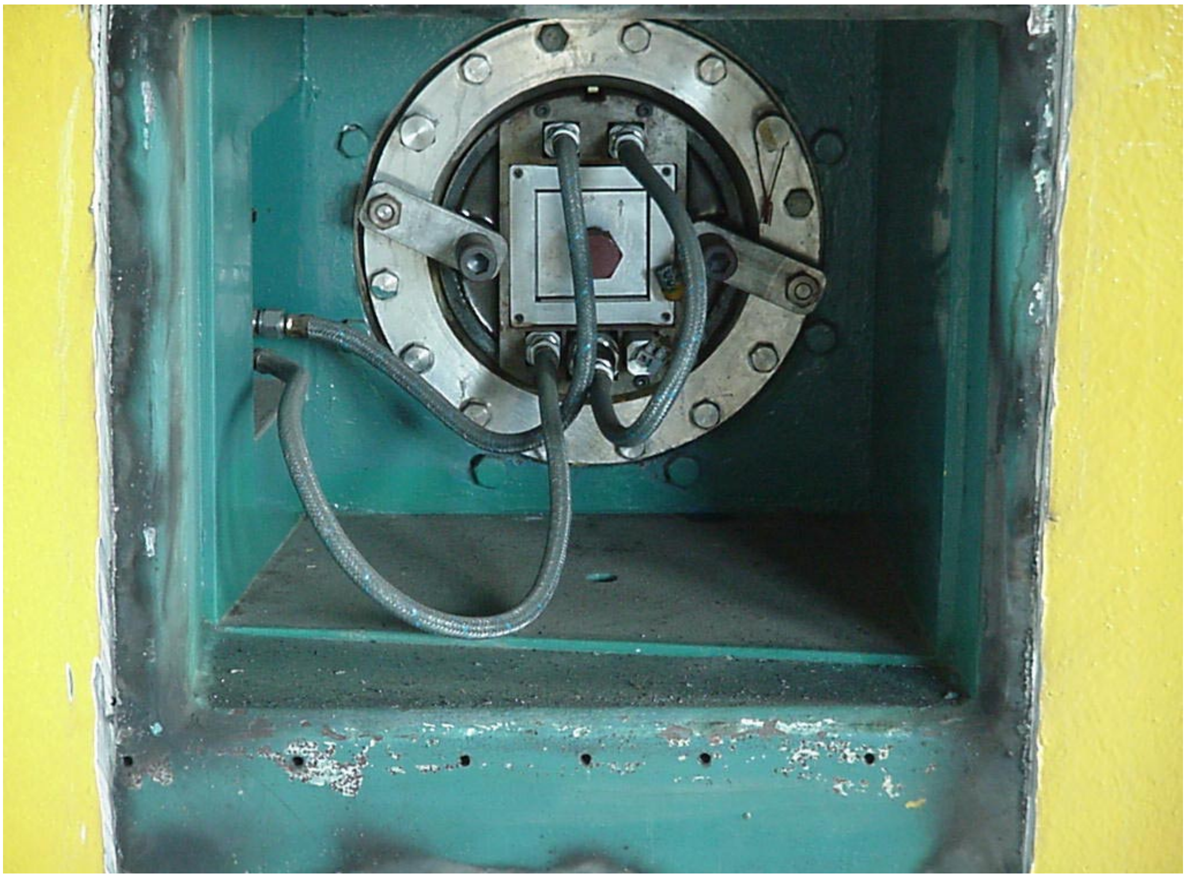

Figure A30. The vestibule box of a beam tube after removal of the steel plate.

Figure A31. Removal of a beam plug from the reactor block.

Figure A32. Measurement of the γ-dose rate along a beam plug.

Figure A33. Removal of a beam hole sleeve from the reactor block.

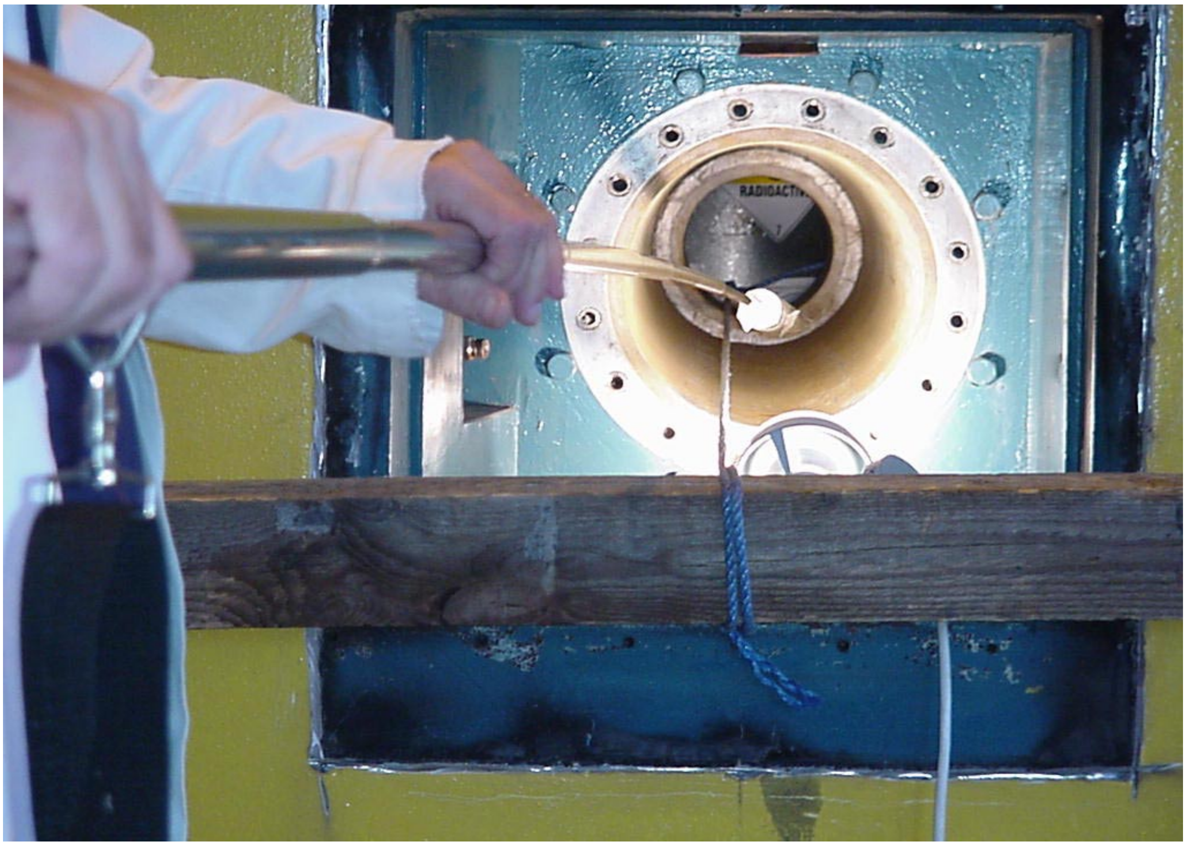

Figure A34. Measurement of the γ-dose rate through an empty beam hole.

Figure A35. Removal of a S-tube.

Figure A36. Measurement of the γ-dose rate through an empty instrument thimble.

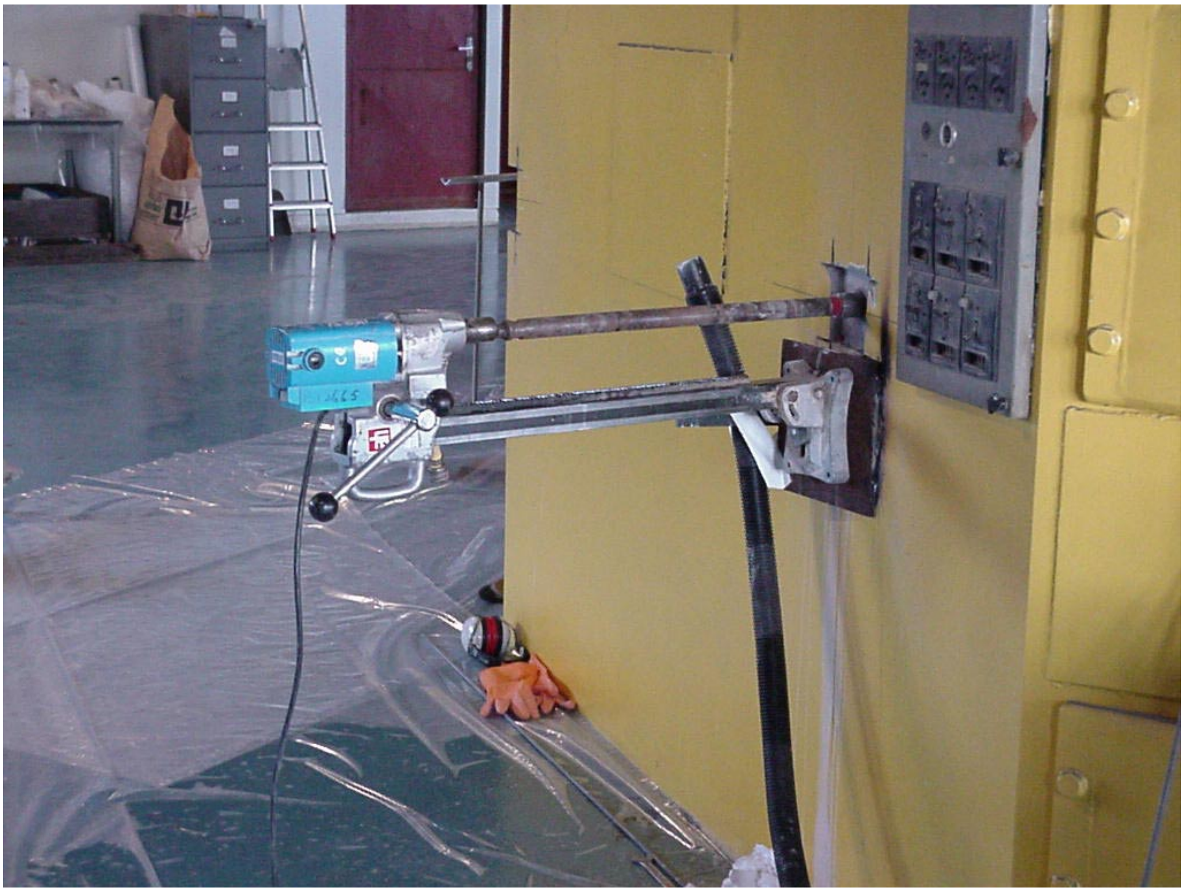

Figure A37. Equipment for drilling cored holes through the concrete shield.

Figure A38. A borehole core.

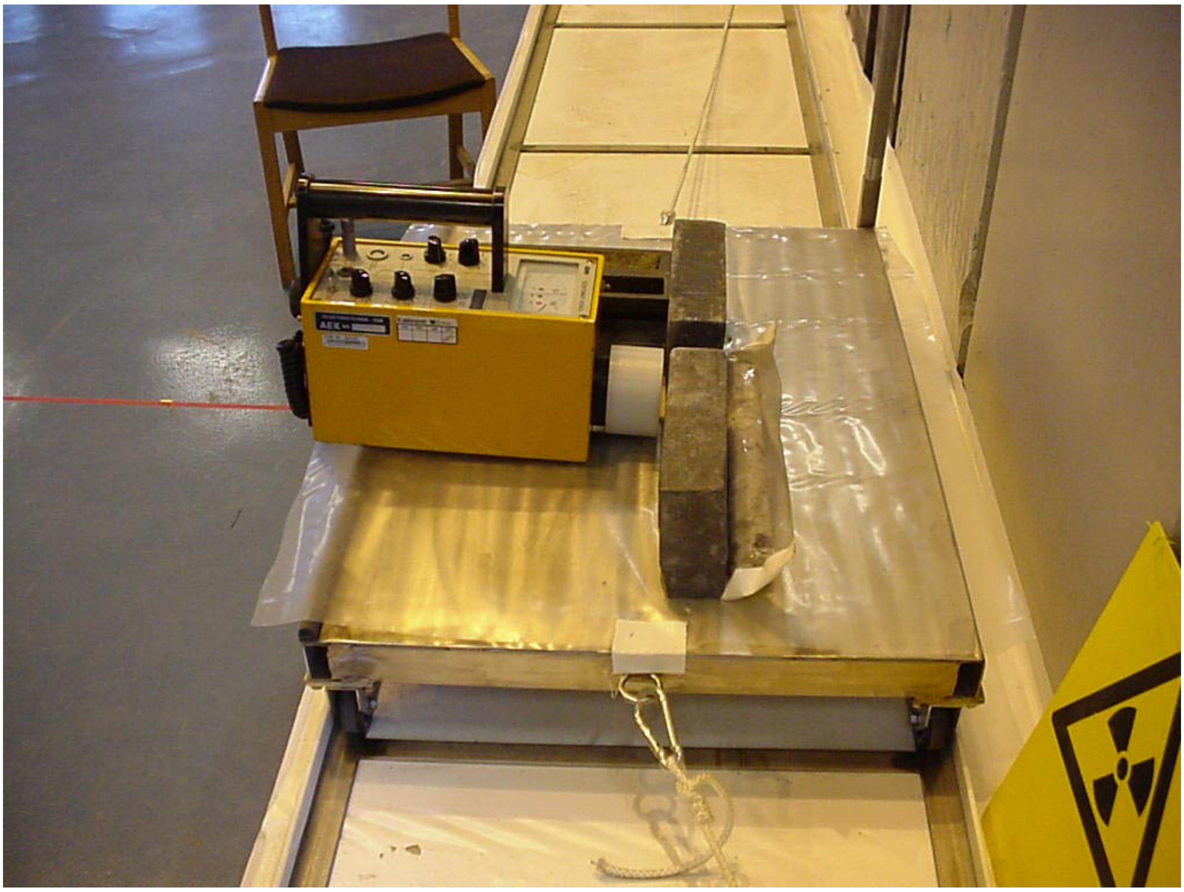

Figure A39. Measurement of the γ-dose rate along a borehole core.

Bibliographic Data Sheet **Risø-R-1412EN)**

Title and author

The DR-2 Project

Povl L. Ølgaard

ISBN
87-550-3255-9; 87-550-3256-7 (Internet)

ISSN
0106-2840

Department or group
Risø Decommissioning and
Radiation Research Department

Date
June 2003

Groups own reg. number(s)

Project/contract No(s)

Pages	Tables	Illustrations	References
89	14	66	19

Abstract (Max. 2000 characters)

DR-2 was a 5 MW tank type, water moderated and cooled research reactor, which was operated at the Risø National Laboratory from 1959 to 1975. After the close-down in1975 the DR-2 has been kept in safe enclosure until now. The aim of the DR-2 project reported here was to characterize the present state of the reactor and to determine, which radionuclides remain where in the reactor in what amounts.

The first part of the reactor to be investigated was the reactor tank. The lids at the reactor top were removed, air samples taken and smear test made in the tank. Then the control rods, the magnet rods and other active components were removed from the tank, measured, cut up, and disposed of in waste drums. The beryllium reflector elements were stored in specially prepared containers. When all movable parts had been taken out, the remaining radiation field was measured by use of thermo-luminescence dosimeters.

Next the hold-up tank room and the concrete cave (the igloo) in front of the thermal column were opened. They had been used as storage rooms for various components and all movable components were removed, measured and, if active, cut into waste drums. Only large and active objects remain stored in the igloo and the hold-up tank room.

A number of graphite stringers were taken out of the thermal column and their activity measured. It was a surprise to find, that the stringers contained significant ^{152}Eu and ^{154}Eu activity.

Some of the beam plugs and irradiation tubes were extracted and reinserted after their activity had been measured.

The activity of the radiation shield of the reactor was measured in three different ways: By drilling two cored holes through the shield, by thermo-luminescence dosimeter measurements in vertical tubes in the concrete shield and by measurements through an open beam hole.

At the start of the project the activity in DR-2 was about 45-50 GBq. Now it is about 5-10 GBq.

Based on the results of the DR-2 project it is believed that the reactor can readily be dismantled.